Modelling of Renewable Energy Systems in the Maldives

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Abstract

In this report results are presented of a modelling study to determine optimal renewable energy systems to be implemented in the Maldives. The simulation programme HOMER was used to design the systems and to analyse their technical and economic performances. The analysis has been performed for the capital of the Maldives named Malé and four inhabited outer islands, i.e, Fehendhoo, Uligamu, Nolhivaranfaru and Hanimaadhoo, which are representative for most Maldivian islands.

Several systems consisting of photovoltaic (PV), wind, and biomass electricity generators were studied and compared. Concerning the four outer islands in the Maldives, a PV-wind-biomass hybrid system is the most interesting option for these islands as the use of biomass is a good method to supplement the fluctuation in PV-wind power generation under variable weather conditions. The cost of electricity for these systems lies between 0.61 and 0.67 \$/kWh, which is high compared to the present cost of 0.26 - 0.39 \$/kWh. The systems are dimensioned such that loads are matched during the whole year. This leads to a surplus of electricity, which could be used for other purposes such as water desalination. This reduces the cost of electricity to 0.40-0.44 \$/kWh.

In the case of Malé, it is estimated that about 8% of the electricity load can be covered by renewable energy systems (6% from PV and 2% landfill gas), which prevents the emission of 5432 tCO_2 per year. A wind system was not studied on Malé as there is no available place. However, an offshore wind farm would be a possibility.

In addition, a public transport system with fuel cell powered taxis in Malé was modelled, where hydrogen for the fuel cells was generated by means of a PV-powered electrolysis system. Associated costs are 0.56 \$/km and a reduction of GHG emission of 1051 ton CO_2/year can be reached. Present costs for the diesel-fuelled taxis are 0.12 \$/km.

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I. Introduction

1. FRAMEWORK

In December 1997, the Kyoto Protocol set binding greenhouse gas (GHG) emissions targets for countries that sign and ratify the agreement. The gases covered under the protocol include carbon dioxide, methane, nitrous oxide**,** hydrofluorocarbons, and perfluorocarbons, and sulphur hexafluoride. Although the Maldives does not emit a significant amount of GHGs, it is particularly vulnerable to the harmful effects of climate change: they are liable to floods (80% of the area is one meter or less above sea level) and coral reef bleaching.

Maldives is a party to the United Nations Framework Convention on Climate Change (UNFCCC) and the first country to sign the Kyoto Protocol. Maldives is a non-annex I party to the UNFCCC and is not obliged to implement GHG mitigation measures. However, mitigation measures have been developed not only to reduce the Maldives emission of GHGs, but as a step towards achieving greater energy independence for sustainable development.

The Asia Pro Eco programme of the European Commission was designed to improve environmental performance and technology partnership between the 25 member states of the European Union and 17 Asian countries. See *appendix 1* for a list of all eligible countries.

One of the 31 projects selected by the Asia Pro Eco programme in 2003 is SMILES, which is the acronym for Strengthening Maldivian Initiatives for a Long-term Energy Strategy. Its lead applicant is the Agency for the Environment and Energy Management (ADEME) in France; its two partners are the Ministry of Communication, Science and Technology (MCST) in the Maldives and the Utrecht Centre for Energy research (UCE) in the Netherlands. The goal of this project is to assist the MCST and the stakeholders in the Maldives to formulate energy policy strategies concerning in particular these two points: the rapid growth of electricity demand in the capital Malé and the rural electrification in the outer islands which is unreliable and expensive

As mentioned above, Maldives develops mitigation measures to reduce emission of GHGs and to achieve greater energy independence. The mitigation of GHG emissions is possible by lowering the demand on the imported fossil fuel. This can be achieved by increasing the efficiency in generating and utilising electricity, and improving the efficiency of the transportation mechanisms, as the two major areas of energy uses in the Maldives are the electricity and the transport sectors. Reducing methane (CH_4), the main source of emission of GHGs from landfills and sewage discharges, is another possibility. This can be achieved through improving the solid waste disposal methods, management practices and providing treatment of sewage discharges.[6]

Since the sites under examination do not have any special resources like streams for hydropower or geothermal sources, the only renewable sources investigated in this project are sun, wind and biomass. In order to determine the optimal RE systems that use one or more of these RE systems I will focus on GHG emission reduction due to the reduction in Diesel Fuel Oil (DFO) consumption and the investment costs as well as the costs of energy (COE)[1].

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[1] See for an explanation paragraph II.7.3

The structure of this report is as follows. First, I will present briefly the situation in the Maldives, the computer model I used and the islands in the Maldives I studied. Then, in the Supporting study chapter I will show you all the information I had to collect in order to be able to realize the simulations and after, of course, the results of the simulations I have carried out.

2. ENERGY NEEDS

2.1. ENERGY

The Maldives has no reserves of oil, natural gas or coal. Wood had been the main source of energy, which was mainly used for cooking in the residential sector. Presently, very few people use wood for cooking but instead use kerosene or gas.

2.2. OIL

The Maldives produces no oil. Motor gasoline, jet fuel, kerosene and gas diesel are imported. Gas diesel is the largest import, which was around 139 thousand metric tons in the year 2000. Kerosene was the smallest import, at around 5 thousand metric tons in 2000, see Table 1.

The economy of the Maldives is particularly tributary of fossil fuels importation.

Year	**1998**	**1999**	**2000**
Motor Gasoline	5	8	9
Jet Fuel	72	79	69
Kerosene	NA	4	5
Gas Diesel	98	131	139
Total	*175+Kerosene*	*222*	*222*

Table 1: imports of Motor Gasoline, Jet Fuel, Kerosene and Gas Diesel in thousands of metric tons[17]

2.3. ELECTRICITY

Of the 199 inhabited islands 24 have full day electricity through the State Electricity Company (STELCO). The remaining inhabited islands utilize privately generated electricity or electricity produced by generators operated by the Islands Developing Committees (IDCs). The total capacity was around 36 MW in 2000 and rose to 106,2 MW in 2002. Electricity production in 1991 was 31 million kWh, increasing by 1995 to 63 million kWh. In the year 2000, 44 million kWh was consumed by the household sector, while a total of 116 million kWh was produced. And electricity generation is expected to continue to increase significantly in coming years, see Figure 1.

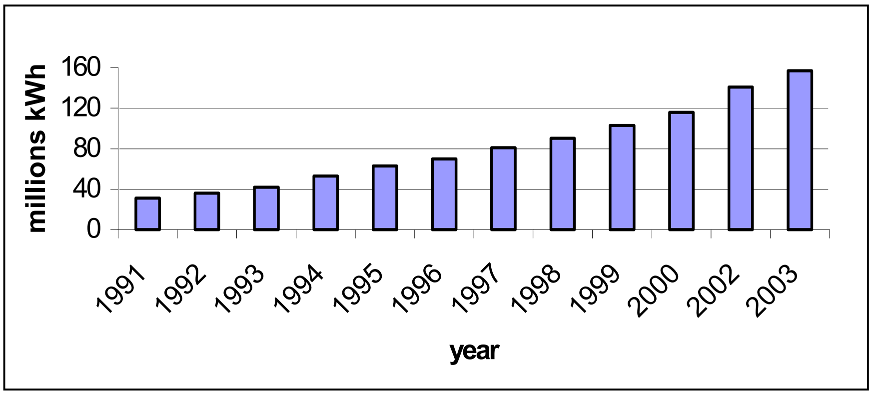


Figure 1: the electricity production in the Maldives[17]

2.4. LAND TRANSPORT

The main land transport occurs in Malé where most roads are paved. Traffic is on the left. Transport in Malé is mostly on foot or by bicycle. However, there are increasing numbers of cars and lorries on the island as well as quite a number of motorcycles, see Table 2. Taxis are the only public transport.

Year	*1990*	*2000*	*2002*	*2003*
Motor cars	623	1860	1948	2074
Motor cycles	2943	10880	14248	16774

Table 2: registered vehicles and vessels in the Maldives [9]

3. HOW TO DESIGN THE SYSTEM?

In order to determine the optimal renewable energy hybrid system design that can cover the load for each of the five studied islands in the Maldives I will use HOMER (Hybrid Optimization Model for Electric Renewables) [13]. HOMER is a computer model that is developed by NREL (National Renewable Energy Laboratory) and performs comparative economic analyses on proposed and actual distributed generation power systems. HOMER can also model systems that are not hybrids, like stand-alone PV systems. For a particular application scenario, inputs to HOMER include load data, renewable resource data, system component specifications and costs, and various information of optimization (e.g. number of components). Furthermore, HOMER can perform "sensitivity analyses," where the values of certain parameters (e.g. fuel cell cost) can be varied to determine their impact on the COE for the system in question. Further details of HOMER will be given when appropriate in the various sections on technology.

To obtain the input data for HOMER, component information was collected from research literature and manufacturers to obtain estimates of costs. I have to gather enough information to make it possible for me to evaluate the following parameters:

- the technologies' investment costs and technical features
- their useful life and maintenance requirements
- the quantities of energy required annually
- the costs of the energy produced by the various plants

4. LOCATION OF THE ISLANDS

The Maldives consists of a chain of coral atolls, 80-120 km wide, stretching 860 km from latitudes 7, 6'35"N to 0, 42'24"S, and lying between longitudes 72, 33'19"E to 73, 46'13"E. These coral atolls are located on the southwest coast of the Indian sub-continent, extending into the Indian Ocean (Figure 2).. It is believed that the Maldives was formed about 65 -225 million years ago in the Mesozoic Era. There is more than a single theory on how the Maldives was formed, and one of them suggests that the Maldives grew above foundered continental crustal segments[4].

The 26 geographic atolls in the Maldives vary enormously in shape and size. The largest atoll is Huvadhu Atoll with an area of approximately 2.800 km^2 [8] and the smallest atoll Thoddoo Atoll has an area in the order of 5,4 km^2 [5]. The characteristics of the atolls, reefs and reef islands vary considerably from north to south. The northern atolls are broad banks, discontinuously fringed by reefs with small reef islands and with numerous patch reefs and faros in the lagoon[12]. In the southern atolls, faros and patch reefs are rarer in the lagoon, the continuity of the atoll rim is greater, and a larger proportion of the perimeter of the atolls is occupied by islands.

A total of 1.192 islands are found in the chain of 26 geographic atolls, and the islands differ depending on location, form and topography[12]. The islands vary in size from 0,5 km^2 to around 5 km^2 and in shape from small sandbanks with sparse vegetation to elongated strip islands. Many have storm ridges at the seaward edges and a few have swampy depressions in the centre. The largest island is Gan in Laamu Atoll with an area of 5,16 km^2 [8]. The total land area of the Maldives is about 300 km^2.

The maximum height of land above mean sea level within the Maldives is around 3 meters and around 80% of the land area is less than 1 meter above mean high tide level.

The 26 geographical atolls in the Maldives are grouped into 20 administrative regions. These administrative regions are also referred to as atolls. The capital, Malé forms a separate administrative unit. Out of the 1.192 islands 199 are inhabited[8] and 87 have been developed as tourist resorts[7].

I will study four of the 199 inhabited islands and the capital Malé. I mention the latitude of the sites, which are used in HOMER to calculate the radiation incident on a tilted surface (a PV module) and to synthesize the hourly solar radiation.

Site	**Latitude**	**Households**	**Inhabitants**
Fehendhoo	4°90 N	40	245
Uligamu	7°08 N	63	437
Nolhivaranfaru	6°72 N	100	650
Hanimaadhoo	6°45 N	240	1.290
Malé	4°17 N	9.700	82.069 (2003)

Table 3: some characteristics of the studied islands

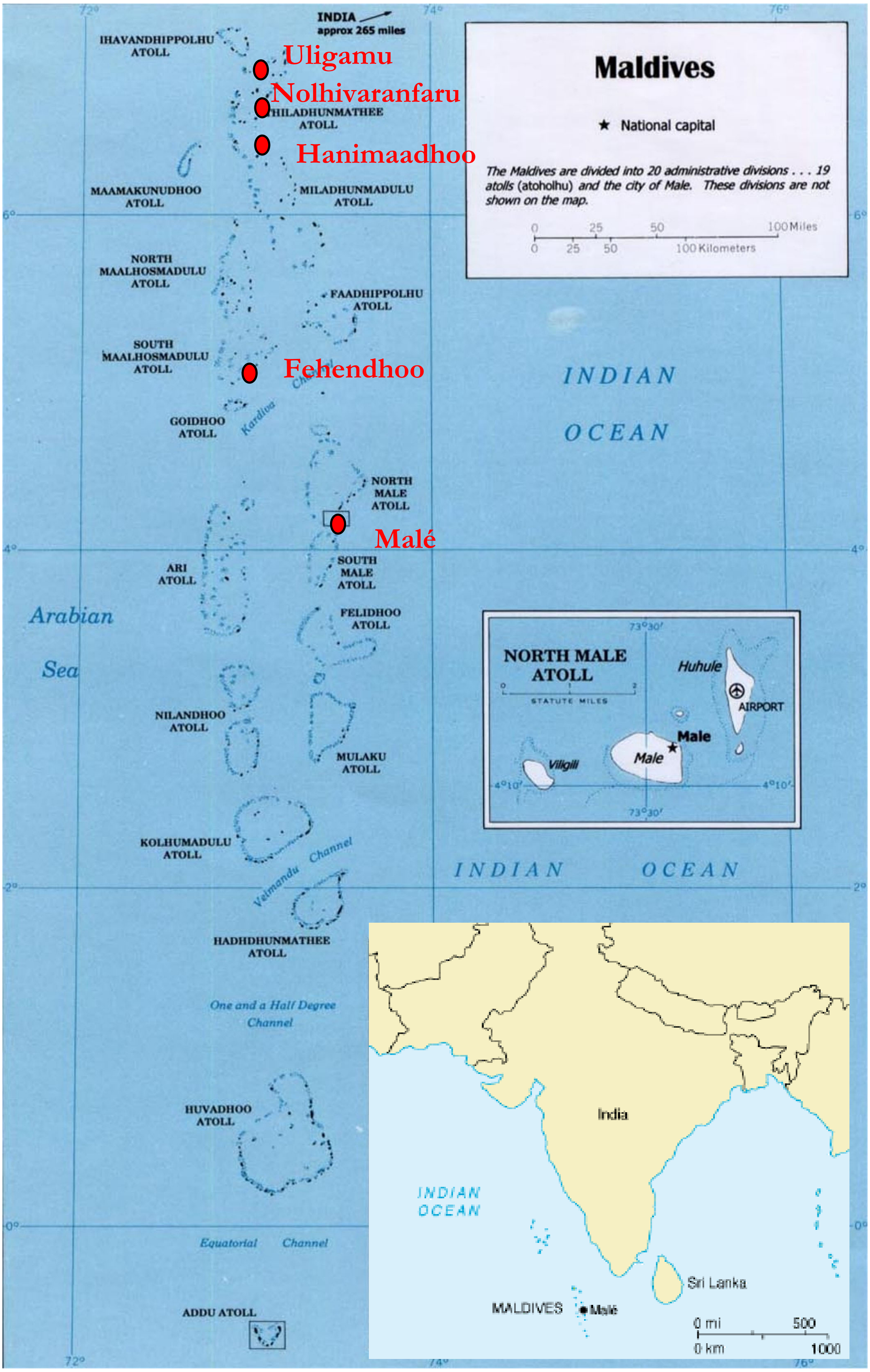


Figure 2: location of the studied islands [14], [15]

Description of Malé:

Malé is an island of about 2 km long and 1 km wide with a population of 83.500 inhabitants in 2004. Malé is completely covered with roads and buildings, so it will be difficult to find place to install PV modules and wind turbines (WTs). In this report I will consider that it is impossible to install a wind turbine in Malé and the area for solar panels is 20.000 m^2 on the rooftops of the new and old government and office buildings. However we can't reduce the capital to the only island of Malé. Today we can speak of an agglomeration, which is spread on several islands, natural or artificial (Figure 3).

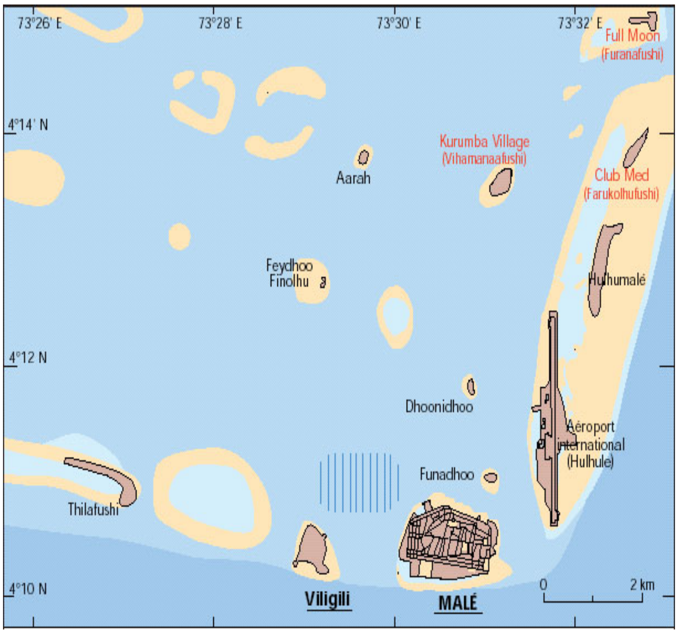


Figure 3: agglomeration of Malé

The most known is certainly Hulhule where there is the airport. Then you have Viligili, a "dormitory island". The smaller islands have precise assignments. Aarah is used as residence of holidays to the Maldivian president. The holiday camps of the school establishments are installed on the island of Feyhdoo Finolhu. Dhoonidhoo shelters political prisoners. Funadhoo is covered with tanks being used for fuelling the Maldives. And Thilafushi, called trash or rubbish Island, receives the biologically degradable waste of the agglomeration.

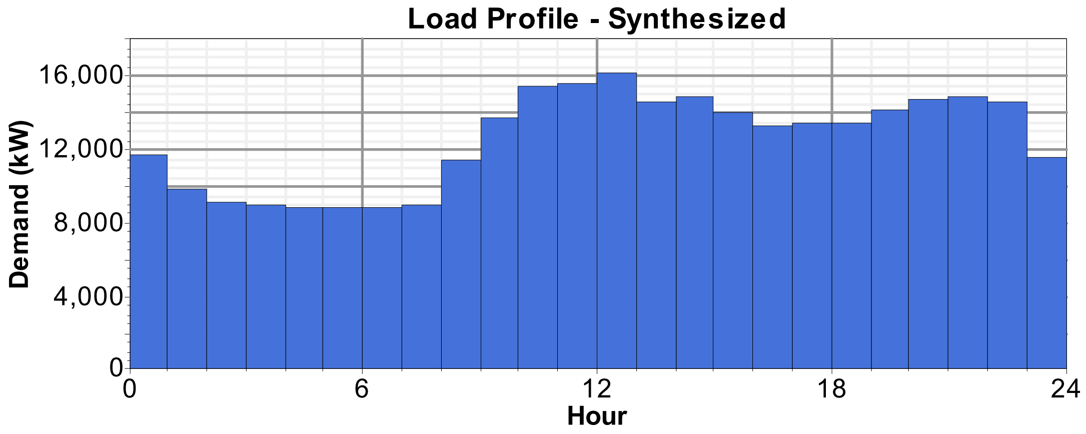
II. Supporting study

1. LOAD

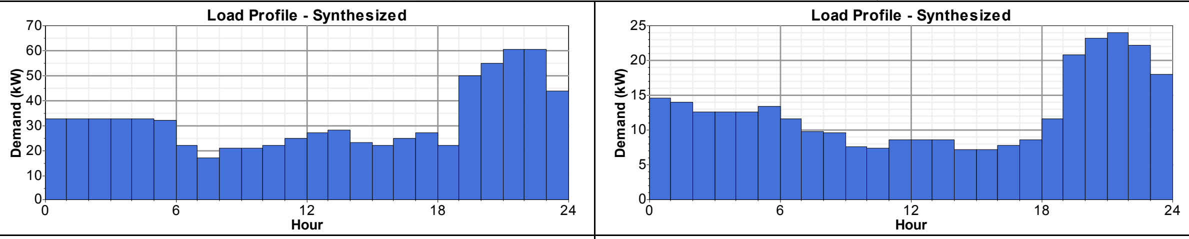
Having knowledge of the load characteristics, especially the peak load is essential to design the system.

HOMER simulates the operation of a system by making energy balance calculations for each of the 8,760 hours in a year. The hourly load profiles are not available for a whole year, so HOMER was used to synthesize the load profiles (with randomness) by entering the values for a typical day.

I have obtained the following load curves (Figure 4) thanks to Klaas van Alphen[3].

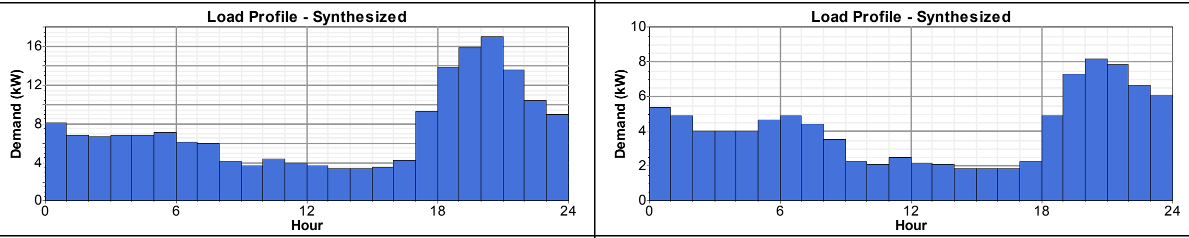


Island: Malé
Peak load (AC): 25 MW Total demand: 300 MWh/day



Island: Hanimaadhoo
Peak load (AC): 90 kW Total demand: 765 kWh/day

Island: Nolhivaranfaru
Peak load (AC): 38 kW Total demand: 300 kWh/day



Island: Uligamu
Peak load (AC): 26 kW Total demand: 178 kWh/day

Island: Fehendhoo
Peak load (AC): 13 kW Total demand: 100 kWh/day

Figure 4: Typical daily load profiles (demand in kW) of the sample Outer islands and the capital Malé (STELCO 2003, Transenergy 2004, ADB 2000)

The demand curves show that load profiles between the outer islands are quite similar, except that the overall electricity demand increases with the same magnitude as the number of households. The peak demand in the evening is mainly caused by the lights, air fans and TVs that are switched on. During the night time, many (street) lights and air fans remain turned on, in opposition to the daytime where the load consists of refrigerators and other base load appliances. The load curves within the outer islands do not differ that much, but in comparison with the main island of Malé two major differences can be found. First of all, in Malé, the energy consumption per capita is almost 4 to 5 times higher than in the outer islands and second the load curve is much more flattened, because of the high-energy demand during office hours. This is mainly caused by the rapid penetration of air conditioning systems in Malé.[3]

Note: The islands studied in this report represent the majority of the Outer islands but islands that have industries and resort islands do not correspond to these load profiles and should be studied apart.

2. AVAILABILITY OF RESOURCES

2.1. SOLAR RADIATION

Knowing the solar radiation is of great importance because the energy output of the PV array is function of this.

The solar global radiation had been measured by pyranometers at the airport (Hulhule). It was decided to put up only one solar measurement station in the Maldives, because the amount of solar radiation in the Maldives does not differ significantly over the longitude of the country.[3] The values that are used in HOMER are shown in Table 4.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	*Avg*
5.53	6.54	6.41	5.82	5.02	4.56	4.90	4.86	5.27	5.59	5.35	5.05	*5.4*

Table 4: monthly solar radiation data in the Maldives in kWh/m^2/day

I use HOMER to synthesize data, for that I enter the twelve average monthly values of solar radiation, then HOMER builds a set of 8760 solar radiation values, one for each hour of the year. HOMER creates the synthesized values using the Graham algorithm. This algorithm produces realistic hourly data, and it is easy to use because it requires only the latitude and the monthly averages. The synthetic data displays realistic day-to-day and hour-to-hour patterns. If one hour is cloudy, there is a relatively high likelihood that the next hour will also be cloudy. Similarly, one cloudy day is likely to be followed by another cloudy day. The synthetic data is created with certain statistical properties that reflect global averages. So data generated for a particular location will not perfectly replicate the characteristics of the real solar resource. But our tests show that synthetic solar data produce virtually the same simulation results as real data. Differences in key performance output variables like annual PV array production, fuel usage, generator run time, and battery throughput are typically less than 5%. Differences in key economic output variables like total net present cost and levelized cost of energy are typically less than 2%.[13]

2.2. WIND SPEEDS

In order to calculate the power of a WT, we must have knowledge of the wind speeds; anemometers placed at a height of 10 m are normally used to obtain these values. When hourly wind speed measurements are not available, hourly data can be generated synthetically from monthly averages. HOMER's synthetic wind data generator is a little more difficult to use than the solar data generator because it requires four parameters:

- The *Weibull* k value is a measure of the distribution of wind speeds over the year. It is 2 by default because this has been shown to represent most wind regimes fairly accurately. Lower *k* values correspond to broader wind speed distributions, meaning that the wind speeds vary over a wide range. Wind regimes where the wind tends to vary over a narrower range (like tropical trade wind environments) have higher *k* values. As an example, Figure 5 shows three Weibull distributions.

All three have the same average wind speed of 6 m/s, but each has a different Weibull *k* value. A Weibull factor *k* of 3 is assumed for the wind regime in the Maldives.

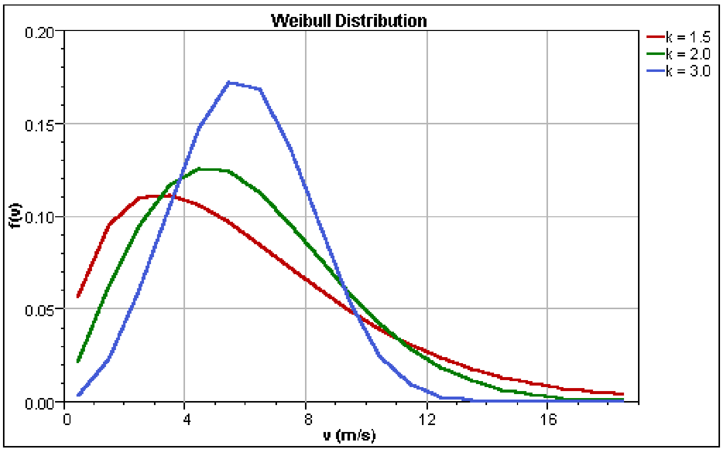


Figure 5: three Weibull distributions with the same average wind speed of 6 m/s but different Weibull k [13]

- The *autocorrelation factor* is a measure of the randomness of the wind. Higher values indicate that the wind speed in one hour tends to depend strongly on the wind speed in the previous hour. Lower values indicate that the wind speed tends to fluctuate in a more random fashion from hour to hour. This parameter is influenced by local topography. Autocorrelation factors tend to be lower (0.70 - 0.80) in areas of complex topography and higher (0.90 - 0.97) in areas of more uniform topography. In the case of the Maldives an autocorrelation factor of 0.9 is supposed.
- The *diurnal pattern strength* is a measure of how strongly the wind speed depends on the time of day. In most locations, for example, the afternoon tends to be windier than the morning. Higher values indicate that there is a relatively strong dependence on the time of day. Lower values indicate that the wind speed is not strongly related to the time of day. A low value of 0.08 is assumed for the Maldives.
- The *hour of peak wind speed* is simply the time of day that tends to be windiest on average throughout the year. In the Maldives, the wind speeds tend to be higher during the night (01H00).

The monthly wind speeds averages for the Outer[2] islands and Malé have been extracted from the doctoral thesis of Klaas van Alphen [3]. The readings are in m/s, recalculated at a height of 10 m, see Tables 5 and 6.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	*Avg*
5.08	4.23	3.55	3.82	5.98	7.23	4.11	5.11	4.39	4.83	2.97	4.71	*4.7*

Table 5: wind resource data in the Outer islands

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[2] All islands, except Malé are considered as Outer Islands.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	*Avg*
5.87	4.16	3.15	3.38	5.23	5.37	3.48	4.60	4.31	4.81	3.06	4.89	*4.4*

Table 6: wind resource data in the capital Malé

Note: The weather is dominated by two monsoon periods: the southwest (rainy) monsoon from May to November; and the northeast (dry) monsoon from January to March when winds blow predominantly from either of these two directions. As you can see, there's low wind during the month of November but the solar radiation is quite high; on the contrary, during the months of May and June the wind density is high and the solar radiation is low.

2.3. BIOMASS POTENTIAL RESOURCE

I have obtained all the information concerning the potential of biomass in the Maldives in a report called Biomass Survey that had been prepared by Energy Consulting Network and supported by Tech-wise, Danish Technological Institute and Gas Con for the MCST.[1]

2.3.1 The Outer islands

In the inhabited islands (not including Malé and the resorts islands), types of biomass are solid biomass and agro waste, animal waste and household waste.

Agro waste products that are suitable for combustion (cooking/smoking) include:

- Fuel wood
- Saw dust (from wood processing)
- Palm fibres (from felling, cuttings, etc)
- Coconut shells (from coconuts processing)
- Coconut tree parts (from cuttings, etc)

The animal waste is the manure from cow, goats, chicken and ducks; but it also included shredded kitchen waste and shredded green biomass residues from agricultural production.

In the studied islands, the potential for use of biomass is as indicated in Table 7.

Site	Solid agro waste (t/yr)	Animal waste (t/yr)
Fehendhoo	21.85	24.24
Uligamu	38.97	43.22
Nolhivaranfaru	57.98	64.32
Hanimaadhoo	115.06	127.59

Table 7: potential biomass available for utilisation in the Outer Islands

2.3.2 The capital Malé

There is no agro or animal waste in Malé. The biomass and waste resource in this area is defined from the waste deposits from domestic and industrial sectors made to the landfill in Thilafushi Island.

The island of Thilafushi, located to the South West of Malé, was reclaimed totally by waste materials. Since December 1991 this area has been used as a landfill.

Figure 6: a view of the island of Thilafushi

A total of 3646 ton/year of wood fuel and sawdust can be properly sorted and used as biomass.

Another potential resource is the extraction of landfill gas from the site. It had been estimated that 1,024,684 m^3/year can be extracted in 2006; I will use this value but as it is estimation and I will use the current load demand in Malé, it will just give us an idea of the percentage that landfill gas production can covered.

3. DESCRIPTION OF THE MAIN COMPONENTS OF PV/WIND SYSTEMS AND THEIR ASSOCIATED COSTS

In this part, I study the capital, replacement and O&M costs of the main components present in a PV-wind-diesel hybrid system: PV system, wind turbine, batteries, inverters and generators, see Figure 7.

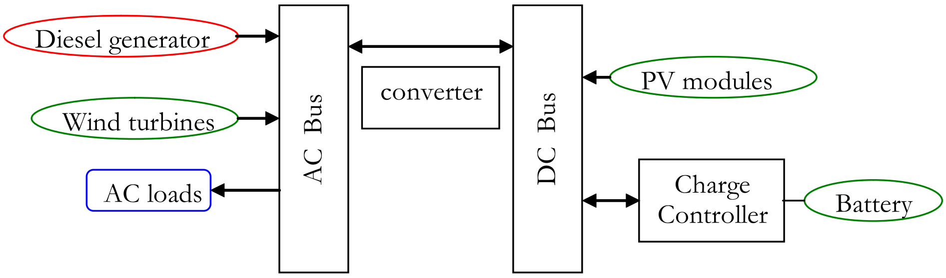


Figure 7: schematic of a PV-wind-battery hybrid power system
Note; Some WTs provide DC power.

The capital costs include the cost to purchase, to install, and to transport the components and the training costs. The capital costs also encompass the costs of a feasibility study that include system design and engineering and site investigations. The costs for the detailed feasibility study for wind projects (between \$1000 and \$2500 per kW capacity) are higher than for photovoltaic projects (between \$500 and \$1000 per kWp) because a WT makes noise, has a visual effect on the landscape and has an impact on the flora and fauna. I take into account the feasibility costs in the Economic inputs window of HOMER.

PV modules and WTs have an anticipated 20-year lifetime. Therefore I choose project lifetimes (the length of time over which the costs of the system occur) of 20 years. The project lifetime is used to calculate the annualized replacement cost and annualized capital cost of each component, as well as the total net present cost of the system.

3.1. TRANSPORTATION COSTS

Costs of transportation have to be taken into account in the capital costs but we can determine them only when we know the equipment we need. In order to reduce these costs my main interest is in suppliers not so far away for the Maldives, mainly in India.

The cost of shipping of one AOC 15/50 wind turbine to the Maldives is in the range of \$15,000 US Dollars. (AOC)

3.2. PV SYSTEM

3.2.1 PV modules

A solar cell is a semiconductor device designed to turn solar irradiance into electricity. If solar cells are connected in series, then the current stays the same and the voltage increases. If solar cells are connected in parallel, the voltage stays the same, but the current increases. Solar cells are combined to form a module to obtain the voltage and current (and therefore the power) desired. A PV array is a group of PV modules put together to generate electricity. A PV array produces DC voltage and current those are used to power the load.

There are three main types of cells (made of silicon), see also Figure 8:

- Monocrystalline cells that have efficiency to 12 from 16 %.
- Polycrystalline cells that have efficiency to 11 from 13 % and are cheaper than monocrystallines.

➩ The crystalline silicon cells are cells of the first generation with a reasonable efficiency.

- Amorphous cells have efficiency to 6 from 10 % but have lower production costs; they are cells of the second generation (thin film).

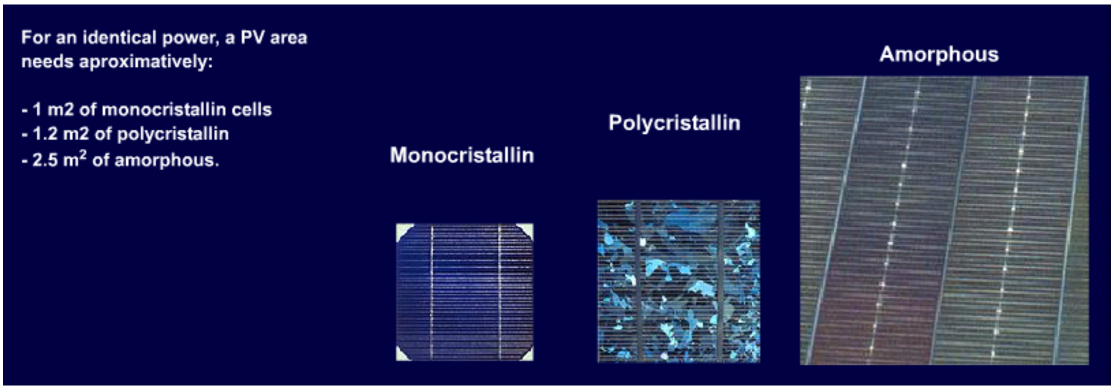


Figure 8: energy production of three different types of modules[20]

Concerning the capital Malé where place is a very important issue, the choice for efficient modules appears obvious.

3.2.2 Balance of system (BOS)

BOS is constituted by the components added to the modules to complete a PV-system

- *Mounting structure*: Photovoltaic arrays have to be mounted on some sort of stable, durable structure that can support the array and withstand wind, rain, and other adverse conditions.[3]

Figure 9: Thin-film PV arrays in New Delhi

_Ground mounting is preferable for the four outer islands because it allows greater ease of installation, maintenance, and operation.

_Rooftop mounting and louvers are chosen in Malé because of lack of space, but access for seasonal adjustment & installation can be difficult.

In both cases, stationary structures will be installed.

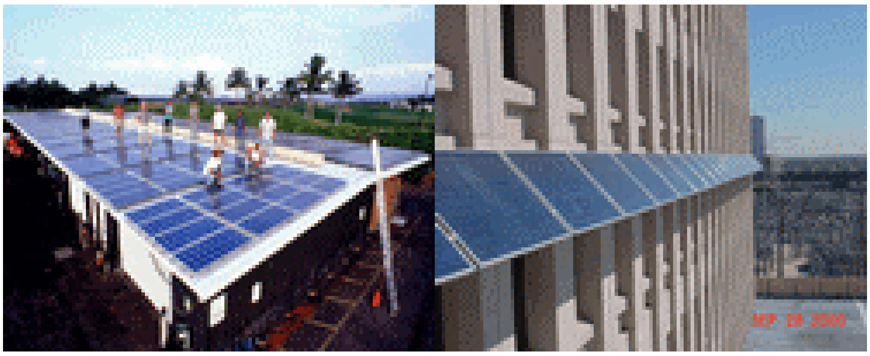


Figure 10: Left; rooftop power system installed in Hawaii. Right; PV awnings at the University of Texas Health Science Centre at Houston

- *Inverter:* an inverter converts DC voltage and current into AC Sine wave power.
  An inverter is required in all the systems we study because AC loads are present.
- *Battery*: batteries are more accurately explained in paragraph 3.4.
- *Regulator*: a regulator controls the amount of voltage and current to maintain a battery bank at its optimum level, therefore maintaining maximum efficiency and battery life. A regulator prevents overcharging of the battery bank resulting in reduced battery life.
- *MPPT* (maximum power point tracker): it maintains the voltage of to array to a value that maximises the output.

Concerning PV system, the purchasing costs encompass the costs of the PV modules, the mounting structure, the regulator and the MPPT.

3.2.3 the capital costs

Training costs

It is not so difficult to maintain and operate a PV system but some people have to be trained as it becomes more complex with the size of the system.

System size (kW)	0-25	25-75	75-150	>150
Costs ($)	550	1,650	3,850	7,700

Table 8: training costs for different sizes of PV systems

Installation costs

Figure 11: installation of ground-mounting structures at Austin (Texas)

The installation costs vary from \$800 to \$1500 per kWp depending on the mounting structure; it is easier and cheaper to install ground-mounting structure in the outer islands than roof mounting structure in Malé.

The cost of a PV system is expressed in \$ per peak-watt and are detailed in Table 9. Peak-watt is defined as the power at Standard Test Conditions (STC, 1000 W/m^2, AM1.5, 25 °C).

Size (kWp)	Capital (\$)	Replacement (\$)	O&M (\$/yr)
2	14,550	10,415	115
3	21,770	15,623	173
25	181,400	130,199	1438
30	218,780	156,239	1726

Table 9: PV inputs data in HOMER

The capital costs were calculated from the "ready to install packages" that include Sanyo modules, UniRac SolarMount mounting kits, Sunny Boy inverters, cables and all necessary hardy electrical components[18]. As the costs for the inverter have their own inputs window, I subtract the cost of the inverter. As an example, I detailed the capital costs for the PV array of 2 kWp: 14550 = 10900 + 1600 + 1500 + 550 that corresponds respectively to the costs to purchase, install, and transport of components and the training costs.

3.2.4 Energy output

HOMER always deals with the PV array in terms of rated kW, not in m^2. So it does not need to know the efficiency. By the way, HOMER assumes that the output of the PV array is linearly proportional to the incident radiation, so if the radiation is 0.75 kW/m^2, the array will produce 75% of its rated output (HOMER assumes the PV array has a maximum power point tracker).

STC is the test condition used to determine the power ratings of PV panels. Basically, the PV panel is flashed with a controlled light source at 1,000 W/m^2, with the cell and air temperature at 25°C and 0 m/s wind speed, the power output is measured (typically shown as Maximum Power: P_{max}). These conditions are, in fact, far from daily practice.

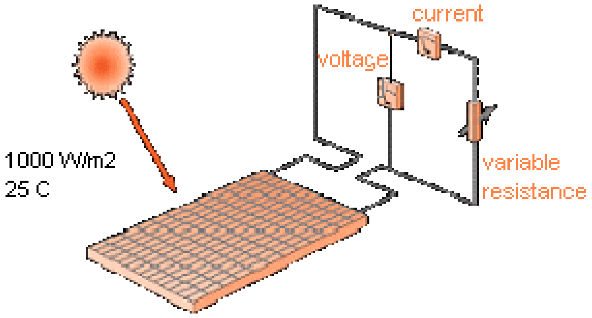


Figure 12: representation of STC

PV panels become less efficient as their temperature increase. The power produced is roughly anti-linear in the temperature range under which PV panels are exposed. Manufacturers assign a value to this characteristic, and it is usually expressed as a percentage change of the total power per °C. For example, if a panel has a temperature coefficient of power that is –0.50%/°C, the panel produces 0.5% less power for every 1°C increases in temperature.

PV panels are exposed to sunlight, they absorb the infrared radiation produced by the sun and they heat up. Moreover, they are dark coloured and tend to warm significantly: as hot as 80°C when there's no wind blowing. It is worth noting that HOMER's PV input page has a derating factor. This is used to compensate for the reduction in efficiency because real world conditions are somewhat less favourable than standard test conditions. The most important factor is array temperature, but dust and wiring losses have a small effect also. The default value is 90%. A slightly lower number should be used in very hot climates.

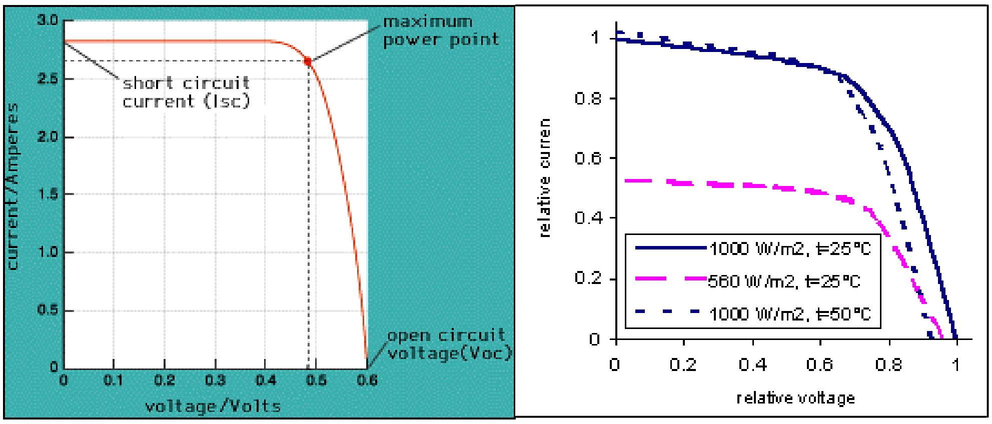


Figure 13: examples of I-V curves that show the characteristics of a PV cell.

To account for these loses and these due to soiling of the PV panels, we enter a derating factor that is a scaling factor applied to the PV array output and, for the Maldives I have assumed a derating factor of 85%.

The energy produced by the PV array is calculating using the following formula:

Equation 1: $E_{PV} = D \times C \times I$

where D is the derating factor, C is the total installed capacity of the PV array and I is the solar radiation.

3.3. WIND SYSTEM

Solar energy absorbed by the earth produces the upward motion and expansion of air, which creates areas of high and low pressure. The latter contain air currents (wind) whose direction is influenced by the earth's rotation and the force of gravity. The kinetic energy in these currents is called wind energy[21].

3.3.1 description of a WT

Wind generators can be divided into two groups: those with horizontal axes and those with vertical axes. The former (unlike the latter) do not have moving parts that are faster than the wind, and they must rotate around a vertical axis for the rotor to be in operating position.

The most complete versions include (see Figure 14):

- ✓ A rotor with a device for regulating the blades' pitch (to keep the rotation constant when wind speed varies)
- ✓ A brake (generally disc) to stop the machine for maintenance or when wind speed is excessive
- ✓ An overgear
- ✓ An electric generator
- ✓ An orientation system (not included in vertical machines)

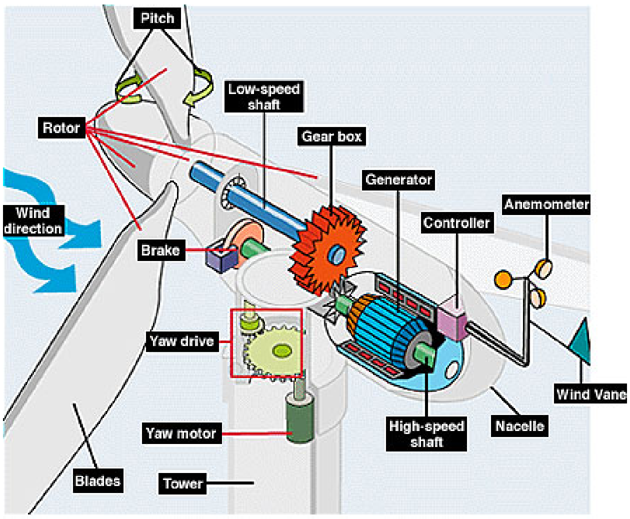


Figure 14: the main components of a wind turbine

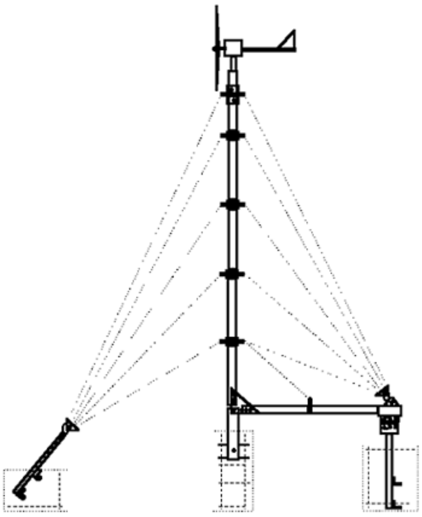


Figure 15: a tilt-up power system

The rotor is the most important component; the blades must have a special shape, and their fatigue strength and resistance to stress have to be high (wind speed varies constantly, and this causes the structure to vibrate). [21]

There is also a **tower** that carries the nacelle and the rotor high above the ground, since the wind speeds increases farther away from the ground. Towers for large wind turbines may be tubular steel towers, lattice towers, or concrete towers. Guyed tubular towers are only used for small wind turbines.

The AOC WT can provide a tilt up tower option that allows the machine to be raised using a bulldozer, mid sized truck or similar equipment. This option is also good for areas that experience severe weather such as monsoons so that the machine may be lowered and secured when storms are predicted that have wind speeds in excess of 59,5 m/s. And historical records show that the northern part of Maldives experiences the fury of cyclones. There have been several cases of islands even being uninhabited due to damage caused by such cyclone driven storms. Historical records show that about 18 islands from the northern atolls were abandoned after being devastated by the storm events[4].

For wind turbines that produce direct current it is necessary to add an *inverter* as we are in presence of AC load.

The purchasing costs for a wind system include the rotor, the drive train, the blades, the tower, and the basic control system.

3.3.2 the capital costs

Installation costs

Installation costs comprise foundations made of concrete and roads construction in order to move the WT to the building site, when it does not exist a road capable of carrying 30 tonne trucks. So, these costs are depending on soil conditions and moreover they are depending on the equipment available on the site.

Figure 16: Left; Novar Wind Farm, Scotland, under construction in a moor, July 1997. Right; a man is using mount/crane to lift turbine to operating position.

Local skills can be utilized to install a WT and for example, AOC charges a per diem of $500 for each staff member present at the site. AOC requires that the turbine be commissioned by AOC staff to validate the one-year warranty.

Training costs

Some persons have to be trained in order to assure the operation and maintenance of the WTs, see Table 10.

System size (kW)	0-25	25-75	75-150	>150
Costs ($)	2,000	8,400	12,600	18,400

Table 10: training costs for different WTs sizes

AOC for example, mentions that the commissioning includes training of personnel in operation and maintenance of the turbine.

Operating and maintenance costs

The maintenance schedule is lubrication of certain points on the turbine, visual inspection of major components and checking of the tightness (torque) of the various bolts on the tower and turbine. As is shown in Table 11, the O&M costs increase as the same time as turbine age.

Machine size	150 kW	300 kW	5-60 kW
Year 1-2	1.2	1.0	1.0
Year 3-5	2.8	2.2	1.9
Year 6-10	3.3	2.6	2.2
Year 11-15	6.1	4.0	3.5
Year 16-20	7.0	5.0	4.5

Table 11: average O&M costs as a percentage of the total investment in the WT (RisØ National Laboratory-Denmark)

For my simulation with the software HOMER, I was interested in WTs that have a low cut in wind speed (around 2 or 2.5 m/s), considering the low wind speeds in the studied sites. The WTs used are listed in Table 12.

Systems	Hub height (m)	Peak power (kW)	Wind speed scaling factor	Capital costs ($)	Replacement ($)	O&M ($/yr)
Ropatec WRE.060	12	6	1.03	37,000	21,500	0
Eoltec Scirocco 5.5-6	18	6	1.09	47,545	28,245	838
Eoltec windrunner 10-25	24	25	1.13	82,700	63,700	1,869
AOC 15/50	30	50	1.17	154,000	120,000	3,170
Eoltec Chinook 15-75	32	75	1.18	180,633	162,233	5,576
Nordex 27/150	30	150	1.17	141,900	277,500	17,880

Table 12: the different wind turbines I used with HOMER

Decowicon is able to offer two-used N27/150 kW (30 m tubular tower). The turbines are dismantled but complete and ready for shipment. It has kept them in its storage since they were taken down a couple of years ago. The turbines were operating for 10 years and then they were taken down. There were no technical problems with the turbines but they do belong to what they in Denmark call "old" or "small" turbines, which in these years are being taken down and replaced by larger and newer turbines. Both turbines are in a very fine shape. The turbines should be able to function correctly for another 10 years. After 10 years of operation we must expect that gear and generator will need an overhaul before continued operation. The price is 33,500 euros per wind turbine.

Notes: The prices of the Eoltec and the Ropatec products are given in euros. The prices are converted in $ with the exchange rate 1 euro = 1.2019 dollars (valid 17 June 2004).

The wind turbine AOC 15/50 is already in HOMER's component library but be careful it is the data of the 60 Hz model and in the Maldives we have to install the 50 Hz model. Figure 17 shows the differences in the power curves.

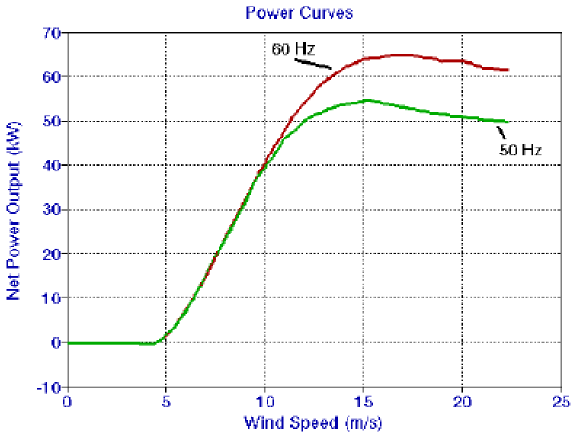


Figure 17: the power curves of the AOC 15/50 60 Hz and the AOC 15/50 50 Hz model

3.3.3 Energy output

In HOMER you have to select a WT in the library component or create a new one by entering its properties, mainly the power curve.

Then, you have to enter a wind speed scaling factor that is used to adjust the wind speed data to account for a difference in the anemometer height and the hub height of the wind turbine. HOMER multiplies the wind resource data by this factor to find the wind speed at the wind turbine hub height. You can use any method you want to determine the effect of the difference in height. The easiest method is to assume that the wind speed varies with height above the ground according to the power law:

Equation 2: $$\frac{v}{v_0} = \left(\frac{Z}{Z_0}\right)^{\alpha}$$

where v is wind speed at desired height, Z; v_0 is wind speed at the reference height, Z_0; α is the ground surface friction coefficient, here; the one-seventh-power law ratio is used. (α =0.143)[13]

Finally, HOMER multiplies that power output value by the power curve scaling factor (assumed to be 1 in the case of the Maldives) to find the actual output of the wind turbine at the expected conditions. The power curve scaling factor is used to account for any difference between the expected output of the wind turbine and that predicted by the power curve. For example, if the site under consideration is at a high elevation above sea level, the reduced air density will lead to reduced output from the wind turbine compared with its power curve, so the power curve scaling factor would be less than one.

3.4. BATTERIES

Batteries are used to store excess electricity for the RE system and to operate the system when power from the RE system is insufficient or absent. Batteries are charged and discharged daily, this is called a cycle. Battery life depends on how many times the battery is cycled at a certain percentage of discharge per day. DC power is stored in batteries.

I point out two manufacturers that have deep cycle lead acid batteries in their line up that are frequently used in renewable energy applications: Rolls Battery and Trojan

Battery Company. Trojan batteries can be bought at Kathmandu in Nepal (there are also distributors in Malaysia and Singapore) and Rolls batteries at Springhill in India; these places are not so far away from the Maldives so that costs of shipping are limited. An overview of the used batteries in this study is given in Table 13.

Battery type	N° of batteries	Capital ($)	Replacement ($)	O&M ($/yr)
Surrette 6CS25P	1	1,080	1,020	25
	48	37,295	34,560	1,440
Surrette 4KS25P	1	1,190	1,135	30
	48	41,135	38,400	1,440
Trojan L16P	1	385	345	5
Trojan T-105	1	165	109	5

Table 13: the different batteries used in HOMER

A deep cycle battery is designed to provide a steady amount of current over a long period of time. It can provide a surge when needed and it has the ability to be deeply discharged and charged many times during its service life. This is what makes a deep cycle battery ideal for powering electrical equipment for long periods of time.

The advantages of lead acid batteries are their interesting costs, the facility of maintenance and the fact they can be recycled at a high rate. (97 percent of the lead is recycled and reused in new batteries). As an example, preventive maintenance measures of deep cycle batteries are listed in appendix 2.

A battery charger allows the diesel generator to charge the battery if the electricity from the RE system is insufficient; and it is used for maintenance.

The purchasing costs of the battery include the prices of the battery, the battery charger and the battery strings. A grid-connected system does not need a battery because the grid functions as a storage system.

Note: The Outer islands, which are remote location, are not connected to a grid (off-grid islands). On the contrary, Malé is a grid connected island; Energy produced by the PV modules can either be used directly, or if there is an excess, flow out through the utility grid.

3.5. INVERTERS

Figure 18: Inverter and controllers at Bullard, Kent - National Park Service

An inverter converts DC voltage and current, from PV system and/or WTs into AC Sine wave power.

For my study, I take as reference for inverter costs the costs of the Xantrex inverters. The Xantrex complete kit includes inverter, isolation transformer, AC disconnect switch, DC disconnect switch, combiner box, 10 poles, and 15 ADC 600V fuse.

The Xantrex inverters are reliable, easy to install and have an efficient design, with over 95% peak efficiency for the inverter, and overall efficiency including transformer losses, in excess of 93% [19]. The rest of the electric power is converted into heat.

It is assumed that the capital costs and the replacement costs are the same, details are shown in Table 14.

Inverter size (kW)	**Capital costs ($)**	**Replacement ($)**	**O&M ($/yr)**
10	12,083	12,083	115
15	17,221	17,221	170
20	20,860	20,860	227
30	27,155	27,155	340

Table 14: the input data in HOMER concerning the inverters

3.6. GENERATORS

The five islands in the Maldives that we study have diesel generators installed to provide electricity to their citizens (Table 15); this is the classic solution for the production of electricity in isolated areas, thanks to their low level of consumption.

Site	Fehendhoo	Uligamu	Nolhivaranfaru	Hanimaadhoo	Malé
generators (kW)	1*10 1*25	1*20 1*31	1*22 1*39	1*125 1*200	3*2,250 1*4,500 1*6,000 2*6,750

Table 15: numbers of generators present in the different locations and their powers

Generators are added in a PV/wind hybrid system to cover the peak load. Moreover, they can supply the electric demand when the RE system is producing insufficient power. They are useful in an off-grid system. We will use these existing generators for PV-wind-diesel hybrid systems. So, we have no capital costs concerning the generators.

A rectifier is necessary to convert the alternating current produced by a generator in direct current needed to charge the battery.

Note: In HOMER we add a *converter* that includes both an inverter and a rectifier but we can just use an inverter by entering a percentage of 0 for the rectifier.

4. BIOMASS

The term biomass is used to describe organic substances that are directly (vegetable) or indirectly (animal) derived from photosynthetic activity. The two types of biomass generally considered for energy purposes are vegetable substances and animal waste. [21]. In considering the methods for extracting the energy, it is possible to order them by the complexity of the processes involved:

- Direct combustion of biomass.
- Thermochemical processing to upgrade the biofuel. Processes in this category include pyrolysis, gasification and liquefaction.
- Biological processing. Natural processes such as anaerobic digestion and fermentation, which lead to a useful gaseous or liquid fuel.

4.1. ANAEROBIC DIGESTION

Anaerobic digestion is a biochemical process resulting in the breakdown of organic substances (proteins, lipids, glucides and their polymers, such as cellulose), starting from biomass with a high moisture content (>60%) and utilizing various groups of anaerobic bacteria.

The products obtained include a gas with useful energy properties (biogas or biological gas) and a biomass whose volatile solid content is lower than that of the original material.

In the absence of O_2, the process takes place in three phases, involving distinct types of bacteria:

- Hydrolytic and fermentative bacteria first break down the carbohydrates, proteins and fats present in biomass feedstock into fatty acids, alcohol, carbon dioxide, hydrogen, ammonia and sulphides. This stage is called hydrolysis (or "liquefaction").
- Next, acetogenic (acid-forming) bacteria further digest the products of hydrolysis into acetic acid, hydrogen and carbon dioxide. This stage is called acidification.
- Methanogenic (methane-forming) bacteria then convert these products into biogas. This stage is called methanization.

For example, the following reactions occur with the use of cellulose:

$C_6H_{10}O_5 + H_2O \rightarrow C_6H_{12}O_6$ (hydrolysis)

$C_6H_{12}O_6 \rightarrow 3\ (CH_3CO_2H)$ (acidification)

$3\ (CH_3CO_2H) \rightarrow 3\ CH_4 + 3\ CO_2$ (methanization)

The result of anaerobic digestion is a gas called biogas, which is around 60-65% methane (CH_4), 40-35% CO_2, and small amount of nitrogen and H_2 and other gases. It is produced from animal dung, human excrement and other biomass waste in a biogas digester (Figure 19).

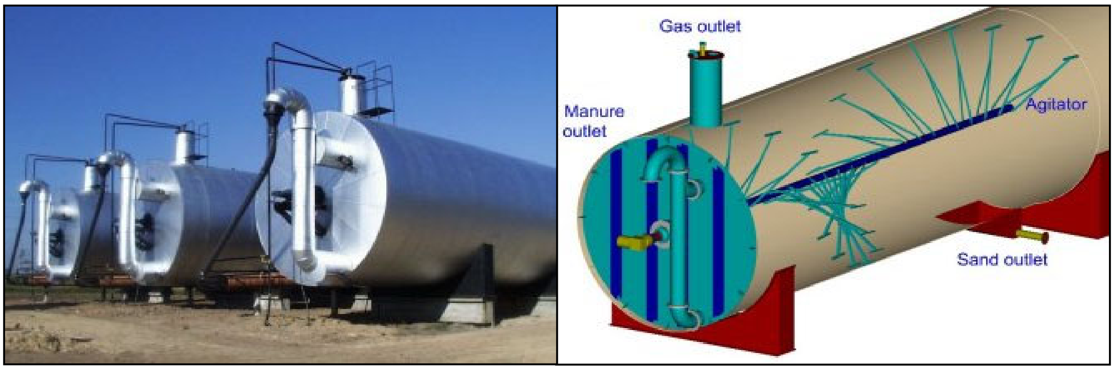


Figure 19: outside (left) and inside (right) views of a digester

The process is carried out in an airtight reactor. Sludges (precipitates produced by sewage treatment) are introduced continuously or intermittently and retained in the reactor for varying periods of time. The stabilized sludge, that is withdrawn continuously or intermittently from the process, is for all practical purposes biologically inert and odorless.

Two types of digester are now in use, fixed volume digesters and fixed pressure digesters.

- Fixed volume digesters produce a gas that has a variable pressure, depending on the amount of gas being produced.
- Fixed pressure digesters (also referred to as floating dome digesters) have a variable volume, which also depends on the amount of gas being produced. The fixed pressure digester has the advantage of being able to supply gas to an appliance like a gas fridge, or a gas generator, since they require a constant gas pressure.

After filtering and drying, digester gas is suitable as fuel for an internal combustion engine, which, combined with a generator, can produce electricity.

Note: One cubic meter of methane at standard temperature and pressure has a net saturated low heating value of 35,800 kJ/m^3 approximately. Since the gas in a digester contains only about 60-65% methane, the saturated low heating value of digester gas is 22,400 kJ/m^3 approximately. By comparison, natural gas, which is a mixture of methane, ethane, and slight traces of propane, has a low heating value of 37,300 kJ/m^3 approximately.

The theoretical gas production value is 0.35 m^3 biogas for every 1 kg feedstock. A typical digester system has a retention time of 20 days. To size a digester, I take the daily manure production and multiply by 20. For Fehendhoo this leads to 45 m^3.

The cost of processing; cleaning, drying, grinding, densification, loading and moving, and storage, is either under estimated or not included at all in the biomass supply curves. If the complete cost of processing would be included in the supply curves, biomass quantities at the lower price range of $20-40 per dry tons will decrease substantially. The waste comes from the island; consequently the transport cost is negligible.

It is assumed that the investment and maintenance for the gas and generator is similar to a diesel system.

To have an idea of the costs of such a system, I find the existing system in South-eastern Colorado installed in 1999 well detailed, see Tables 16 and 17.

System component	Capital cost ($)
Complete mix digester	138,848
Secondary storage basin	10,179
Engine/generator costs	114,588
Special equipment (pumps, valves, meters)	58,003
Engineering	48,943
Labour	8,881
Miscellaneous	4,760
Total	384,202

Table 16: cost breakdown for the anaerobic digester of 120 kW in Colorado

A feasibility study will have to be made too, so that the waste disposal site will be appropriately located, that means not so close to the shoreline and there are no odour nuisances for the inhabitants. Moreover, to decrease the costs of transportation, householders should agree to carry their waste to disposal sites.

System size (kW)	Capital costs ($)	O&M costs ($/yr)
25	96,000	5,000
120	384,202	10,000

Table 17: capital and O&M costs for the systems in Colorado

As there is no appliance for modelling a gas digester I take the capital and the O&M costs concerning the digester into account in the Economic Inputs window. The estimated total system operation and maintenance cost is about 4% of capital costs annually, while the plug flow digester portion of the system cost was 2.9% of capital costs to operate and maintain annually.

A biogas digester offers many ***benefits***: it generates a useful fuel product and it produces a regular supply of nitrogen-enriched fertilizer: anaerobic digestion does not lower the total amount of nitrogen, phosphorus and potassium in the manure but does increase the amount of ammonia nitrogen. The manure effluent will have a higher nutrient availability and plant uptake may be improved with digestion. Fertilizers purchases are expected to be reduced and crop yields possibly improved. [26]

This is a plus for the Maldives, because, since soils are poor and land for agriculture is scarce, agricultural production is low. Unlike many other developing countries, agriculture's share of GDP is low, declining from 3,6% in 1995 to 2,8% in 2000 [6].

Note: The most widely grown agricultural product in the Maldives is coconut. Coconut production in 2000 was about 18 million [6]. Some islands grow root crops such as taro, cassava and sweet potato as well as other crops such as banana, papaya, watermelon, melon, mango, cucumber, pumpkin, betel leaves, chillies, limes, breadfruit and egg plant. In addition, increased use of chemical fertilizers in agriculture has potential to adversely affect the groundwater resources.

Moreover, after digestion, compounds, which usually produce odors, are greatly reduced. Digester systems, properly designed and operated, significantly reduce the odors associated with manure storage and distribution. Also depending on the operating conditions, pathogenic organisms may be reduced by as much as 90%.

4.2. GASIFICATION

Gasification is a thermochemical process that converts biomass into a combustible gas called producer gas (Figure 20).

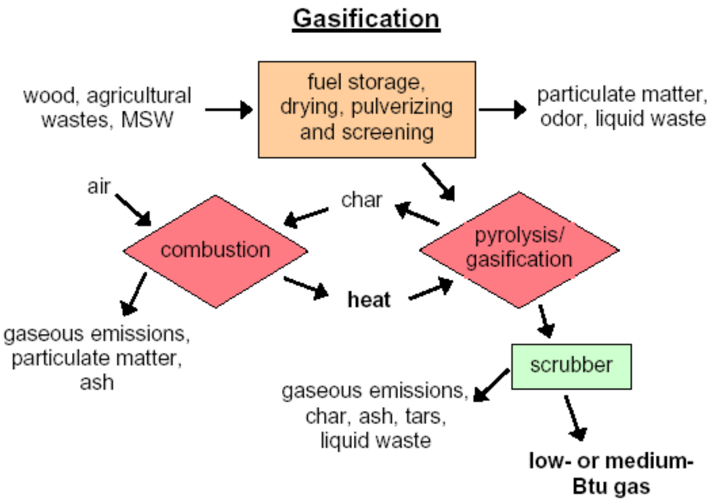


Figure 20: description of the process of gasification [22]

Producer gas contains carbon monoxide, hydrogen, water vapour, carbon dioxide, tar vapour and ash particles. Gasification produces a low-Btu or medium-Btu gas, depending on the process used. Producer gas contains 70 percent to 80 percent of the energy originally present in the biomass feedstock.

Filters and gas-scrubbers remove tars and particulate matter from producer gas. The clean gas is suitable for use in an internal combustion engine, gas turbine or other application requiring a high-quality gas.

Gasification technology is in the development stage. There are a few demonstration projects that use varied gasifier designs and plant configurations. However, pre-treatment of biomass feedstock is generally the first step in gasification. Pre-treatment involves drying, pulverizing and screening. Optimal gasification requires dry fuels of uniform size, with moisture content no higher than 15 percent to 20 percent.

Biomass gasification is a two-stage process. In the first stage, called pyrolysis, heat vaporizes the volatile components of biomass in the absence of air at temperatures ranging from 450° to 600° C. Pyrolysis vapour consists of carbon monoxide, hydrogen, methane, volatile tars, carbon dioxide and water. The residue, about 10 percent to 25 percent of the original fuel mass, is charcoal.

The final stage of gasification is called char conversion. This occurs at temperatures of 700° to 1200° C. The charcoal residue from the pyrolysis stage reacts with oxygen, producing carbon monoxide.

4.3. LANDFILL SITE

The same anaerobic digestion process that produces biogas from animal manure and wastewater occurs naturally underground in landfills (Figure 21). Most landfill gas results from the decomposition of cellulose contained in municipal and industrial solid waste. Unlike animal manure digesters, which control the anaerobic digestion process, the digestion occurring in landfills is an uncontrolled process of biomass decay.

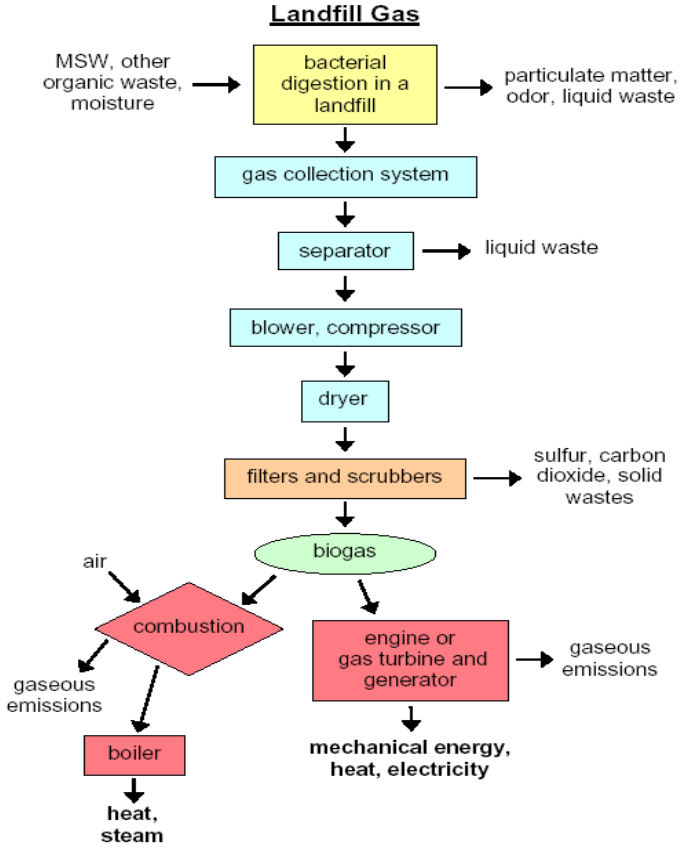


Figure 21: description of a landfill gas-to-energy system [22]

The efficiency of the process depends on the waste composition and moisture content of the landfill, cover material, temperature and other factors. The biogas released from landfills, commonly called "landfill gas," is typically 50% methane, 45% carbon dioxide and 5% other gases. The energy content of landfill gas is 14.9 to 20.5 MJ/m^3.

Capturing landfill gas before it escapes to the atmosphere allows for conversion to useful energy. A landfill must be at least 12 m deep and have at least one million tons of waste in place for landfill gas collection and power production to be technically feasible. A landfill gas-to-energy system consists of a series of wells drilled into the landfill. A piping system connects the wells and collects the gas. Dryers remove moisture from the gas, and filters remove impurities.[22]

5. HYDROGEN ENERGY SYSTEM

According to the national GHG inventory, the generation of electricity and transportation sector contributes to the major GHG emissions from the Maldives. We have just seen some possible solutions to lower the demand on imported fossil fuel by utilising sun, wind and biomass for producing electricity but something should be done for the transportation sector too.

CO_2 is contained in the exhaust gases of vehicles burning gasoline. As we want to reduce the emission of CO_2, it is interesting to regard the introduction of fuel cell vehicles in Malé and a public land transport. There are 500 taxis so I assume that the total amount of kilometres travelled per year is 7,500,000 (15.000 km/year * 500 vehicles). In a city a motor gasoline car has a consumption of roughly 6 L of gasoline per 100 km. Consequently, 450,000 L are used every year by taxis. As one litre of gasoline contains 0.002335879 t of CO_2; we could thus prevent the emission of 1,051 t of CO_2 per year. For comparison, this is approximately 4 times the emission of CO_2 for the production of electricity in Hanimaadhoo.

Hydrogen can be used in fuel cells as a source of electricity for buildings and as a electrical power source for electric motors propelling vehicles (cars, motorcycles). FC vehicles will be quieter and will have lower non-GHG tailpipe emissions, but will be more expensive and will require new infrastructures for vehicle maintenance and for producing and distributing hydrogen-fuel.

What is a fuel cell vehicle?

A fuel cell vehicle (FCV) is an electric vehicle that uses a fuel cell rather than a battery to provide electricity that powers the electric motor and turns the wheels of the vehicle. While a battery must be recharged after all its fuel has reacted, a fuel cell is a "refillable battery"—filling the fuel tank recharges the vehicle. The fuel cell of the vehicle produces electricity directly by electrochemically combining onboard hydrogen with oxygen taken from the air outside.

How to obtain the onboard hydrogen?

Hydrogen is the simplest element. An atom of hydrogen consists of only one proton and one electron. It is also the most plentiful element in the universe. Despite its simplicity and abundance, hydrogen does not occur naturally as a gas on the Earth, it is always combined with other elements. Water, for example, is a combination of hydrogen and oxygen (H_2O). Hydrogen is also found in many organic compounds, notably the hydrocarbons that make up many of our fuels, such as gasoline, natural gas, methanol, and propane.

Hydrogen can be separated from hydrocarbons through the application of heat, a process known as ***reforming***. Currently, most hydrogen is made this way from natural gas. An electrical current can also be used to separate water into its components of oxygen and hydrogen. This process is known as ***electrolysis***.[16].

To have a pure sustainable hydrogen economy, the hydrogen must be derived from renewable sources rather than fossil fuels so that we stop releasing carbon into the atmosphere. The production of hydrogen via electrolysis powered by renewable electricity yields 'renewable' hydrogen. So, I will consider systems composed of a PV array (there is no place for WTs in Malé) integrated with a hydrogen energy system (electrolyzer, hydrogen storage, fuel cell).

Advantages of the hydrogen economy:

1. **The elimination of pollution caused by fossil fuels** - When hydrogen is used in a fuel cell to create power, it is a completely clean technology. The only by-product is water. There are also no environmental dangers like oil spills to worry about with hydrogen.
2. **The elimination of greenhouse gases** - If the hydrogen comes from the electrolysis of water, then hydrogen adds no greenhouse gases to the environment. There is a perfect cycle: electrolysis produces hydrogen from water, and the hydrogen recombines with oxygen to create water and power in a fuel cell.
3. **The elimination of economic dependence** - The elimination of oil means no dependence on the Middle East and its oil reserves.

From the above it will be clear that a hydrogen hybrid system is similar to a diesel hybrid system, where the generator is replaced with a fuel cell. This system is based on the following principles (Figure 22):

- Replacement of the conventional system by a Fuel Cell
- Introduction of an electrolyzer, powered by the photovoltaic modules, to produce the fuel for the FC.
- A water tank: water is needed for conversion.
- H_2 storage
- Inverter in order to provide AC power to the electric motor.

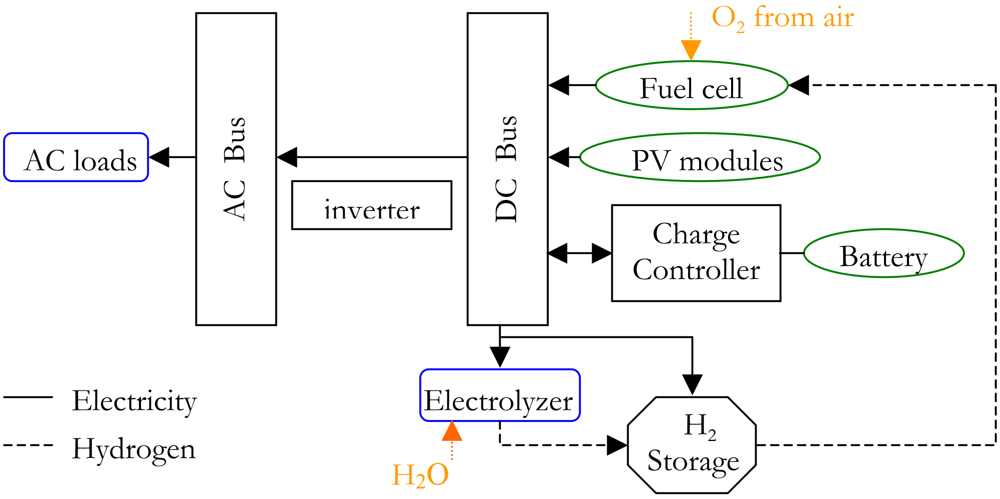


Figure 22: schematic of a PV-hydrogen-battery hybrid system.

5.1. ELECTROLIZER

Working principle:

An electrolyzer is responsible for changing the chemical state of water into its constituent components hydrogen and oxygen. It uses water and electricity, to directly generate hydrogen, a non-polluting and totally recyclable fuel.
The chemical equation for electrolysis is: energy (electricity) + $2\,H_2O \rightarrow O_2 + 2\,H_2$.

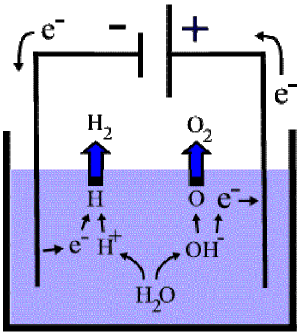


Figure 23: principle of electrolysis

At the cathode, there is a negative charge. This means that there is an electrical pressure to push electrons into the water at this end. At the anode, there is a positive charge, so that electrode would like to absorb electrons. But the water is not a very good conductor. Instead, in order for there to be a flow of charge all the way around the circuit, water molecules near the cathode are split up into a positively charged hydrogen ion H^+ (proton), and a negatively charged hydroxide ion, symbolized OH^{-} : $H_2O \rightarrow H^+ + OH^-$

The water molecule does not break up into a neutral H and a neutral OH because the oxygen atom more strongly attracts the electron from the H; the oxygen atom is more electronegative than the hydrogen atom. The resulting hydroxide ion has a completely filled outer shell, making it more stable. On the other hand, the H^+ ion now can take up an electron from the cathode, to become a regular, neutral hydrogen atom: $H^+ + e^- \rightarrow H$. This hydrogen atom can react with another hydrogen atom to form a hydrogen gas molecule: $H + H \rightarrow H_2$, and this molecule bubbles to the surface.

Meanwhile, the positive anode has caused the negatively charged hydroxide ion (OH^-) to travel across the container to the anode. When it gets to the anode, the anode removes the extra electron, and the hydroxide ion then recombines with three other hydroxide molecules to form one molecule of oxygen, which bubbles to the water surface, and two molecules of water:
$4\,OH^- \rightarrow O_2 + 2\,H_2O + 4e^-$

In this way, a closed circuit is created, involving negatively charged particles (e^-) in the wire and hydroxide ions in the water.

Costs

As estimation, I use the price of the HOGEN 40 6kW electrolyzer from Proton Energy Inc.

Figure 24: the HOGEN 40 6kW electrolyzer (Proton Energy Inc.)

The production cost of this electrolyser, including power electronics and control system is 2,700 $/kW. Projected costs are expected to be approximately $700/kW within 10 years. Cost reductions are expected to stem from improvements in the PEM stack, power electronics, control system, and manufacturing improvements such as replacing fittings with welded tube assemblies. These costs assume production of 500 units per year.

A profit margin of 30% was added to these costs to estimate the capital cost of the electrolyzer. The total cost is then $3,500/kW. The installation cost was deemed to be negligible because the HOGEN 40 is a self-contained unit. It produces pure hydrogen at 99,99% at 15 bars. The O&M for the electrolyzer system is estimated to be 7% of the capital cost per year; this includes the cost of the water treatment.

Feed water and cooling water are required for the electrolyzer. To avoid contaminating the electrolyzer, feed water should be purified and deionized[16]; a water recycling system between the fuel cell and electrolyzer could also reduce the amount of water needed. The electrolyzer is assumed to last 20 years.

Energy input:

The commercial production of hydrogen uses 1.7 volts of electricity through the following process (I used the definition of a Faraday, 96485 Coulombs per mole of electrons):

$$1.7_{J/Coulomb} \times 96485_{Couloms/mole.e^-} \times 2_{e^-} = 328049 J/mole$$

$$328049_{J/mole} \times 1_{Ws/J} \times \frac{1_h}{3600_s} \times \frac{1_{kW}}{1000_W} \times \frac{1_{mole}}{2_{gH2}} = 0.0456 kWh/g$$

Each kilogram of hydrogen requires 45.6 kWh of electrical energy to produce through electrolysis. So, during a complete year, the total electric consumption is 4,446,000 kWh.

In HOMER we enter the electrolyzer efficiency: the efficiency with which the electrolyzer converts electricity into hydrogen. This is equal to the energy content (based on higher heating value) of the hydrogen produced divided by the amount of electricity consumed. The higher heating value of hydrogen is 142 MJ/kg, which is equal to 39.4 kWh/kg. So an electrolyzer that consumes 45.6 kWh of electricity to produce one kilogram of hydrogen has an efficiency of 39.4 kWh/kg divided by 45.6 kWh/kg, which is 86%.

5.2. HYDROGEN STORAGE

During an inner-city travel, a fuel cell car has a consumption of 1.30 kg of H_2 for 100 km. For storing this quantity (1.30 kg) at atmospheric pressure it is needed to have a volume of:

$$V = \frac{nRT}{p} = \frac{650 \times 8.314 \times 300}{10^5} = 16.2\ m^3$$

The problem of storage appears clearly.

The main options for storing hydrogen are as compressed gas, as a liquid, or combined with a metal hydride. Compressed gas storage competes with liquid hydrogen and metal hydride storage for small quantities of hydrogen. Compressed gas storage is generally limited to 1,300 kg of hydrogen or less because of high capital costs[11]; and 650 kg approximately will need to be stored (it is the quantity needed if the 500 cars will need hydrogen for running 100 km the same day). Moreover, compressed gas storage of hydrogen is the simplest storage solution; the only equipment required is a compressor and a pressure vessel[11]. Consequently, I choose to store hydrogen as a compressed gas.

Capital costs include the compressor and pressure vessel. The capital cost of a compressed hydrogen pressure vessel is around 1,320 $/kg with long-term target of 165 $/kg. The capital cost of a compressor is based on the amount of work done by the compressor:

Size (kW)	**Cost ($/kW)**
10	6,600
75	2,400
250	990

Table 18: capital cost of a compressor

Total operating costs for compressed gas storage include the maintenance of the storage vessel ($0.46/kg) and the compressor ($0.06/kg), and the electricity that uses the compressor (it is assumed that the compressor power is 2.2 kWh/kg). Conventional electrolyzers produce hydrogen at low pressure (6-14 bars). Compressors are used to elevate the pressure for gas storage. However, 200 bars production pressures have been demonstrated at Proton energy and are expected to be in production in the near future; targets are upwards of 400 bars. Such technologies will likely eliminate the need for compressors.

Safety:

For compressed gas, there are two dangers. First, a high-pressure vessel always presents some level of risk, whether it is an inert gas or a reactive gas such as hydrogen. Second, if a compressed gas tank develops a leak, it will result in the release of a large amount of hydrogen very quickly. That’s why the system of storage of hydrogen should be periodically checked for leakage. In open areas there is, however, little chance of detonation, because hydrogen diffuses into air quickly [11].

The storage of hydrogen cylinders or tanks should be located in a secure, external purpose compound, which should be well vented. The water tank, electrolyzer and compressor system components will also be located in this compound. This will protect all these components against extremes of weather.

5.3. FUEL CELL

A fuel cell is an electrochemical energy conversion device that converts hydrogen (or methane, propane, etc.) and oxygen into water, producing DC electricity in the process. There are several different types of fuel cells, each using a different chemistry. Fuel cells are usually classified by the type of electrolyte they use.

The "electrolyte" is that part of any fuel cell which separates the positively and negatively charged ions (e.g. protons and electrons in a PEMFC) which are formed by catalysis of the fuel (hydrogen) at the anode, allowing the protons but not the electrons to pass through to the cathode, and forcing the electrons to reach the cathode through an external circuit where the electrons can do work as electricity. The electrolyte used is what gives a particular type of fuel cell its name: alkaline, molten carbonate, phosphoric acid, PEM, etc. [23]

The proton exchange membrane fuel cell (PEMFC) is one of the most promising technologies. One of its typical applications is a car; its size ranges from 3 to 250 kW and a car would need a 50 kW fuel cell. The PEMFC is integrated in the car and: the taxis are estimated to cost about 7,400 $ more than a conventional diesel taxi [24].

Figure 25 shows the four basic elements of a PEMFC [25]:

- The **anode**, the negative post of the fuel cell, has several jobs. It conducts the electrons that are freed from the hydrogen molecules so that they can be used in an external circuit. It has channels etched into it that disperse the hydrogen gas equally over the surface of the catalyst.

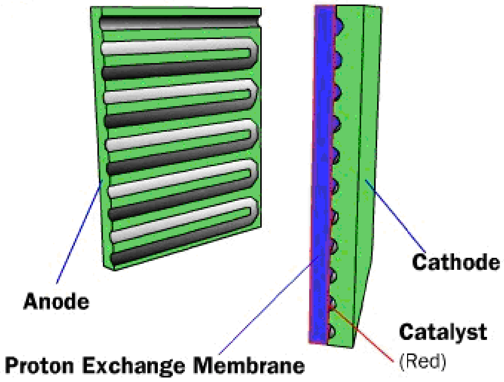


Figure 25: the parts of a PEM fuel cell [25]

- The **cathode**, the positive post of the fuel cell, has channels etched into it that distribute the oxygen to the surface of the catalyst. It also conducts the electrons back from the external circuit to the catalyst, where they can recombine with the hydrogen ions and oxygen to form water.
- The **electrolyte** is the **proton exchange membrane**. This specially treated material, which looks something like ordinary kitchen plastic wrap, only conducts positively charged ions. The membrane blocks electrons.
- The **catalyst** is a special material that facilitates the reaction of oxygen and hydrogen. It is usually made of platinum powder very thinly coated onto carbon paper or cloth. The catalyst is rough and porous so that the maximum surface area of the platinum can be exposed to the hydrogen or oxygen. The platinum-coated side of the catalyst faces the PEM.

Principle:

The pressurized hydrogen gas is entering the fuel cell on the anode side. This gas is forced through the catalyst by the pressure. When an H_2 molecule comes in contact with the platinum on the catalyst, it splits into two H^+ ions and two electrons (e^-). The electrons are conducted through the anode, where they make their way through the external circuit (doing useful work such as turning a motor) and return to the cathode side of the fuel cell. The reaction is: $H_2 \rightarrow 2H^+ + 2e^-$

Meanwhile, on the cathode side of the fuel cell, oxygen gas (O_2) is being forced through the catalyst, where it forms two oxygen atoms. Each of these atoms has a strong negative charge. This negative charge attracts the two H^+ ions through the membrane, where they combine with an oxygen atom and two of the electrons from the external circuit to form a water molecule (H_2O). The reaction is: $O + 2H^+ + 2e^- \rightarrow H_2O$

A fuel cell combines thus hydrogen and oxygen to produce electricity, heat, and water. The net reaction of a fuel cell is: $H_2 + O \rightarrow H_2O$.

This reaction in a single fuel cell produces only about 0.7 volts. To get this voltage up to a reasonable level, many separate fuel cells must be combined to form a **fuel-cell stack**.

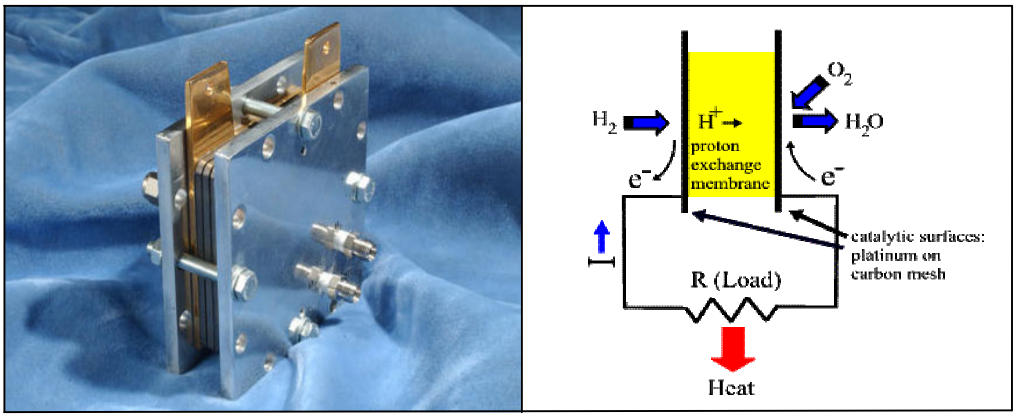


Figure 26: Left; 25 W FC (three cell stack). Right; principle of a PEMFC

For this study, I use PEMFC stacks that have an efficiency of about 50%. The O&M for the fuel cell is assumed to cost 1/10 that of a diesel or 0.0033 $/h/kW. The PEMFC has an estimated service life of 4000-5000 hours if operated in a vehicle. The relatively short life span is caused by intermittent operation. The associated lifetime of a FC-powered vehicle is about 10 years.

6. ENVIRONMENTAL ANALYSIS

The utilization of RE systems brings a reduction in GHG emissions. In the modelling of hybrid RE systems in the Maldives, I will study the reduction of CO_2 emission due to the reduction in DFO (for power generation) and gasoline (for land transport) consumption. The amount of carbon dioxide emissions (ton CO_2) that can be reduced by implementing RE based systems is calculated using the formula:

Equation 3: $tCO_2 = 3,667 \times 10^{-6} * m_f * HV_f * CEF_f * X_c$

in which m_f is the fuel quantity (liter), HV_f is the fuel heating value (MJ/lit), CEF is the carbon emission factor (ton Carbon/TJ) and X_C is the oxidized carbon fraction. The ratio of the mass of CO_2 to that of carbon are 3.667. For diesel fuel oil, $tCO_2 = 0.002643907 * m_f$ and for gasoline, $tCO_2 = 0.002335879 * m_f$.

The fuel quantity m_f is the amount of fossil fuel that is replaced by the different RE based systems; it is calculated by subtracting the amount of fossil fuel that is consumed in the proposed RE system from the fossil fuel consumption in the base case system. The amount of CO_2 that is mitigated by implementing the RE based system under consideration is the indicator for its “sustainability” and it is assumed that a higher sustainability (amount of CO_2 emission reduction) will lead to a higher probability of adoption for this technology by decision makers.[3]

7. ECONOMIC ANALYSIS

7.1. DIESEL AND GASOLINE PRICES

At present diesel fuel oil is used for electricity generation for both Malé and the Outer islands. All the fuel that is imported in the Maldives is stored in or around Malé and from there it is distributed to the outer islands. Therefore the costs of diesel in the outer islands are higher than in the main island and depends a lot on the transportation distance. Typical diesel prices in the Maldives are in the range of $0.32 up to $0.40 per litre, whereby the high prices are paid in the more remote islands with low diesel consumption.[3]

Site	Diesel price ($/L)
Fehendhoo	0.35
Uligamu	0.37
Nolhivaranfaru	0.35
Hanimaadhoo	0.34
Malé	0.35

Table 19: the diesel prices in the different islands

The price of gasoline is 0.46 $ per litre (valid 24 August 2004).

7.2. THE ANNUAL REAL INTEREST RATE

The annual real interest rate is the discount rate used to convert between one-time costs and annualized costs. The annual real interest rate is related to the nominal interest rate by the equation given below:

Equation 4: $$i = \frac{i' - f}{1 + f}$$

Where: i = real interest rate

i' = nominal interest rate (the rate at which you could get a loan)

f = annual inflation rate

For all my simulations, I will assume nominal interest rates of 5% and 10% and the inflation rate is around 1.5%; so I will deal with annual interest rates of respectively 3.4% and 8.4%. In HOMER it is assumed that all prices inflate at the same rate.

To analyze the economic soundness of the different studied systems, I will calculate for each system the levelized COE and the NPV.

7.3. LEVELIZED COE

The cost of energy (COE), that is the ratio between the total cost per year of the system and the power it supplies over the same period. The costs to be included are of two types:

- Fixed costs of construction and installation
- Variable operating and maintenance costs.

To evaluate the fixed costs, that are the depreciation value of the equipment, we have to assume the lives of the systems and of the principal components. The life of the PV systems and the wind turbines are assumed to be of 20 years, sometimes more, while the life of the storage batteries is around 5 years, and the diesel generator can be used for 5-10 years. The fixed costs are calculated at year zero, so we need to discount them back to every year. Similarly, the replacement costs have to be firstly discounted to year zero, and then discounted back to every year so as to be summed to capital expenses. Levelized replacement costs in the systems include replacement of diesel generator and batteries. The levelized COE (\$/ kWh) can therefore be obtained from:

Equation 5: $$levelizedCOE = \frac{(C_F \times CRF + C_{OM} + C_R \times PVF \times CRF)}{N_{kW}}$$

where C_F = initial capital cost, C_{OM} = annual operating and maintenance costs, C_R = replacements costs, PVF = present worth factor (based on discount rate i=5%), and CRF= capital recovery factor (also based on discount rate i=5%), N_{kW} = annual generation.

CRF is calculated using the following equation:

Equation 6: $$CRF = \frac{i}{1-(1+i)^{-L}}$$

where i is the annual real interest rate and L is the project lifetime (20 years).

7.4. THE NET PRESENT VALUE

The Net Present Value (NPV) gives an indication on how profitable a certain project is. The NPV of the project is the value of all future cash flows, discounted at the real interest rate. Under the NPV method, the present value of all cash inflows is compared against the present value of all cash outflows associated with an investment project. The difference between the present value of these cash flows, called the NPV, determines whether or not the project is generally an acceptable investment. Positive NPV values are an indicator of a potentially feasible project.[3]

Equation 7: $$NPV = \sum_{j=1}^{L} \frac{B_j - C_j}{(1-i)^j}$$

where B_j are the total annual benefits in year j and C_j are the total annual costs in year j, i is the annual real interest rate and L is the lifetime of the project. Many activities consist of an initial investment, followed by an annual net benefit that is constant in time. In that case the calculation of the net present value is highly simplified making use of the capital recovery factor.

Equation8: $$NPV = -I \times \frac{B - C}{CRF}$$

where I is the initial investment.

7.5. THE EXCESS ELECTRICITY

In order to decrease the levelized COE and the NPV and use as maximum the potential of the systems that could be implemented, I will assume that the surplus electricity is used and thus sold. In the report called "Assessment of Alternatives", prepared by Energy Consulting Network for the MCST [2], two possibilities of applications of excess electricity are mentioned: ice production and desalination. Moreover, the electricity demand is expected to increase.

Application	Technology	Input/output ratio
Ice production	Compressor based cooling plant	Output: 1 ton ice per day Input: 105 MWh/yr
Desalination	Reverse osmosis	Output: 1 m^3 water per day Input: 2.2 MWh/yr

Table 20: the possible application for excess electricity [2]

I will focus on desalination, as, in the Maldives, water is a very scarce resource. The hydrogeology of the country is that of typical coral islands. The small islands are surrounded by large expanses of seawater, and the freshwater aquifer lying beneath the islands is a shallow lens, no more than a few meters thick (generally 1.2 m), formed by the percolation of rainwater through the porous sand and coral. Freshwater being lighter than saline water, the lens floats atop the saline water. The aquifers change in volume with season and rise and fall with the tide. Such aquifers form the main source of water for human consumption and agricultural purposes. Increased extraction, exceeding natural recharge through rainfall has dramatically depleted the freshwater lens in Malé and other densely populated islands.

The traditional sanitary wastewater practices have led to the pollution of groundwater due to the close proximity of the aquifers to ground surface. Unregulated construction of septic tanks and application of agrochemicals have led to biological and chemical pollution of aquifers. In some of the islands, the salinity of the groundwater, which is caused due to over abstraction, has limited the groundwater availability to meet the demand.

For drinking purposes, rainwater is the traditional source for the Maldivian. Rainwater is harvested by individuals from roofs of houses during rain showers. The harvested rainwater is stored in tanks and other vessels. In almost all inhabited islands there are public rainwater storage facilities. Before harvesting rainwater, the roofs and storage vessels are allowed to be cleaned by the initial burst of rain.

The population of the Maldives mainly depends on groundwater and rainwater as a source of freshwater, but both of these sources of water are vulnerable to changes in the climate and sea level rise. With the islands of the Maldives being so low-lying, the rise in sea levels would force saltwater intrusion into the freshwater lens. The groundwater is replenished by bursts of rain and although there is a predicted increase in the amount of rainfall to the region, the spatial and temporal change in rainfall pattern is uncertain. Therefore, for the Maldives, climate change poses a threat to water availability. That is why it is interesting to look for desalinated water as a use of excess electricity.

Presently, more than a quarter of the population depends on desalinated water for drinking and other uses. Desalinated water is used only in two inhabited islands, including Malé. Desalinated water has been available in Malé for more than a decade and all households in Malé now have access to piped desalinated water. However, rainwater is still harvested in Malé during the rainy season.[6]

Use of solar energy for desalination

Desalination with reverse osmosis is widely used in the Maldives as a portable water resource. About 28% of the population of the Maldives and all the resorts depend on desalinated water to meet their water demands. Reverse osmosis desalination technology, is an energy intensive process that depends on diesel. Introduction and utilisation of solar distillation or desalination with solar energy would reduce the dependence on diesel for water production and hence has the potential to reduce GHG emissions from the Maldives. Changing to such technology could increase the security of water resources and make it less vulnerable to the fluctuation of the oil price on the international market.[6]

The unit cost of production of desalinated water decreases as the plant capacity increases. The turnkey capital cost of a plant of 76 m^3/day is approximately $200,000. For a plant of 3,785 m^3/day, the cost is approximately $4,500,000. The major operating costs consist of energy (primarily), labour, replacement membranes, and spare parts. The staff required is 1 person for a 200 m^3/day plant, and 3 persons for a 4,000 m^3/day plant.

III. Five case studies in the Maldives

To study the feasibility of the renewable energy systems, the optimization software HOMER was used. In particular, 5 case studies were performed, encompassing 4 outer islands and the capital of Malé.

I will compare the different alternatives to the existing equipment that consists of diesel generators. For each alternative of the five studied islands, I will describe on a data sheet the characteristics of the system (capacities, energy…), the reduction in emission of CO_2 and some economical points like the investment and the Net Present Value. For ease of reading, these datasheets are presented in the appendices 3-7. This chapter summarizes the most important findings.

1. THE OUTER ISLANDS

As the conclusions were found to be more or less the same for each of the four outer islands under study, the results for the island of Uligamu are used to illustrate the findings. The following systems were simulated with HOMER:

- PV or wind or biomass- diesel hybrid system
- Solar stand alone system
- Wind stand alone system
- PV-wind hybrid system
- PV-wind-biomass hybrid system

1.1. PV OR WIND OR BIOMASS- DIESEL HYBRID SYSTEM

The main results of the HOMER optimization on solar-diesel and wind-diesel hybrid systems are presented in Table 21, and compared with the base case, i.e., 2 diesel generators (20 and 31 kW). The levelized COE of the base case is 0.39 \$/kWh. By employing additional solar or wind capacity the price increases with 5-6 cents, while the fraction of renewable produced electricity varies between 30 and 40 %. As it is our aim to supply all the electricity demand using only a complete renewable source of energy, hybrid systems containing diesel generators are not considered further. This ensures the supply of the electricity without producing any pollutant effects on the environment, in particular CO_2.

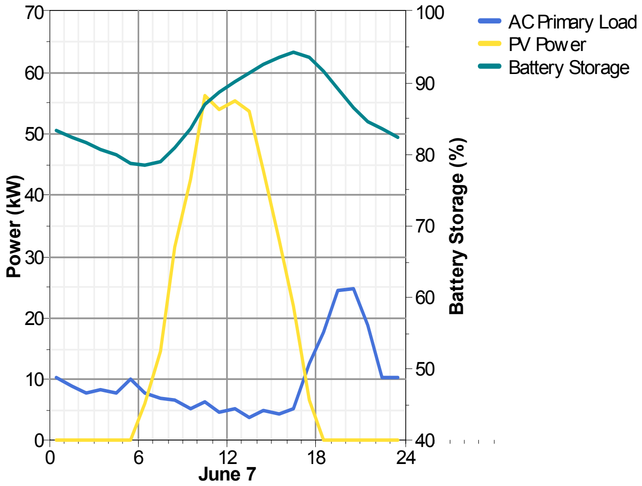
		base case	solar-diesel hybrid	wind-diesel hybrid
System configuration	PV panels (kWp)	-	13	-
	wind turbines (kW)		-	25
	diesel generator (kW)	20+31	20	20
	batteries (kWh)	-	65	38
	convertor (kW)	-	6	2
RE fraction (%)		0	30.1	42
GHG reduction (tCO_2/y)		0	20.4	31.6
Investment (\$)		-	115,941	97,152
Levelized COE (\$/kWh)		0.39	0.46	0.45

Table 21: the results of the simulations for Uligamu

1.2. SOLAR STAND ALONE SYSTEM

The technical design for the PV stand alone system on Uligamu consists of a 26 kW inverter, that means a capacity equal to the peak load as all the electricity produced by the PV modules or the batteries is DC and the load is AC. Further, a 66 kWp PV panel that is sufficient to carry the daily load and a battery bank with a capacity of 1185 kWh that could provide the system with at least 6 days of autonomy.

This system is oversized due to the intermittent character of the solar radiation and so the investment are high, 678,477 $, as well as the COE 0.94 $/kWh, compare to only 0.39 $ in the base case system.



The PV modules create electricity between 6 o'clock and 18, they are able to meet the load during these hours and to charge the batteries that provide electricity during the night.

Figure 27: Covering of the load at Uligamu (typical day).

1.3. WIND STAND ALONE SYSTEM

The battery bank is designed in such a way that it provides enough electricity to completely store the energy produced by the WTs, so that the load is covered during the month of November (the month of the least wind). This leads to an excess electricity as shown in Figure 28.

The excess electricity is very important during the month of June because this system needs four Chinook 15-75 wind turbines to supply all the electricity, and a battery bank of 1178 kWh. Thus, the wind stand alone system, like the solar stand alone system, is highly oversized and needs 1,175,466 $ as investment costs and creates electricity at a cost of 1.76 $/kWh. This clearly is too expensive; the wind stand alone system is not the ideal one.

A large quantity of WTs is needed because during the month of November the wind speed is almost between 2 and 4 m/s (See Figure 29), and at this wind speed, a WT typically produces very few electricity. To illustrate this, the power curve of the Chinook 15-75 from the Eoltec company is shown in Figure 30.

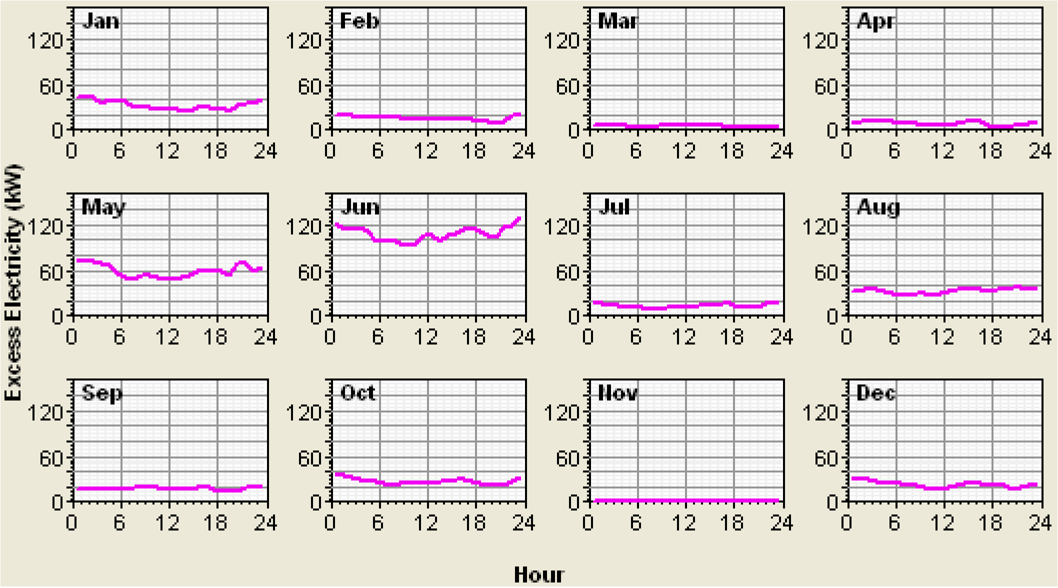


Figure 28: excess electrical production profiles of the optimal wind stand alone system of Uligamu

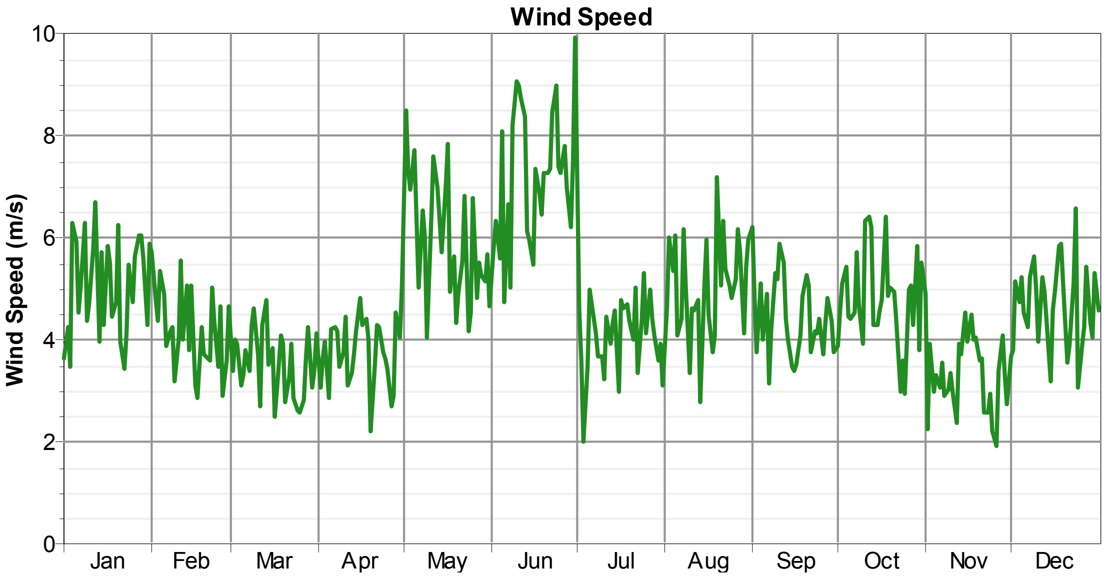


Figure 29: wind speed in the Maldives

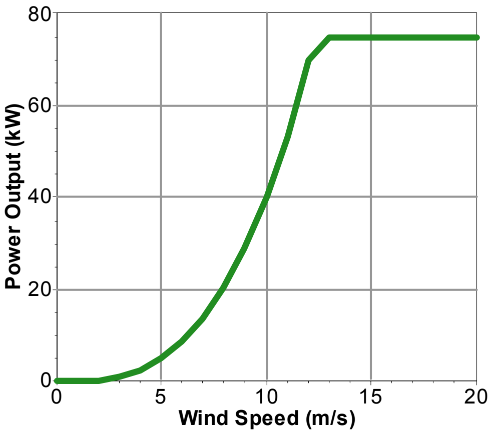


Figure 30: power curve of the Chinook 15-75

1.4. PV-WIND HYBRID SYSTEM

In a PV/wind hybrid system the size of the battery storage can be reduced as there is less reliance on one method of power production and maybe, the solar radiation and the wind speed can well complement each other.

The technical design of the system consists of a Chinook 15-75, 30 kWp PV panel, 874 kWh battery bank and a converter of 20 kW. There are less WTs and PV modules than in a wind stand alone and a solar stand alone system, respectively. These numbers are determined so that the load is covered and the investment and the cost of energy are as cheap as possible. Nevertheless, these costs are still high: 608,351 $ of investment cost and 0.88 $/kWh because the PV panel should have an important capacity to complete the electricity produced by the WT during the month of November and this technology is expensive with around 7,200 $/kWp of capital costs. The system will certainly be cheaper if we could reduce the capacity of the PV panel.

Figure 31 shows the monthly excess electricity produced as a result of covering the load demand in the month of November.

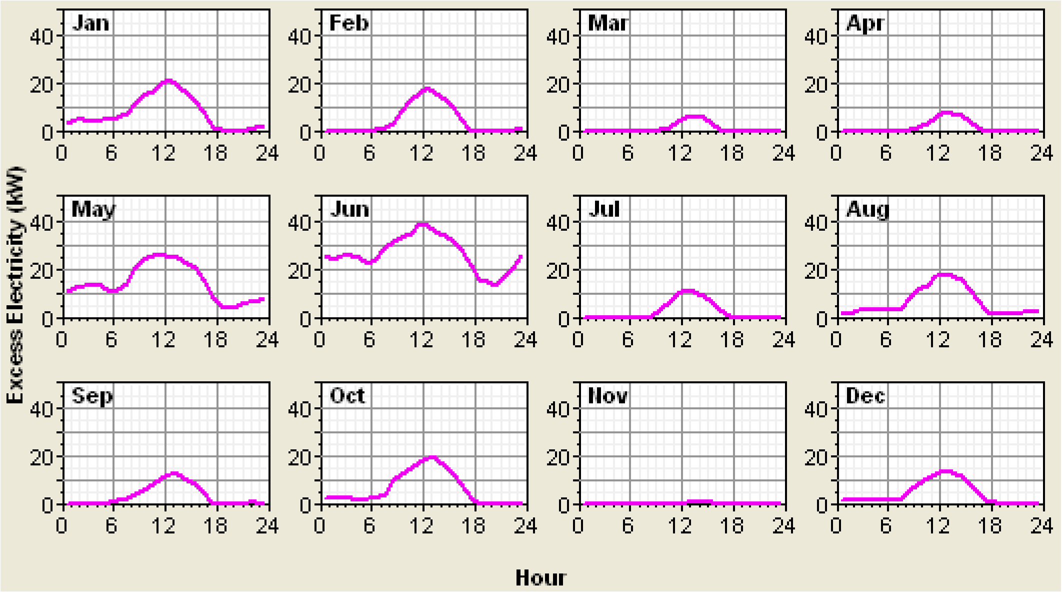


Figure 31: excess electrical production profiles of the optimal PV-wind system of Uligamu

1.5. PV-WIND-BIOMASS HYBRID SYSTEM

Instead of increasing the number of RE systems, the periods of insufficient wind and sun and peak load are often covered by a diesel generator. But as we only want RE systems, a biogas generator, thus using the biomass potential, could replace this diesel generator. Therefore a PV-wind-biomass hybrid system is simulated with HOMER. The average monthly electric production is shown in Figure 32.

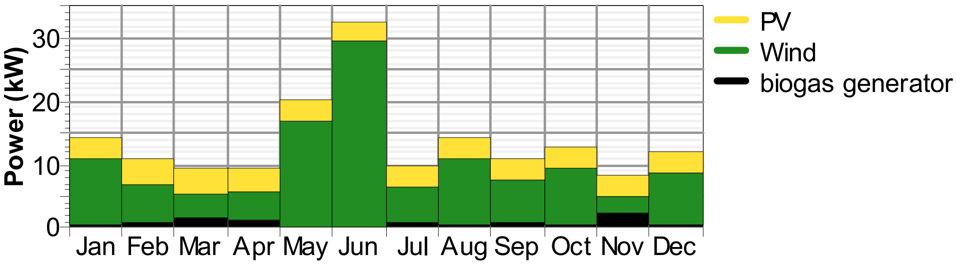


Figure 32: monthly average electric production of the optimal PV-wind-biomass system of Uligamu

It is clear that the biogas generator mainly functions during the month of November. So, there are less PV modules to install than in a PV-wind hybrid system (18 instead of 30) and the investment cost as well as the COE is lower (480,489 $ and 0.67 $/kWh).

1.6. COMPARISON OF THE TESTED SYSTEMS IN ULIGAMU

Table 22 summarizes the most important findings for the solar and wind stand alone systems and the wind-solar and wind-solar-biomass hybrid systems for Uligamu. These data should be compared with the base case (see Table 21), especially the levelized COE of 0.39 $/kWh. The base case system produces 64,787 kWh/year and releases 96.8 tCO_2 per year. All RE systems in Table 22 produce 100% renewable electricity and reduce the GHG emissions with 96.8 tCO_2 per year.

For the island of Uligamu the optimal system in terms of investment and levelized COE is the wind-solar-biomass hybrid system. This conclusion also holds for the other outer islands, of which details can be found in the appendices 3-6.

		solar stand alone	wind stand alone	wind-solar hybrid	wind-solar-biomass hybrid
System configuration	PV panels (kWp)	66	-	30	18
	wind turbines (kW)	-	4 × 75	75	75
	biogas generator (kW)	-	-	-	12
	batteries (kWh)	1,185	1,178	874	213
	convertor (kW)	26	20	20	12
Investment ($)		678,477	1,175,466	608,351	480,489
Levelized COE ($/kWh)		0.94	1.76	0.88	0.67

Table 22: the results of the simulations for Uligamu

1.7. THE OPTIMAL SYSTEMS

The optimal systems for all four outer islands are shown in Table 23. The investment costs of the optimal systems are between 1,000 and 1,545 $ per capita. However, the levelized COE (between 0.61 and 0.67 $/kWh) is very high compared to the present base-case system (between 0.26 and 0.39 $/kWh). In order to reduce these COE and use the maximum potential of the systems that could be implemented, it is important to use the surplus electricity for other purposes (creating desalinated water).

			Fehendhoo	**Uligamu**	**Nolhivaranfaru**	**Hanimaadhoo**
Inhabitants			245	437	650	1290
Base case	Demand	kWh/year	36,390	64,787	110,595	279,666
	Levelized COE	$/kWh	0.38	0.39	0.35	0.26
Optimal	Excess	kWh/year	17,886	55,979	60,714	208,954
	GHG emission reduction	*tCO$_2$/year*	67.3	96.8	168.1	260.3
	Investment	$	244,950	480,489	754,063	1,993,780
	Investment per capita	*$/capita*	1,000	1,099	1,160	1,545
	Levelized COE (no excess)	*$/kWh*	0.61	0.67	0.61	0.65
	Levelized COE (with excess)	*$/kWh*	0.44	0.40	0.43	0.41

Table 23: description of the base case and the optimal system for each of the outer islands

Wind-Solar-Biomass hybrid		
System configuration		
Wind turbine(s)	2 x 150	*kW*
PV panels	50	*kWp*
Biogas generator	44	*kW*
Battery	798	*kWh*
Convertor	44	*kW*
Energy Output		
PV panels	83.976	*kWh/year*
Wind turbine	592.352	*kWh/year*
Biogas generator	23.056	*kWh/year*
Excess	420.255	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	98.453	*L/year*
GHG emission reduction	260,3	*tCO$_2$/year*
Cost parameters		
Total Investment	1.278.647	*$*
Annualized (IR 5%)	89.546	*$/year*
with desalination plant	121.649	*$/year*
O&M	47.011	*$/year*
biogas	1.019	*$/year*
Fuel	0	*$/year*
Replacement	30.386	*$/year*
Financial feasibility		
NPV (IR 5%)	-1.374.788	*$*
(IR 10%)	-1.333.219	*$*
Levelized COE	0,60	*$/kWh*
(with excess electricity)	0,28	*$/kWh*

Table 24: description of a wind- solar-biomass hybrid system on Hanimaadhoo

By using the excess electricity the levelized COE then is decreased to 0.40-0.44 $/kWh. They are in all cases more expensive than the base case system but they present the advantages to reduce the GHG emission, to be less dependent on the import of DFO and to improve live of the Maldivians by using the surplus electricity.

Note: For the case of Hanimaadhoo a Wind-Solar-Biomass system is simulated using the two-used Nordex N27/150 kW. The levelized COE and the initial investment are quite low but after 10 years, the wind generators need replacement and the excess electricity is 420.255 kWh/year. If all this electricity is used for producing desalinated water, 191 m^3 will be produced per day for the 1290 inhabitants (148 L water per day per capita). A part of the excess electricity should be used for another application or the surplus water should be send to islands that need it. The price of desalinated water in this case is around 0.008$/L.

2. THE CAPITAL MALÉ

2.1. RE SYSTEMS FOR POWER GENERATION

In on-grid applications the PV system feeds directly into the utility grid to meet a part of the electricity demand in a certain part the grid region. The maximum percentage of the total load that could be met by PV in such a grid-connected application is usually between 5-10% [3]. In case of Malé, PV could meet only 6% of the total load, as is shown in Table 25. In Malé there is no place for a WT and the place for PV modules is limited. The area for solar panels is roughly 23000 m^2 on the rooftops of the new and old government and office buildings and some at windows. Thus 3700 kWp of PV array could be installed at a cost of 8.11 \$/Wp and provide 6% of the total load demand in Malé.

inhabitants			82,069
base case	demand	MWh/year	109,000
	levelized COE	\$/kWh	0.18-0.30
PV grid connected	PV (3700 kWp)	MWh/year	6,195
	GHG emission reduction	*tCO2/year*	4,258
	RE fraction	%	6
	investment	\$	30,023,120
	investment per Wp	*\$/Wp*	8.11
	Levelized COE (PV)	*\$/kWh*	0.38

Table 25: description of the PV grid-connected system in Malé

Another possibility to meet the demand in Malé is to use the landfill gas that could be extracted from the site of Thilafushi.

A lot of information is to considered to be as precise as possible concerning the capital costs of a LFG site. Unfortunately, not enough information was available so only the amount of load covered could be calculated, see Figure 33, being 2%.

PV-LFG grid-connected		
System configuration		
PV panels (plus invertor)	3.700	*kWp*
LFG generator	200	*kW*
Grid (max demand)	16,5	*MWh*
Energy Output		
PV panels	6.195	*MWh/year*
LFG generator	1.708	*MWh/year*
Grid	101.074	*MWh/year*
Diesel savings	2.054.720	*L/year*
GHG emission reduction	5.432	*tCO_2/year*

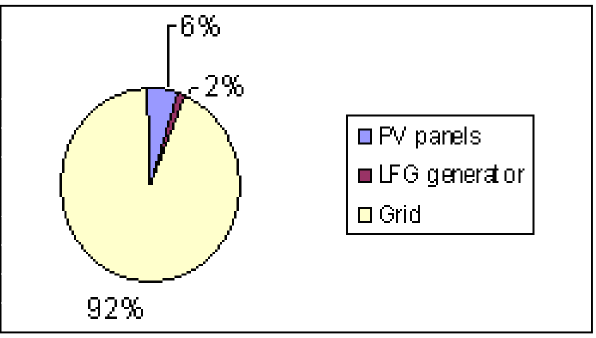


Figure 33: percentage covered by each component in the total production of electricity in Malé

Even if the fraction of RE systems does not seem important enough (it represents only 8% of the total production), it could prevent the emission of 5,432 tCO_2

per year and the import of more than 2 million litre per year of DFO. So, it is far from being negligible.

2.2. RE SYSTEMS FOR VEHICLES

To have a purely sustainable hydrogen economy (no emission of carbon), the hydrogen must be derived from renewable sources rather than fossil fuels. Therefore I will consider systems composed of a PV array integrated with a hydrogen energy system.

2.2.1 actual technology's costs

To produce the 4,446,000 kWh necessary for the electrolyser (see paragraph II.5.1) and the 214,500 kWh for the compressor, a PV array of 2800 kWp should be installed. That means that only 900 kWp (3700-2800) will be available for covering the AC load.

The investment costs that are needed for the system, encompassing the PV modules, the electrolyser, the storage system, and the FC vehicles are very high because fuel cells and their associated components are still a largely experimental technology and therefore cost a significant amount of money, see table 26. The reduction in GHG emission is 1051 ton CO_2/year.

conventional taxis	costs ($/km)	0.12
FC taxis	PV panel (kWp)	2800
	Electrolyser (kW)	2000
	investment cost ($)	38,785,300
	costs ($/km)	0.56

Table 26: description of the PV-hydrogen system, calculated with the actual costs

2.2.2 expected costs (future)

Future developments indicate that a compressor will no longer be needed in an electrolysis system. Therefore a study was performed assuming that a compressor was not required, which saves over 200 MWh of electricity. It appears that 2665 kWp of PV modules are sufficient to meet the demand of the electrolyzer.

As is shown in table 27, a decrease of 25% in the investment costs. However, if the prices drop off as expected, the FC taxis would be 3.5 times more expensive than the conventional taxis. This is without a doubt too expensive.

conventional taxis	costs ($/km)	0.12
FC taxis	PV panel (kWp)	2665
	Electrolyser (kW)	2000
	investment cost ($)	28,757,790
	costs ($/km)	0.41

Table 27: description of the PV-hydrogen system, calculated with the expected costs

The cost of electrolysis depends on the cost of electricity being run through the water. The electricity generated by solar panels is expensive due to the high cost of solar-electric technology. It is interesting to look at the costs per km if the electricity is supplied by the actual power generating system (diesel generators). I assume that the costs of energy are 0.18 $/kWh. I obtain the results summarized in the table 28.

conventional taxis	costs ($/km)	0.12
FC taxis	Electrolyser (kW)	2000
	investment cost ($)	7,507,250
	costs ($/km)	0.3

Table 28: description of the diesel-hydrogen system, calculated with the expected costs

In this case, the costs associated with hydrogen technology are more than twice those of the traditional system. That means that the way we produce electricity for the electrolyzer is of great importance. But whatever the way of electricity production, the use of FC vehicles is at present not economically viable.

IV. Conclusion and discussion

The aim of this report was to determine optimal renewable energy systems that could be implemented in the Maldives. A modelling approach was chosen as high implementation costs inhibit field tests on the Maldives. The simulation programme HOMER was used to design the systems and to analyse their technical and economic performances. In this report, the analysis has been affected on the capital of the Maldives named Malé and four inhabited outer islands, i.e, Fehendhoo, Uligamu, Nolhivaranfaru and Hanimaadhoo.

Several systems consisting of photovoltaic, wind, and biomass electricity generators were studied and compared. Concerning the outer islands in the Maldives, a PV-wind-biomass hybrid system seems to be an interesting option for these islands as the use of biomass is a good method to supplement the fluctuation in PV-wind power generation under variable weather conditions. Moreover, the introduction of a biogas digester sounds like a good investment.

In this report, only the biomass was considered that is available and not utilized actually for cooking However, this biomass could be used to produce biogas that can be used for cooking; thus providing a health improvement for the Maldivians.

The optimal system in the outer islands (PV-wind-biomass hybrid system) generates excess electricity that is very important to use in order to decrease the cost of electricity. If this excess is used for desalination of water it can improve Maldivians's lives on the islands. A detailed study should be done to determine the most appropriate technology that makes use of this surplus electricity.

In the case of Malé, about 8% of the load covered by RE systems (PV and landfill gas) can prevent the emission of 5432 tCO_2 per year (20 times the CO_2 emission in Hanimaadhoo), which is a significant amount not to be overlooked. A wind system was not studied on Malé, as there is no place there. However, an offshore wind farm would be an option.

In addition, a public transport system with fuel cell powered taxis in Malé was modelled, where hydrogen for the fuel cells was generated by means of a PV-powered electrolysis system. Associated costs are 0.56 $/km and a reduction of GHG emission of 1051 ton CO_2/year can be reached. Present costs for the diesel-fuelled taxis are 0.12 $/km.

All these power generating systems have quite high investment costs, between 1000 and 1500 $ per capita. So, it is my opinion that Maldivians have first to preoccupy themselves about their distributed generation power systems and second to focus on a public land transport system. By 2010 all components of a fuel cell technology are expected to decrease and become more accessible. I have tested in this study fuel cell taxis but fuel cell buses are a more effective means to enhance the public land transport in Malé.

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[13] Homer version 2.09 help files

Useful Web Sites:

[14]http://www.lib.utexas.edu/maps/islands_oceans_poles/maldiveislands.jpg
[15]http://www.tiscali.co.uk/reference/encyclopaedia/countryfacts/maldives_map.html
[16]http://www.nrel.gov
[17]http://sari-energy.org/Publications/eia/MariyamSabaMaldives.pdf
[18]http://store.aapspower.com/resosy.html
[19]http://atlantasolar.com
[20]http://www.demosite.ch/page/index.html
[21]http://www.fao.org
[22]http://www.energy.state.or.us/biomass/Biogas.htm
[23]http://www.h2fc.com
[24]http://www.fuelcells.org
[25]http://science.howstuffworks.com/fuel-cell2.htm
[26]http://www.slurrystore.com/Literat/PDFS/dgstrCLR.pdf
[27] http://www.rollsbattery.com

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* Decowicon is a Danish service company, specializing in the service and maintenance of Nordex wind turbines.

List of acronyms and abbreviations

AC: Alternating Current
ADEME: Agence De l'Environnement et de la Maîtrise de l'Energie
AOC: Atlantic Orient Corporation
BOS: Balance Of System
CH_4: methane
CO_2: carbon dioxide
COE: Cost Of Energy
DC: Direct Current
DFO: Diesel Fuel Oil
FAO: the Food and Agriculture Organization of the United Nations
FC: fuel cell
FCV: fuel cell vehicle
GDP: Gross Domestic Product
GHG: Greenhouse Gas
H_2: hydrogen
HOMER: Hybrid Optimization model for Electric Renewables
IDCs: Islands Developing Committees
LFG: landfill gas
LHV: Low Heating Value
MCST: Ministry of Communication, Science and Technology
MPPT: Maximum Power Point Tracker
MSW: Municipal Solid Waste
NA: Not Applicable
NASA: National Aeronautics and Space Administration
NPV: Net Present Value
NREL: National Renewable Energy Laboratory
O&M: operating and maintenance
PEM: Proton Exchange Membrane
PEMFC : Proton Exchange Membrane Fuel Cell
PV: Photovoltaic
RE: Renewable Energy
SMILES: Strengthening Maldivian Initiatives for a Long-term Energy Strategy
STC: Standard Test Conditions
STELCO: State Electric Company
UCE: Utrecht Centre for Energy research
UNFCCC: United Nations Framework Convention on Climate Change
WT: Wind Turbine

List of units

°C: Celsius
g: gramme
J: joule
m: meter
L: litre
Wh: watt-hour
t: tonne (1000 kg)
yr: year
W: watt
Wp: peak watt
$: United States dollar

1 metric ton= 1000 kilograms.
1 Btu (British thermal unit) = 1055,06 J

<u>Prefix</u>:

k: kilo (10^3)
M: mega (10^6)

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Appendices

Appendix 1: the eligible countries of the Asia Pro Eco programme

Appendix 2: the preventive maintenance of deep cycle batteries

Appendix 3: the results of the tested systems for Fehendhoo

Appendix 4: the results of the tested systems for Uligamu

Appendix 5: the results of the tested systems for Nolhivaranfaru

Appendix 6: the results of the tested systems for Hanimaadhoo

Appendix 7: the results of the tested systems for Malé

Appendix 1: the eligible countries of the Asia Pro Eco programme

✓ The 25 member states of the European Union:

_ Austria
_ Belgium
_ Cyprus
_ Czech Republic
_ Denmark
_ Estonia
_ Finland
_ France
_ Germany
_ Greece
_ Hungary
_ Ireland
_ Italy
_ Latvia
_ Lithuania
_ Luxembourg
_ Malta
_ Netherlands
_ Poland
_ Portugal
_ Slovakia
_ Slovenia
_ Spain
_ Sweden
_ United Kingdom

✓ The 17 Asian countries[*] / territories:

_ Afghanistan
_ Bangladesh
_ Bhutan
_ Cambodia
_ China
_ East Timor
_ India
_ Indonesia
_ Laos PDR
_ Malaysia
_ Maldives
_ Nepal
_ Pakistan
_ Philippines
_ Sri Lanka
_ Thailand
_ Vietnam

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[*] *Brunei, Hong Kong, Macao and Singapore may be considered as participants, but are not eligible to receive funding under this programme. (European Commission)*

Appendix 2: the preventive maintenance of deep cycle batteries [27]: you have to

_ insure that the battery compartment is well vented and will prevent the entrance of water, dirt, etc. The most severe abuses that a deep cycle battery will receive are cleanliness, or lack of it. Dirt, corrosion, water and acid will rob a battery of a full life. A clean well-kept battery will extend the useful life of the battery. Remove dirt and dust accumulations from the top of the battery. Wash the top of the battery with clean water and soda solution to neutralize any acid accumulation. Approximately 100 grams to a litre of water is sufficient. Baking soda used in the home is satisfactory. Rinse with clean water and dry. Ensure vent caps are in place and no soda solution enters the battery.

_ check the height of the electrolyte twice a month.

_ fully charge the battery system every three to four weeks. During discharge sulphate is formed. If the sulphate is allowed to remain for too long a period it will become very difficult to remove and the battery system will not accept a charge.

Appendix 3: the results of the tested systems for Fehendhoo

Base Case system		
System Characteristics		
Generator (10&25KW)	36390	*kWh/year*
Efficiency	0,7	*L/kWh*
Diesel use	25469	*L/year*
GHG-emissions	67,3	*tCO2/year*
Fuel price	0,35	*$/L*
Fuel costs	8914	*$/year*
O&M	1976	*$/year*
Replacement	2958	*$/year*
Levelized COE	0,38	*$/kWh*

Solar-diesel hybrid		
System configuration		
PV panels	7,0	*kWp*
Battery	37,0	*kWh*
Converter	4,0	*kW*
Generator	10,0	*kW*
Energy Output		
PV panels	11 708	*kWh/year*
Generator(s)	27 196	*kWh/year*
Excess	2 519	*kWh/year*
RE fraction	30,1	*%*
Diesel use	17 066	*L/year*
Diesel savings	8 403	*L/year*
GHG emission reduction	22,2	*tCO2/year*
Cost parameters		
Total Investment	66 756	*$*
Annualized (IR 5%)	4 675	*$/year*
O&M	1 730	*$/year*
Fuel	5 973	*$/year*
Replacement	2 332	*$/year*
Financial feasibility		
NPV (IR 5%)	-12 307	*$*
(IR 10%)	-30 338	*$*
Levelized COE	0,40	*$/kWh*

Wind-diesel hybrid		
System configuration		
Wind turbine	2 x 6	*kW*
Battery	30	*kWh*
Converter	5,0	*kW*
Generator	10,0	*kW*
Energy Output		
Wind turbine	16 796	*kWh/year*
Generator(s)	22 454	*kWh/year*
Excess	2 862	*kWh/year*
RE fraction	43	*%*
Diesel use	15 394	*L/year*
Diesel savings	10 075	*L/year*
GHG emission reduction	26,6	*tCO2/year*
Cost parameters		
Total Investment	92 985	*$*
Annualized (IR 5%)	6 512	*$/year*
O&M	1 652	*$/year*
Fuel	5 388	*$/year*
Replacement	2 459	*$/year*
Financial feasibility		
NPV (IR 5%)	-30 880	*$*
(IR 10%)	-51 446	*$*
Levelized COE	0,44	*$/kWh*

Solar stand alone		
System configuration		
PV panels	38,0	*kWp*
Battery	654,0	*kWh*
Converter	12,0	*kW*
Energy Output		
PV panels	63 686	*kWh/year*
Excess	27 329	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	25 469	*L/year*
GHG emission reduction	67,3	*tCO2/year*
Costs		
Investment costs	385157,0	*$*
Annualized (IR 5%)	26973,4	*$/year*
O&M	4904,0	*$/year*
Fuel	0,0	*$/year*
Replacement	2383,0	*$/year*
Financial feasibility		
NPV (IR 5%)	-291 468	*$*
(IR 10%)	-322 493	*$*
Levelized COE	0,94	*$/kWh*

Wind stand alone		
System configuration		
Wind turbine(s)	4 x 25	*kW*
Battery	646,0	*kWh*
Converter	9,0	*kW*
Energy Output		
Wind turbine(s)	134 486	*kWh/year*
Excess	98 132	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	25 469	*L/year*
GHG emission reduction	67,3	*tCO2/year*
Costs		
Investment costs	439436,0	*$*
Annualized (IR 5%)	30774,7	*$/year*
O&M	10130,0	*$/year*
Fuel	0,0	*$/year*
Replacement	2355,0	*$/year*
Financial feasibility		
NPV (IR 5%)	-419 970	*$*
(IR 10%)	-426 416	*$*
Levelized COE	1,19	*$/kWh*

Wind-Solar hybrid		
System configuration		
Wind turbine(s)	25	*kW*
PV panels	21	*kWp*
Battery	480	*kWh*
Convertor	10	*kW*
Energy Output		
PV panels	35.195	*kWh/year*
Wind turbine	29.518	*kWh/year*
Excess	28.355	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	25.469	*L/year*
GHG emission reduction	67,3	*tCO2/year*
Cost parameters		
Total Investment	336.543	*$*
Annualized (IR 5%)	23.569	*$/year*
O&M	5.082	*$/year*
Fuel	0	*$/year*
Replacement	1.749	*$/year*
Financial feasibility		
NPV (IR 5%)	-236.342	*$*
(IR 10%)	-269.524	*$*
Levelized COE	0,84	*$/kWh*

Wind-Solar-Biomass hybrid		
System configuration		
Wind turbine(s)	25	*kW*
PV panels	11	*kWp*
Biogas generator	7	*kW*
Battery	144	*kWh*
Convertor	5	*kW*
Energy Output		
PV panels	18.433	*kWh/year*
Wind turbine	29.518	*kWh/year*
Biogas generator	6.308	*kWh/year*
Excess	17.886	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	25.469	*L/year*
GHG emission reduction	67,3	*tCO2/year*
Cost parameters		
Total Investment	244.950	*$*
Annualized (IR 5%)	17.154	*$/year*
O&M	4.026	*$/year*
biogas	204	*$/year*
Fuel	0	*$/year*
Replacement	743	*$/year*
Financial feasibility		
NPV (IR 5%)	-118.219	*$*
(IR 10%)	-158.238	*$*
Levelized COE	0,61	*$/kWh*
(with excess electricity)	0,44	*$/kWh*

Appendix 4: the results of the tested systems for Uligamu

Base Case system		
System Characteristics		
Generator (20 & 31KW)	64.787	*kWh/year*
Efficiency	0,57	*L/kWh*
Diesel use	36.622	*L/year*
GHG-emissions	96,8	*tCO2/year*
Fuel price	0,37	*$/L*
Fuel costs	13.550	*$/year*
O&M	7.920	*$/year*
Replacement	3.818	*$/year*
Levelized COE	0,39	*$/kWh*

Solar-diesel hybrid		
System configuration		
PV panels	13	*kWp*
Battery	65	*kWh*
Converter	6	*kW*
Generator	20	*kW*
Energy Output		
PV panels	21.727	*kWh/year*
Generator(s)	50.499	*kWh/year*
Excess	7.517	*kWh/year*
RE fraction	30,1	*%*
Diesel use	28.912	*L/year*
Diesel savings	7.710	*L/year*
GHG emission reduction	20,4	*tCO2/year*
Cost parameters		
Total Investment	115.941	*$*
Annualized (IR 5%)	8.120	*$*
O&M	7.594	*$/year*
Fuel	10.697	*$/year*
Replacement	3.576	*$/year*
Financial feasibility		
NPV (IR 5%)	-67.097	*$*
(IR 10%)	-83.272	*$*
Levelized COE	0,46	*$/kWh*

Wind-diesel hybrid		
System configuration		
Wind turbine	25	*kW*
Battery	38	*kWh*
Converter	2	*kW*
Generator	20	*kW*
Energy Output		
Wind turbine	29.055	*kWh/year*
Generator(s)	40.116	*kWh/year*
Excess	4.409	*kWh/year*
RE fraction	42	*%*
Diesel use	24.682	*L/year*
Diesel savings	11.940	*L/year*
GHG emission reduction	31,6	*tCO2/year*
Cost parameters		
Total Investment	97.152	*$*
Annualized (IR 5%)	6.804	*$*
O&M	11.403	*$/year*
Fuel	9.132	*$/year*
Replacement	1.979	*$/year*
Financial feasibility		
NPV (IR 5%)	-57.545	*$*
(IR 10%)	-70.661	*$*
Levelized COE	0,45	*$/kWh*

Solar stand alone		
System configuration		
PV panels	66	*kWp*
Battery	1.185	*kWh*
Converter	26	*kW*
Energy Output		
PV panels	110.952	*kWh/year*
Excess	46.228	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	36.622	*L/year*
GHG emission reduction	96,8	*tCO2/year*
Costs		
Investment costs	678.477	*$*
Annualized (IR 5%)	47.515	*$*
O&M	8.774	*$/year*
Fuel	0	*$/year*
Replacement	4.313	*$/year*
Financial feasibility		
NPV (IR 5%)	-504.255	*$*
(IR 10%)	-561.950	*$*
Levelized COE	0,94	*$/kWh*

Wind stand alone		
System configuration		
Wind turbine(s)	4 x 75	*kW*
Battery	1178	*kWh*
Converter	20	*kW*
Energy Output		
Wind turbine(s)	328.774	*kWh/year*
Excess	264.073	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	36.622	*L/year*
GHG emission reduction	96,8	*tCO2/year*
Costs		
Investment costs	1.175.466	*$*
Annualized (IR 5%)	82.320	*$*
O&M	27.181	*$/year*
Fuel	0	*$/year*
Replacement	4.285	*$/year*
Financial feasibility		
NPV (IR 5%)	-1.263.681	*$*
(IR 10%)	-1.234.468	*$*
Levelized COE	1,76	*$/kWh*

Wind-Solar hybrid		
System configuration		
Wind turbine(s)	75	*kW*
PV panels	30	*kWp*
Battery	874	*kWh*
Convertor	20	*kW*
Energy Output		
PV panels	50.408	*kWh/year*
Wind turbine	83.473	*kWh/year*
Excess	69.155	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	36.622	*L/year*
GHG emission reduction	96,8	*tCO2/year*
Cost parameters		
Total Investment	608.351	*$*
Annualized (IR 5%)	42.604	*$*
O&M	10.979	*$/year*
Fuel	0	*$/year*
Replacement	3.183	*$/year*
Financial feasibility		
NPV (IR 5%)	-449.479	*$*
(IR 10%)	-502.091	*$*
Levelized COE	0,88	*$/kWh*

Wind-Solar-Biomass hybrid		
System configuration		
Wind turbine(s)	75	*kW*
PV panels	18	*kWp*
Biogas generator	12	*kW*
Battery	213	*kWh*
Convertor	12	*kW*
Energy Output		
PV panels	30.245	*kWh/year*
Wind turbine	83.473	*kWh/year*
Biogas generator	7.000	*kWh/year*
Excess	55.979	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	36.622	*L/year*
GHG emission reduction	96,8	*tCO2/year*
Cost parameters		
Total Investment	480.489	*$*
Annualized (IR 5%)	33.650	*$/year*
O&M	8.914	*$/year*
biogas	318	*$/year*
Fuel	0	*$/year*
Replacement	632	*$/year*
Financial feasibility		
NPV (IR 5%)	-260.246	*$*
(IR 10%)	-330.143	*$*
Levelized COE	0,67	*$/kWh*
(with excess electricity)	0,40	*$/kWh*

Appendix 5: the results of the tested systems for Nolhivaranfaru

Base Case system		
System Characteristics		
Generator (22 & 39 KW)	110.595	*kWh/year*
Efficiency	0,57	*L/kWh*
Diesel use	63.588	*L/year*
GHG-emissions	168,1	*tCO2/year*
Fuel price	0,35	*$/L*
Fuel costs	22.256	*$/year*
O&M	11.273	*$/year*
Replacement	4.640	*$/year*
Levelized COE	0,35	*$/kWh*

Solar-diesel hybrid		
System configuration		
PV panels	22	*kWp*
Battery	266	*kWh*
Converter	25	*kW*
Generator	22	*kW*
Energy Output		
PV panels	36.751	*kWh/year*
Generator(s)	81.186	*kWh/year*
Excess	9.094	*kWh/year*
RE fraction	31,2	*%*
Diesel use	46.694	*L/year*
Diesel savings	16.894	*L/year*
GHG emission reduction	44,7	*tCO2/year*
Cost parameters		
Total Investment	224.726	*$*
Annualized (IR 5%)	15.738	*$*
O&M	11.149	*$/year*
Fuel	16.343	*$/year*
Replacement	4.983	*$/year*
Financial feasibility		
NPV (IR 5%)	-143.422	*$*
(IR 10%)	-170.346	*$*
Levelized COE	0,44	*$/kWh*

Wind-diesel hybrid		
System configuration		
Wind turbine	50	*kW*
Battery	53	*kWh*
Converter	5	*kW*
Generator	22	*kW*
Energy Output		
Wind turbine	89.054	*kWh/year*
Generator(s)	53.933	*kWh/year*
Excess	33.266	*kWh/year*
RE fraction	62	*%*
Diesel use	32.281	*L/year*
Diesel savings	31.307	*L/year*
GHG emission reduction	82,8	*tCO2/year*
Cost parameters		
Total Investment	217.234	*$*
Annualized (IR 5%)	15.213	*$*
O&M	10.102	*$/year*
Fuel	11.298	*$/year*
Replacement	3.221	*$/year*
Financial feasibility		
NPV (IR 5%)	-23.788	*$*
(IR 10%)	-87.849	*$*
Levelized COE	0,36	*$/kWh*

Solar stand alone		
System configuration		
PV panels	112	*kWp*
Battery	1.992	*kWh*
Converter	35	*kW*
Energy Output		
PV panels	188.190	*kWh/year*
Excess	77.700	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	63.588	*L/year*
GHG emission reduction	168,1	*tCO2/year*
Costs		
Investment costs	1.141.127	*$*
Annualized (IR 5%)	79.916	*$*
O&M	14.706	*$/year*
Fuel	0	*$/year*
Replacement	7.235	*$/year*
Financial feasibility		
NPV (IR 5%)	-909.408	*$*
(IR 10%)	-986.143	*$*
Levelized COE	0,92	*$/kWh*

Wind stand alone		
System configuration		
Wind turbine(s)	5 x 75	*kW*
Battery	2280	*kWh*
Converter	30	*kW*
Energy Output		
Wind turbine(s)	417.626	*kWh/year*
Excess	307.141	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	63.588	*L/year*
GHG emission reduction	168,1	*tCO2/year*
Costs		
Investment costs	1.560.628	*$*
Annualized (IR 5%)	109.294	*$*
O&M	37.220	*$/year*
Fuel	0	*$/year*
Replacement	8.283	*$/year*
Financial feasibility		
NPV (IR 5%)	-1.665.355	*$*
(IR 10%)	-1.630.674	*$*
Levelized COE	1,40	*$/kWh*

Wind-Solar hybrid		
System configuration		
Wind turbine(s)	75	*kW*
PV panels	63	*kWp*
Battery	1.672	*kWh*
Convertor	35	*kW*
Energy Output		
PV panels	105.857	*kWh/year*
Wind turbine	83.525	*kWh/year*
Excess	78.796	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	63.588	*L/year*
GHG emission reduction	168,1	*tCO2/year*
Cost parameters		
Total Investment	970.240	*$*
Annualized (IR 5%)	67.948	*$*
O&M	16.199	*$/year*
Fuel	0	*$/year*
Replacement	6.077	*$/year*
Financial feasibility		
NPV (IR 5%)	-743.305	*$*
(IR 10%)	-818.456	*$*
Levelized COE	0,82	*$/kWh*

Wind-Solar-biomass hybrid		
System configuration		
Wind turbine(s)	75	*kW*
PV panels	44	*kWp*
Biogas generator	17	*kW*
Battery	585	*kWh*
Convertor	18	*kW*
Energy Output		
PV panels	73.932	*kWh/year*
Wind turbine	83.525	*kWh/year*
Biogas generator	13.704	*kWh/year*
Excess	60.714	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	63.588	*L/year*
GHG emission reduction	168,1	*tCO2/year*
Cost parameters		
Total Investment	754.063	*$*
Annualized (IR 5%)	52.809	*$/year*
O&M	12.572	*$/year*
biogas	586	*$/year*
Fuel	0	*$/year*
Replacement	1.958	*$/year*
Financial feasibility		
NPV (IR 5%)	-424.889	*$*
(IR 10%)	-528.300	*$*
Levelized COE	0,61	*$/kWh*
(with excess electricity)	0,43	*$/kWh*

Appendix 6: the results of the tested systems for Hanimaadhoo

Base Case system		
System Characteristics		
Generator (125 & 200 KW)	279.666	*kWh/year*
Efficiency	0,35	*L/kWh*
Diesel use	98.453	*L/year*
GHG-emissions	260,3	*tCO2/year*
Fuel price	0,34	*$/L*
Fuel costs	33.474	*$/year*
O&M	29.346	*$/year*
Replacement	8.863	*$/year*
Levelized COE	0,26	*$/kWh*

Solar-diesel hybrid		
System configuration		
PV panels	53	*kWp*
Battery	190	*kWh*
Converter	34	*kW*
Generator	125	*kW*
Energy Output		
PV panels	89.014	*kWh/year*
Generator(s)	207.555	*kWh/year*
Excess	16.979	*kWh/year*
RE fraction	30,0	*%*
Diesel use	71.994	*L/year*
Diesel savings	26.459	*L/year*
GHG emission reduction	70,0	*tCO2/year*
Cost parameters		
Total Investment	468.488	*$*
Annualized (IR 5%)	32.809	*$*
O&M	25.144	*$/year*
Fuel	24.478	*$/year*
Replacement	6.022	*$/year*
Financial feasibility		
NPV (IR 5%)	-239.464	*$*
(IR 10%)	-315.306	*$*
Levelized COE	0,32	*$/kWh*

Wind-diesel hybrid		
System configuration		
Wind turbine	2 x 50	*kW*
Battery	479	*kWh*
Converter	24	*kW*
Generator	125	*kW*
Energy Output		
Wind turbine	146.299	*kWh/year*
Generator(s)	193.612	*kWh/year*
Excess	60.321	*kWh/year*
RE fraction	43	*%*
Diesel use	58.457	*L/year*
Diesel savings	39.996	*L/year*
GHG emission reduction	105,7	*tCO2/year*
Cost parameters		
Total Investment	485.261	*$*
Annualized (IR 5%)	33.984	*$*
O&M	21.967	*$/year*
Fuel	19.875	*$/year*
Replacement	4.804	*$/year*
Financial feasibility		
NPV (IR 5%)	-127.759	*$*
(IR 10%)	-246.148	*$*
Levelized COE	0,29	*$/kWh*

Solar stand alone		
System configuration		
PV panels	285	*kWp*
Battery	5.244	*kWh*
Converter	97	*kW*
Energy Output		
PV panels	475.833	*kWh/year*
Excess	196.298	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	98.453	*L/year*
GHG emission reduction	260,3	*tCO2/year*
Costs		
Investment costs	2.923.758	*$*
Annualized (IR 5%)	204.757	*$*
O&M	38.211	*$/year*
Fuel	0	*$/year*
Replacement	19.036	*$/year*
Financial feasibility		
NPV (IR 5%)	-2.717.624	*$*
(IR 10%)	-2.785.886	*$*
Levelized COE	0,94	*$/kWh*

Wind stand alone		
System configuration		
Wind turbine(s)	3 x 250	*kW*
Battery	4598	*kWh*
Converter	80	*kW*
Energy Output		
Wind turbine(s)	1.120.451	*kWh/year*
Excess	841.103	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	98.453	*L/year*
GHG emission reduction	260,3	*tCO2/year*
Costs		
Investment costs	1.971.233	*$*
Annualized (IR 5%)	138.050	*$*
O&M	79.055	*$/year*
Fuel	0	*$/year*
Replacement	16.692	*$/year*
Financial feasibility		
NPV (IR 5%)	-2.314.846	*$*
(IR 10%)	-2.201.057	*$*
Levelized COE	0,84	*$/kWh*

Wind-Solar hybrid		
System configuration		
Wind turbine(s)	4 x 75	*kW*
PV panels	116	*kWp*
Battery	5160	*kWh*
Convertor	81	*kW*
Energy Output		
PV panels	194.824	*kWh/year*
Wind turbine	335.964	*kWh/year*
Excess	251.477	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	98.453	*L/year*
GHG emission reduction	260,3	*tCO2/year*
Cost parameters		
Total Investment	2.578.926	*$*
Annualized (IR 5%)	180.608	*$*
O&M	50.270	*$/year*
Fuel	0	*$/year*
Replacement	18.732	*$/year*
Financial feasibility		
NPV (IR 5%)	-2.540.643	*$*
(IR 10%)	-2.553.321	*$*
Levelized COE	0,89	*$/kWh*

Wind-Solar-biomass hybrid		
System configuration		
Wind turbine(s)	4 x 75	*kW*
PV panels	78	*kWp*
Biogas generator	45	*kW*
Battery	1231	*kWh*
Convertor	45	*kW*
Energy Output		
PV panels	131.002	*kWh/year*
Wind turbine	335.964	*kWh/year*
Biogas generator	21.398	*kWh/year*
Excess	208.954	*kWh/year*
RE fraction	100	*%*
Diesel use	0	*L/year*
Diesel savings	98.453	*L/year*
GHG emission reduction	260,3	*tCO2/year*
Cost parameters		
Total Investment	1.993.780	*$*
Annualized (IR 5%)	139.629	*$/year*
O&M	36.918	*$/year*
biogas	973	*$/year*
Fuel	0	*$/year*
Replacement	4.256	*$/year*
Financial feasibility		
NPV (IR 5%)	-1.572.031	*$*
(IR 10%)	-1.702.403	*$*
Levelized COE	0,65	*$/kWh*
(with excess electricity)	0,37	*$/kWh*

Appendix 7: the results of the tested systems for Malé

Base Case system		
System Characteristics		
Generators (25 MW)	109.000	*MWh/yr*
Efficiency	0,26	*L/kWh*
Diesel use	28.340.000	*L/yr*
GHG-emissions	74.928	*tCO2/yr*
Fuel price	0,35	*$/L*
Levelized COE	0,18 - 0,30	*$/kWh*

PV-LFG grid-connected		
System configuration		
PV panels (plus invertor)	3.700	*kWp*
LFG generator	200	*kW*
Grid (max demand)	16,5	*MWh*
Energy Output		
PV panels	6.195	*MWh/year*
LFG generator	1.708	*MWh/year*
Grid	101.074	*MWh/year*
Diesel savings	2.054.720	*L/year*
GHG emission reduction	5.432	*tCO2/year*

PV grid-connected		
System configuration		
PV panels (plus invertor)	3.700	*kWp*
Grid (max demand)	19	*MWh*
Energy Output		
PV panels	6.195	*MWh/year*
Grid	102.805	*MWh/year*
RE fraction	5,68	*%*
Diesel savings	1.610.640	*L/year*
GHG emission reduction	4.258	*tCO2/year*
Costs		
Investment costs	30.023.120	*$*
Annualized (IR 5%)	2.102.584	*$*
O&M	254.929	*$/year*
Financial feasibility		
NPV (IR 5%)	-14.202.961	*$*
(IR 10%)	-19.441.888	*$*
Levelized COE(Grid sales)	0,18 - 0,30	*$/kWh*
(RE fraction)	0,38	*$/kWh*

Base Case system		
System Characteristics		
investment costs	6.000.000	$
Annualized (IR 5%)	420.193	$
Gasoline use	450.000	*L/year*
GHG-emissions	1.051	*tCO2/year*
Fuel price	0,46	*$/L*
replacement	420.193	*$/year*
O&M	216.244	*$/year*
costs	0,12	*$/km*

PV-hydrogen hybrid system (actual costs)		
System configuration		
PV panels	2.800	*kWp*
Electrolyzer	2.000	*kW*
Storage system	650	*kg*
Fuel cell + inverter	500 x 50	*kW*
Energy Output		
PV panels	4.675.335	*kWh/year*
Electrolyzer (consumed)	-4.446.000	*kWh/year*
Fuel cell + inverter	3.246.750	*kWh/year*
RE fraction	1,00	*%*
Diesel savings	450.000	*L/year*
GHG emission reduction	1.051	*tCO2/year*
Costs		
Investment costs	38.785.300	*$*
Annualized (IR 5%)	2.716.219	*$*
replacement	679.000	*$/year*
O&M	801.447	*$/year*
Financial feasibility		
costs	0,56	*$/km*

PV-hydrogen hybrid system (expected costs)		
System configuration		
PV panels	2.665	*kWp*
Electrolyzer	2.000	*kW*
Storage system	650	*kg*
Fuel cell + inverter	500 x 50	*kW*
Energy Output		
PV panels	4.449.620	*kWh/year*
Electrolyzer (consumed)	-4.446.000	*kWh/year*
Fuel cell + inverter	3.246.750	*kWh/year*
RE fraction	1,00	*%*
Diesel savings	450.000	*L/year*
GHG emission reduction	1.051	*tCO2/year*
Costs		
Investment costs	28.757.790	*$*
Annualized (IR 5%)	2.013.971	*$*
replacement	420.193	*$/year*
O&M	676.801	*$/year*
Financial feasibility		
costs	0,41	*$/km*