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Sustainable Energy Systems in Malé

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Abstract

This report is emerged in the course Sustainable Energy Systems by Prof. Dr. Olav Hohmeyer in the frame of the master studies of Energy and Environmental Management, at the European University Flensburg. The aim of the report is the creation of a pathway for a 100 % renewable energy system on Malé.

Malé is the capital and the biggest island of the Maldives, in terms of population. Malé is one of the islands with the highest population density worldwide. Expressed in numbers, on Malé are living more than 100,000 people on less than 2 km². The electricity on Malé is produced by own diesel generators, like on nearly every island of the Maldives. Researches about the energy demand on Malé has shown that more than half of the electricity demand comes from the residents.

The analysis of the weather conditions, which were provided for a long term, by Meteoblue, shows that solar panels and wind turbines would have good sun and wind conditions for generating electricity. The high population density with the consequence of a lack of space on Malé, turned out as a big challenge. Due to this challenge, it is nearly impossible to build any renewable energy system on the island itself. Therefore, other parts of the North-Malé-Atoll has been proven as compatible for solar and wind energy. Also, the ocean thermal energy conversion (OTEC) has proven as compatible to provide energy for Malé. Certainly, OTEC is a technology which must be developed for the implementation on the real energy market. To provide the renewable electricity dependable, the storing of the electricity is necessary. Large scaled battery storages turned out as the best solution for the requirements of Malé.

Before configure the renewables for the 100 % renewable energy generating on Malé, the demand side should be analysed and optimised. With the help of the deep-sea water, which is pumped to the surface in the OTEC system, it is possible to provide Malé with air conditioning (SWAC) and desalination for providing drinking water. On the resident side, appliances (48 %) and cooling (31 %) are responsible for the biggest consumption of electricity. Demand side management is another option to optimize an energy system and reduce the cost. The charging times of the electric vehicles are flexible and thus can be shifted to times of overproduction.

Furthermore, the mobility sector provides a lot of possibilities for energy savings. Besides replacing the petrol based vehicles with electrical vehicles, it is possible to establish sustainable and intelligent public transportation networks and optimise the traffic. Also, it is possible to support the locomotion by bike or by foot.

For scaling up the capacities of the renewable energies and for optimise the storage size, a simulation tool was established in excel. The simulation tool contains an hourly load curve for Malé. Furthermore, real data of wind speeds and solar irradiation for several years are implemented into the model. By this, the simulation of three different future scenarios is possible.

With the hourly simulation model, three different renewable energy scenarios are developed and simulated. Compared with the results of the business-as-usual scenario, the levelized cost of energy can be lowered in two of the renewable scenarios. Besides a 100 % renewable and emission-free energy supply, the possibility of an independent energy system is verified as well.

As the last part of the report, several suggestions for political measures are provided as an action plan. The action plan is divided in parts of technical aspects, policies, financial aspects, transport sector, social aspects and advises for a back-up system.

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Sustainable Energy Systems in Malé

Semester Paper for Sustainable Energy Systems, Summer Semester 2017

1 Introduction

The Maldives, made up 26 atolls and 1,192 islands is a place with a lot of tourism. As more than 80 % are less than 1 m above sea level, are the Maldives one of the countries which feel the effects of the climate change at first.

Most of the economic activities are situated in the 2 km² overpopulated capital island Malé and due to hope for better prospects, the population still increases. In a country which is attempting to build on considerable economic, but is also still challenged by deep environmental and political issues are more actions requested, because as the population on Malé grows, increases the demand for energy and therefore, the dependence on supplier of diesel fuel. Electricity provider are slowly stretched to their limits as well as the whole country due to the rise of sea level. (UNDP, n.d.) Despite many attempts it has not been managed yet to change the fossil fuel based energy system on Malé to a more sustainable, to become more independent and limit climate changes.

Therefore, the aim of this report is to develop possibilities, to change the energy system on Malé and design a 100 % renewable energy supply

In order to achieve this, the current situation on the capital island, including energy demand and supply as well as topographic barriers and opportunities. To work out several energy and storage potentials, dealing with serious space problems further research on climate and other conditions for renewable energy systems are made. This does not only include the electricity supply, but also other energy demands such as in the transport sector. Based on these researches different scenarios for a transition of the energy system arise. A model is developed, to simulate the different scenarios, by using an hourly load curve for Malé and considering different technologies and their combination. All these scenarios are evaluated regarding the levelised costs of energy and also compared to the business-as-usual scenario. As a result of these researches and analyses, recommendations for local measurements are made, including an action plan.

2 Malé – The Capital City of the Maldives

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Malé is situated in the middle of the Maldives in the Indian Ocean, southwest of India and Sri Lanka. As part of one of the 26 atolls, the capital city is about 470 km north of the equator. Although the area includes two or three more islands nearby, which is the airport island Hulhumalé and a resort island Vilingili, the following study only considers the main island.
Malé covers an area of 1.9 km^2, has a population of 103,693 people and therefore is overpopulated and covered with houses (Seleem, et al., 2013, p. 93).
The following sections should give a short overview about the Malé and the Maldives in general and allow a first impression of potentials and barriers for a fundamental change of the power supply towards a 100 % renewable energy system.

2.1 Geographical Facts

The Maldives are made of exclusively of corals and sand. The mean elevation is 1.8 m and no point on the whole Maldives is higher than 2.3 m above mean sea level. (CIA, n.d.)
As shown in Figure 1 the water depth in the atoll towards north west is between 25 m and 50 m and therefore relatively low. Whereas towards south west comparatively the water is steep and reaches a depth of about 1,000 m within a distance of 5 km (openseamap, 2017).

Figure 1: Water depth around Malé (Source: openseamap)

The climate in Malé is monsoonal with a high humidity. Due to the small distance to the equator the days are constantly 12 hours long during the whole year and the temperature is about 29 °C with a little variation throughout the year and about 23 °C at night. Although the frequency of natural disaster is relatively low in the Maldives, but a Tsunami in 2004 has had an impact. Generally, the climate change is due to their low elevation a significant and an apparent issue for the Maldives and Malé. (NDMC, 2016)

2.2 Economical Facts and Current Policy

To be able to classify the island also economically the main numbers are mentioned in this section. The HDI in Malé is 0.734 (Asia Development Bank, 2015, p. 86).
The GDP per capita of the whole Maldives is 7,222 USD and the cost of importing fossil fuels build 20 %, which illustrates the high dependency. (Trading Economics, 2017) The GDP composition by sector is divided into services as the biggest part with 77 %. In that sector the tourism sector has the biggest share. Industry with 19 % and agriculture with only 4 % of the GDP are mainly based on tuna and other fish. Fishing is the country's largest employer (Trading Economics, 2017).

3 Today's Energy Sector Analysis of Malé

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After getting a first picture of the capital city of the Maldives, this chapter focusses on the energy sector on Malé. First of all, the current energy policy is explained. After that the energy supply is analysed, followed by the energy demand. Based on all these information and analysis is the target here to build a forecast for the energy demand for Malé for the next 20 years until 2037. Within this time period implementing a 100 % renewable energy system is the goal.

3.1 Boundaries

Before starting the analysis, the boundaries of this research need to be pointed out and clear. Even though, the actual capital city Malé stretches over three islands, which is the airport island as well as a resort island, the considered demand is exclusively the energy demand on Malé island. This includes the electricity demand, the on land traffic and the cooking sector, which is additionally mentioned because Malés residents cook with gas (Maldives Energy Authority, n.d.). Excluded from this survey is any electricity demand on other islands as well as shipping and aviation.

3.2 Electricity Pricing and Energy Policy

To provide affordable and also reliable electricity systems to its citizens the government of the Maldives has formulated and adopted several policies. Generally, the prices vary due to different electric production on the islands, consumption and efficiency between 0.28 USD/kWh and 0.49 USD/kWh. Islands with a large electricity consumption, like Malé have the lowest costs. In this case they are 0.30 to 0.32 USD/kWh (Ministry of Environment and Energy, 2012, p. 28).

Currently there is an electricity tariff methodology and structure applied. This divides customers into three different groups, the residential, business and governmental group and uses a monthly correction mechanism in order to adjust the actual tariffs to the high variation in prices. Additionally, the government introduced a subsidy scheme for domestic consumers which is part of the social welfare protection. About 57 % of domestic customer bills are paid by the Government and written off as subsidy (Ministry of Environment and Energy, 2012, p. 28).

Regarding some goals and environmental projects, the Maldives don’t ignore the effects of the climate change and are interested in changing their energy system to become independent and sustainable. Indicators for this are for instance the developing of an action plan and the fact, that they are part of the so called Scaling up Renewable Energy Programm in Low Income countries (SREP). This programme includes an investment plan for financing and introducing renewable energy sources as well as more energy efficiency in the Maldives. Further policy measures are import duty exemptions for renewable energy products or an introduction of net metering. One short term objective is, to provide 30 % of the day time peak load of electricity in the whole Maldives by renewable energy sources until 2018 (Ministry of Environment and Energy, 2012, p. 28)

3.3 Electricity Supply

As already indicated, the electricity supply on Malé is a nearly 100 % diesel based system with a little bit of solar generation on some roofs (Maldives Energy Authority, n.d., p. V). To connect the islands by installing a single national grid is impossible so far due to the fact, that most parts of the atolls are covered by partly deep water. This means that each inhabited island is required to install their own power generation. The one and only electricity provider in Malé is State Electric Company (STELCO). The installed capacity on the capital island is 61.42 MW which includes 21 installed generator sets. The size varies from 1,000 kW to 8,730 kW. (Seleem, et al., 2013, p. 93)

The following load curve is primarily based on data from Malé. More precisely information about the yearly and monthly amount of load in Malé is provided (State Electric Company (a), 2015). To get the hourly load and fluctuation within a month, data from Mahé is taken into account (Hohmeyer, n.d.). Mahé is the capital island of the Seychelles and situated about 2,200 km away from Malé with nearly the same distance of about 500 km from the equator like Malé (Google Maps, 2017). For the hourly load curve for one year in Malé, the hourly proportional load from Mahé within each month is adjusted and postponed to the total monthly amount of load in Malé.

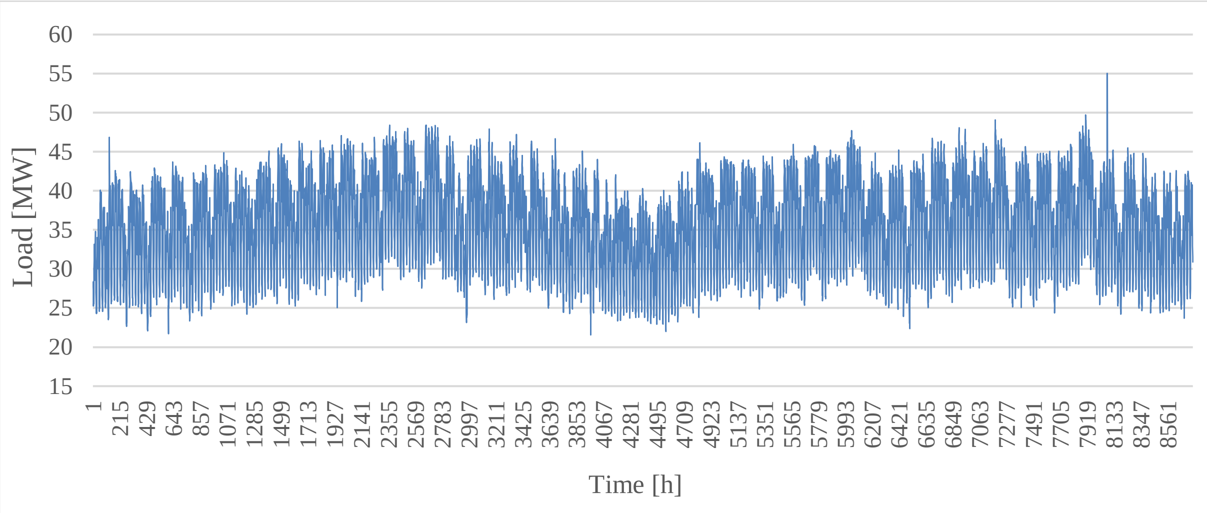

Figure 2: Hourly Load Curve of Malé for One Year (Own Illustration)

The maximum load can be found on the 3rd of June with 45.18 MW and the minimum with 16.75 MW is on the 29th of September.

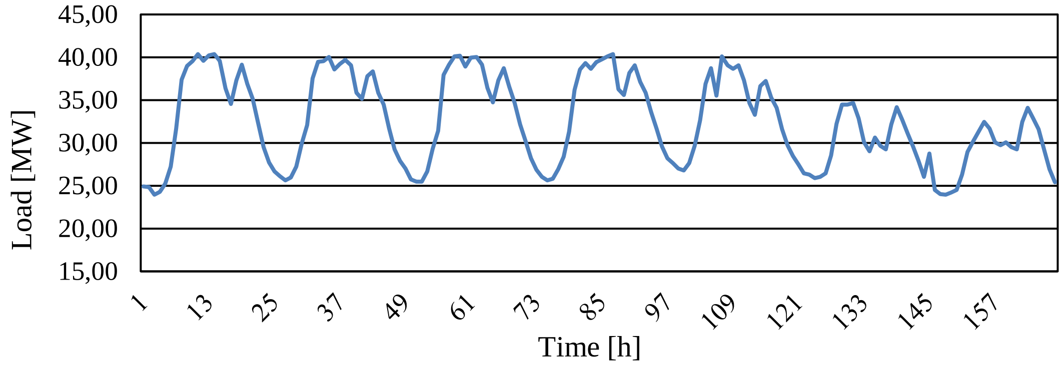

Figure 3: Hourly Load Curve of Malé for One Week (April) (Own Illustration)

Figure 3 shows the hourly load curve for one week in April to visualise the differences between weekdays, Saturday and Sunday. It illustrates a decreasing load on the weekend compared to the days during the week.

3.4 Energy Demand Side Analysis

The total energy demand on Malé is divided into three different sectors, as mentioned in the section 3.1.. First of all, there is the electricity demand, secondly the transport sector and thirdly the demand for LPG for cooking. The following section describes each sector to sum up the energy demand for the whole island at the end.

Electricity Demand

The electricity demand in the year 2015 in Malé was about 260 GWh (State Electric Company (b), 2015). Using the growth rate of a forecast based on data from STELCO head office results in an electricity demand of 306 GWh for this year, 2017. This amount can be divided into the sectors *Manufacturing and Commercials*, *Government Buildings and others* and the biggest part, the *Residential Sector* (State Electric Company (b), 2015).

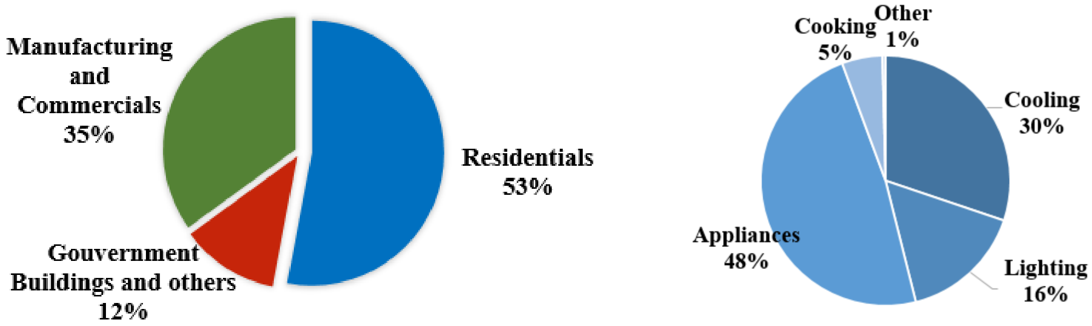

Figure 4: Left: Electricity Demand Distribution in Malé; Right: Electricity Demand Distribution of Residents (Own Illustration)

With more than the half of the total electricity demand has the residential sector the main part of the total amount (See Figure 4). This sector again has five main segments. Almost half of the electricity used by the inhabitants is for their appliances. The second biggest amount of power is used for the cooling with 30 % followed by lighting (Maldives Energy Authority, n.d., p. 21).

Energy Demand in the Transport Sector

One of the emerging environmental issues is the land transport. The road transport in Malé accounts for more than ¾ of the total road transport on the Maldives. There are approximately 60 km paved roads on the island (Fenhann & Ramlau, 2014, p. 66). Table 1 shows the number of registered vehicles including their fuel usage related to the km per year. Looking at the number, there are about 40,000 motor cycles on the island which means one motor cycle for less than three persons and almost 5,000 cars, one for 21 people (Maldives Energy Authority, n.d., p. 26; Transport Authority, 2015).

Table 1: Number of vehicles and their energy consumption (Maldives Energy Authority, n.d., p. 26; Transport Authority, 2015)

Type	Number	Total km/yr	Petrol [l/yr]	Diesel [l/yr]
Motor cycles	38,939	213,191,025	14,212,735.0	-
Cars, Jeeps, Pick-ups	4,835	40,345,275	3,613,712.9	670,951.1
Others (Bus, truck etc.)	1,512	4,484,025	9,198.0	554,754.4
			Total kWh/yr	**168,504,071**

Mainly the effluents from the vehicles and the congestion of traffic degrade the urban environment in Malé (Fenhann & Ramlau, 2014, p. 66). Most of the vehicles still run on petrol with relatively high fuel consumption, which leads to a current energy demand of about 170 GWh.

Here seems to be an advantage of the small size of the city. It indicates that changing the transport system might be easier to enforce than in bigger cities and substituting all the fuel powered by electrical vehicles within the next 20 years is possible. Also promoting pedestrians and public transport is a good option to reduce the energy demand for transport. Due to the small size of the island, a promotion can be successful in this case. Nevertheless, considered in the following study is the assumption, that the vehicles won’t be replaced by bicycles or public transport but completely substituted by e-mobility until 2037.

Table 2: Energy Demand for Transport Considering E-Mobility (Transport Authority, 2015; Sedlak, n.d; elweb, 2013; ÜSTRA, n.d; Kranke, 2014)

E-mobility	Number	Total km/yr	kWh/100 km	kWh/yr
Motorcycles, e-scooters	39,156	214,379,100	4	8,575,164
Cars	4,835	40,345,275	18	7,262,150
Buses	72	1,051,200	200	2,102,400
Trucks	63	919,800	90	827,820
Other vehicles	1,377	2,513,025	40	1,005,210
			Total kWh/yr	**19,772,744**

As shown in Table 2, due to substituting fuel based by electrical vehicles the energy demand can be reduced from 168.5 GWh to less than 12 % which means 19.8 GWh. Therefore, 19.8 GWh are taken into account for simulating a 100 % renewable energy system.

As this is still not the best solution yet, further recommendations for a better transport system by implementing more public transport are given later in this report.

LPG Gas Energy Demand

Regarding the *Maldives Energy Supply and Demand Survey* further 30 GWh LPG are used by the residents of Malé each year (Maldives Energy Authority, n.d.).

Summing up all sectors, the total energy demand for one year in Malé is 356 GWh (see Table 3).

Table 3: Overview of Energy Demand per Sector in Malé (Own Calculations)

Sector	Yearly Demand in Malé	Yearly Demand per Capita
Electricity	306 GWh	2,950 kWh
Transport	20 GWh	190 kWh
LPG (Cooking)	30 GWh	290 kWh
Total	**356 GWh**	**3,430 kWh**

Goal of this report is to develop a plan for a 100 % renewable energy system within the next 20 years. Therefore, a forecast needs to be created. To generate the development of the current electricity demand, a forecast from STELCO until 2021 is used. For further calculation the decreasing growth rate of the forecast for ten years was taken into account (Huzam & Dahidah, 2014).

The trend of the cooking and transport sector is based on the decreasing population growth rate and reaches finally 98.5 GWh (worldometers, 2017).

Figure 5 shows the forecast for the next 20 years with the maximum demand of 562 GWh in year 2037.

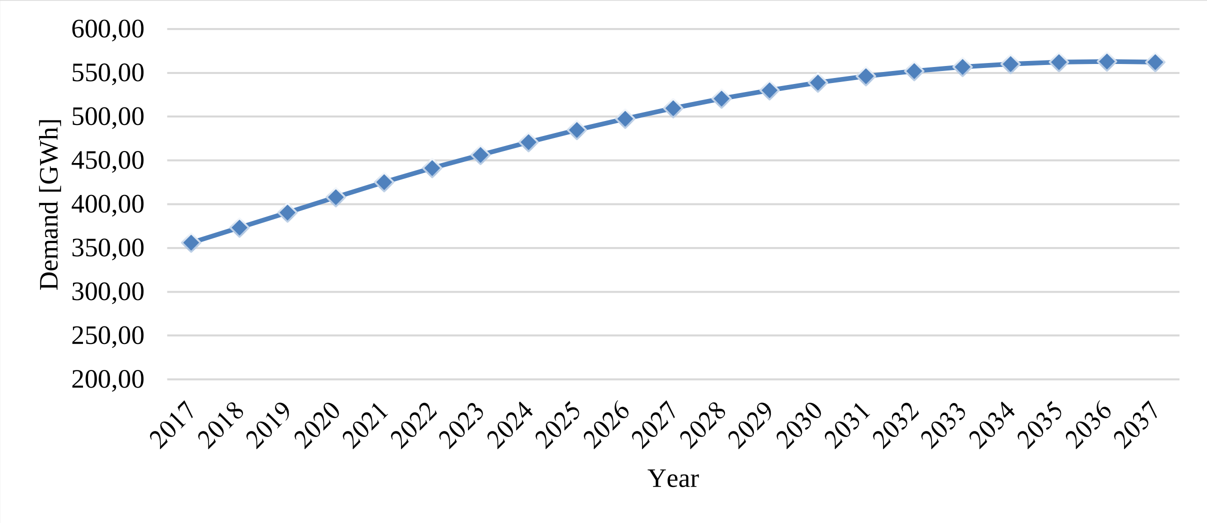

Figure 5: Forecast for Electricity Demand Until 2037 (Own Illustration)

4 Renewable Energy Potential

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In this chapter, the possibilities of several renewable energy technologies on the island Malé will be analysed. The theoretical and the technical potential of each technology will be discussed.

4.1 Solar Energy

In this chapter, the active use of solar energy with the help of solar panels (photovoltaics) will be considered. Therefore, the direct transformation of solar energy into electricity will be examined in the following parts.

4.1.1 Theoretical Potential

The theoretical solar potential is calculated by assuming, that the whole surface of the island can be used for electricity production with photovoltaics. As already mentioned, the Malé island covers an area of 1.9 km². Now, with the assumption that 8 square meters are needed to provide 1 kWp electricity, the theoretical potential can be calculated (Hohmeyer P. D., 2015). By taking this numbers into account the theoretical solar potential on the island amounts 244 MW at peak.

It is important to mention, that this number is a value for the illustration of the theoretical potential, but this case is far away from a realistic area for photovoltaics. Especially on Malé there is very limited space on the island, due to the high density of buildings. In the next part, it will be shown, how to overcome this space problems, but first the potential of solar radiation is analysed.

In Malé the sun rises at 6 am and goes down at 6 pm during the whole year (Worldweatheronline, 2017). With this 12 hours of sunshine on every day, it was calculated, with the meteorological data provided by Meteoblue, that Malé has a global radiation in one year of roughly 1,700 kWh per square meter. In Hamburg, northern Germany, the yearly global radiation is 980 kWh per square meter (Wagemann & Eschrich, 2007). The comparison of the global radiation shows that Malé is a suitable location for solar energy.

Having in mind, that the space on Malé island is very limited, it is necessary to create alternative locations for solar panels. Malé is part of an atoll, named the North-Malé-Atoll, in which Malé island is located in the south east. The atoll has the size of 1,586 km² and a water depth of maximum 25 m (Naseer, 2007). For the theoretical potential of this area, it is estimated, that the whole atoll surface can be used for photovoltaics. Therefore, the atoll provides a nearly unlimited potential of 198,25 GW at peak.

4.1.2 Technical Potential

For the technical potential of photovoltaics, it will be distinguished between the onshore and the floating solar panels.

4.1.2.1 Onshore Potential

As already mentioned, the space on the island Malé is very limited. Therefore, no ground mounted solar panels are imaginable. The only possibility for onshore photovoltaics is mounting the panels on rooftops. Due to land constraints and ownership concerns of the buildings, only a few rooftops of the buildings on Malé are usable. In existing studies, the photovoltaics development potential on rooftops is limited to public owned buildings on Malé (Journeay-Kaler & Taibi, 2015). Figure 6 shows the roofs of the public owned buildings, which can potentially be used for roof mounted solar panels.

Figure 6: PV development potential on public owned buildings (Journeay-Kaler & Taibi, 2015)

If all of these rooftops could be used, the technical potential of this 36,000 m² area is 5 MW_p. In order, to increase the rooftop potential the sports fields on Malé island are a potential area for solar panels. The plan is, to build rooftops on all sports fields and by this, create a potential area for photovoltaics of ca. 95,100 m². So, with the roofs of the sports fields, approximately 13 MW_p of rooftop mounted solar panels can be added. In total the onshore potential is 18 MW_p. But it has to be said, that private owned buildings also could be used, if the owners agree. This would increase the potential.

4.1.2.2 Offshore Potential (floating)

Floating photovoltaics are a technology, mainly installed in protected inland lakes, where wind and waves are reduced to a minimum. But there are also some existing inventions which are promise that their floating platforms can also be used in the ocean.

Acting with the assumption that the technology is available and proofed, the surface of the North-Malé-Atoll is identified as the ideal place for floating solar panels. Especially the small uninhabited islands, which are under water for the most part, fits perfect for the mounting of floating panels, because the water depth is low and there is less trouble in the sea. Figure 7 shows the southern part of the North-Malé-Atoll. In the figure, Malé and a potential uninhabited island for floating photovoltaics are marked.

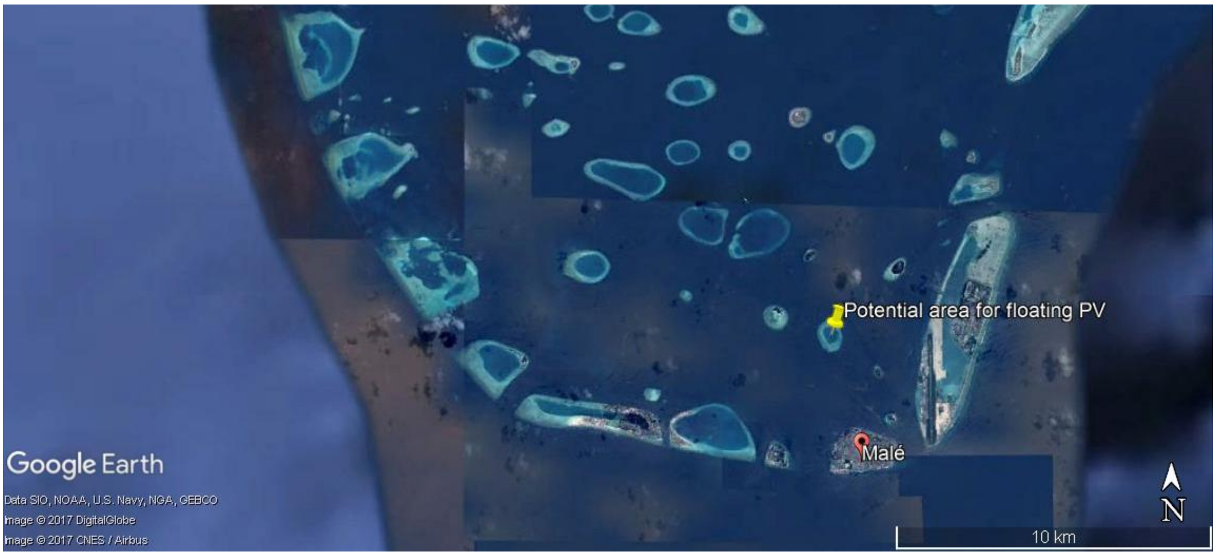

Figure 7: Example of a potential area for floating PV (Google Earth)

The marked example island has a size of ca. 575,000 m². Calculating again with 8 square meters per kilowatt, the potential of this example island is 73 MW_p.

4.1.3 Degree of Sustainability

The term sustainability describes the impact on future generations life quality. The photovoltaic panels are converting solar energy into electricity. They did not need any type of petrol to generate electricity. Therefore, emissions of CO_2 equivalent are not existing.

Solar panels are replacing diesel generators on Malé. So, they not only save CO_2 emissions, they are preventing the dependence on diesel imports and by that, they are saving costs for the energy production. Furthermore, electricity production would be more decentralised. This would mean a lower degree of dependency in one bigger generator. The visual impact of the roof mounted panels is very low. Only the floating panels have a visual impact, but due to the relatively low area requirements for photovoltaics, this impact is admissible.

Summarised, solar energy is an environmental friendly energy source with marginal impacts on the nature. With the climate conditions in Malé, and the possibility of floating panels, it is a very good fit for the substitution of the diesel generators.

4.2 Wind Energy

This part is about the potential of generating electricity with wind turbines in Malé. Therefore, the onshore and the offshore potential will be considered. To evaluate the energy potential, wind statistics for the region should be analysed. The wind statistics, used in the following part are all provided by Meteoblue.

4.2.1 Theoretical Potential

The theoretical onshore potential for wind energy can be calculated, by estimating that the whole area of Malé can be used for onshore wind energy. As already mentioned the area of Malé is 1.9 km². A rule of thumb implied that maximum 10 MW of wind energy can be installed on an area of one square kilometre with the present technology (Hohmeyer P. D., 2015). Therefore, the theoretical onshore potential of Malé is 19 MW installed power of wind energy. Again, it has to be mentioned that the theoretical potential is just a first value to get an imagination of the scale. But it is naturally not possible to build wind turbines on the whole area of Malé. Especially on Malé the space is so limited, that the technical potential is far away from the theoretical.

Before the technical potential is analysed the wind conditions on Malé will be deconstructed. Figure 8 shows the wind rose for Malé on a height of 80 meters. The wind rose visualises that the main wind direction is west, followed by west-south-west and west-north-west. Furthermore, a frequency distribution of the wind speeds is shown. The exact number for the average wind speed, which is not included in the wind rose, is 5.6 m/s on a height of 80 meters. Summarised it can be said, due to the average wind speeds, that the wind conditions on Malé are acceptable for the use of wind turbines. The location cannot be named an “ideal” place for wind turbines, because there are few days of high wind speeds.

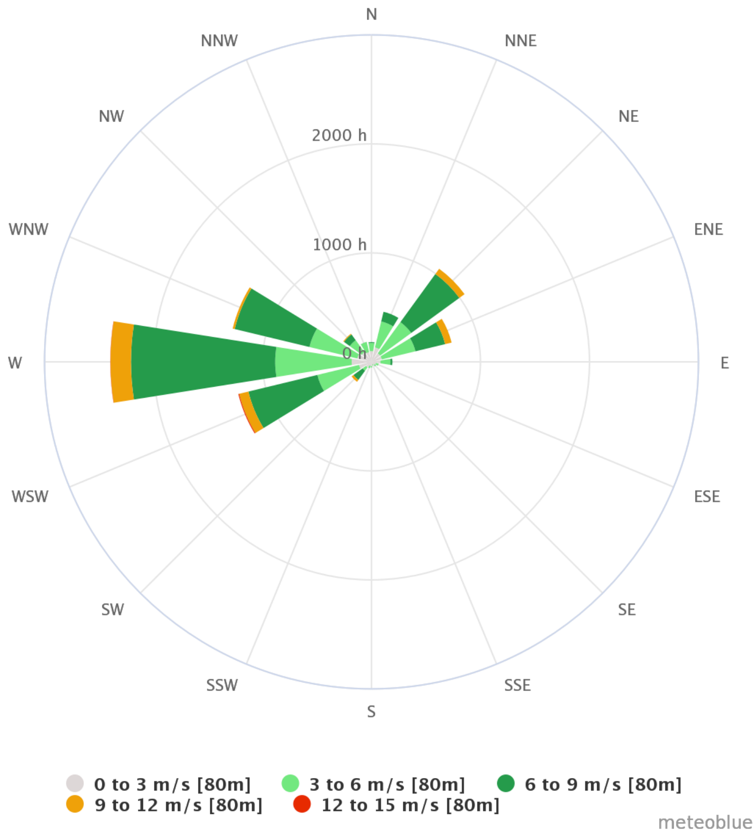

Figure 8: Wind rose of Malé at 80 m, for the year 2016 (Meteoblue)

4.2.2 Technical Potential

The theoretical potential showed that the wind conditions in the Malé region are acceptable for the use of wind turbines. In the following parts, it will be analysed, where the wind turbines can potentially be placed.

4.2.2.1 Onshore Potential

The analytics of the island Malé lead to the conclusion, that there is no possibility to place any wind turbine onshore on the island, due to the lack of space. Therefore, the technical onshore potential on Malé island can be called “none existent”.

4.2.2.2 Offshore Potential

Having in mind that no wind turbines can be placed on the Malé island, it would be a huge drawback, providing Malés electricity with 100% renewables, without the use of wind energy. Therefore, it is necessary to find alternative locations for placing wind turbines near to Malé. One requirement for offshore wind energy is the maximal water depth of 50 meters, with special fundaments up to 100 meters (Bundesministerium für Wirtschaft und Energie, 2015). Therefore, only the area in the North-Malé-Atoll is suitable for wind energy, the deep sea around the atoll is too deep for building fundaments. Figure 9 shows the different sea levels in metres.

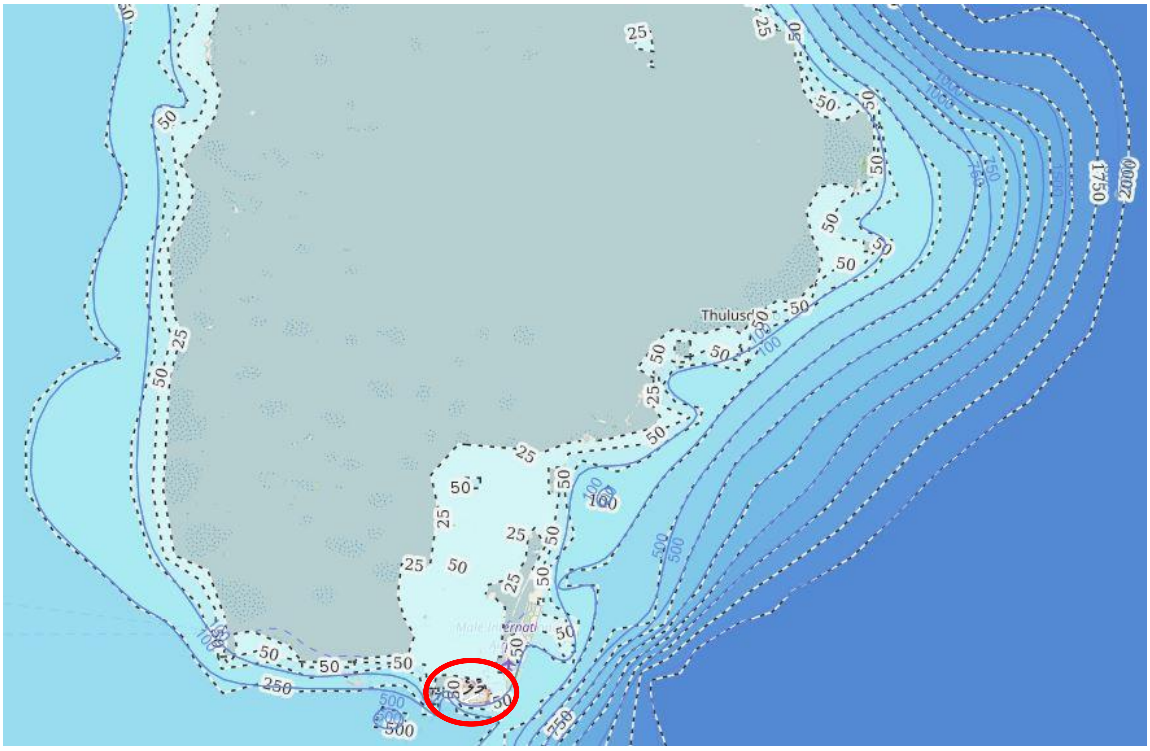

Figure 9: Water depth around Malé (www.openseamap.org)

After analysing the depth of the sea, it can be said that the whole North-Malé-Atoll would fit for offshore wind energy. To keep the installation of the wind turbines as simple as possible, the small uninhabited islands in the atoll are identified as the best fit for installing wind turbines. The water depths on this islands are between 25 and 0 meters, in these depths the mounting of the fundaments is less complex.

Due to the analysed wind direction, the best locations for placing the wind turbines are the uninhabited islands along the west coast of the North-Malé-Atoll. Figure 10 shows the North-Malé-Atoll, the west coast is marked as the potential area for wind turbines. In order to earn the maximal crop of energy it would be optimal to place one row of turbines along the west coast. Though it is necessary to connect these locations with sea cables through the water. So, the farthest island from Malé will provide the highest costs. Therefore, the islands nearer to Malé are the preferred locations.

Due to the wind conditions, with relatively low but constant wind speeds, wind turbines with relatively large rotor diameters were requested. The wind turbine type Enercon E-141 with a diameter of 141 meters and a hub height of 99 meters fulfilled all requirements of the location.

The E-141 has a rated power of 4.2 MW (Enercon, 2017). The length of the islands on the west coast of the atoll is more than 25 kilometres. Therefore, it is possible to put more than 60 of the wind turbines along the west coast, all in one row to the main wind direction (with an interval of three times the rotor diameter). So, the potential for one row along the west coast is more than 60 times multiplied with 4.2 MW rated power. This is more than 252 MW in one row of wind turbines.

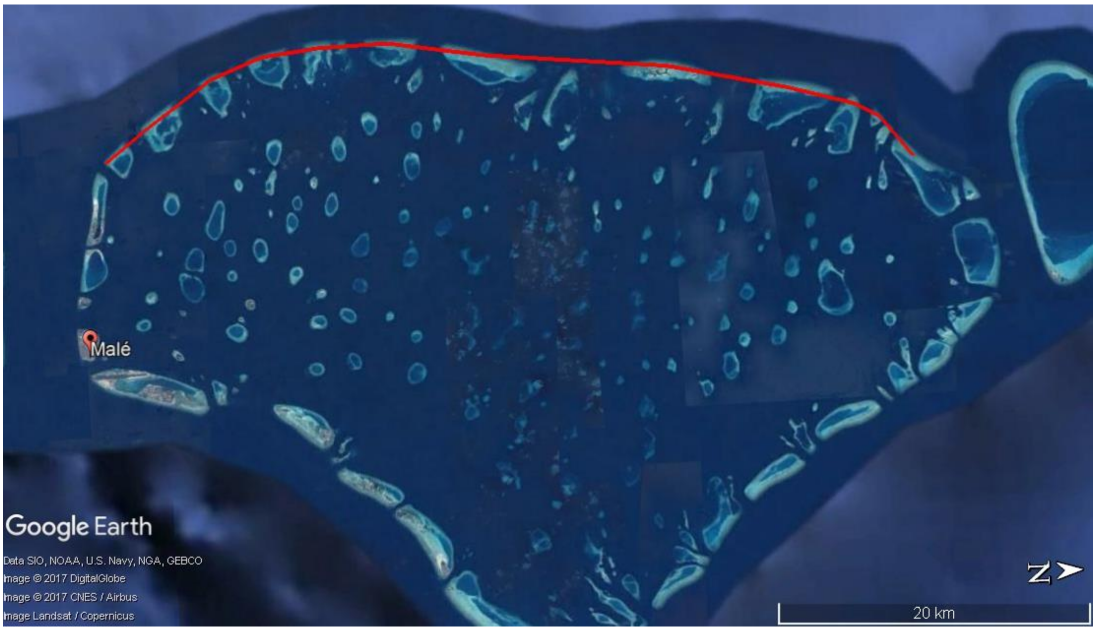

Figure 10: potential area for placing wind turbines (Google Earth)

4.2.3 Degree of Sustainability

In this part the impact of the installation of wind turbines on the future generations living on Malé will be evaluated. Similar to the photovoltaics, the wind turbines are not using petrol's for generating electricity. They are only using the wind, an inexhaustible resource, which does not produce any type of emissions.

The wind turbines can substitute many of the diesel generators which are installed on Malé. Therefore, the energy production of Malé would no longer be based on diesel imports. So, the installation of wind energy will give an independent and emission free production of electricity. Furthermore, the impact on the climate change will be stopped.

The only negative impacts of the wind turbines are the visual impact, which would influence the landscape of the North-Malé-Atoll massively, and the noise and shadow emissions, which can have an impact on the citizens living in the atoll.

Summarised the positive impacts of wind energy are definitive bigger than the negative ones. The fact that Malé is a very flat island, not more than 2.5 meters above the sea level, makes the climate change with consequence of the rising sea level to the biggest threat of Malé. Therefore, the emission free production of electricity is always the preferred.

4.3 Waste to Energy

The waste to energy technology can generate electricity by burning waste and running a turbine. The production of Waste is always a problem for isolated island states. Therefore, a waste to energy plant can solve the waste problem and generate electricity at once.

4.3.1 Theoretical Potential

Malé has more than 100.000 inhabitants on an area smaller than 2 square kilometres. Keeping this numbers in mind, it is imaginable that a lot of waste is produced in Malé and no space for storing is available. Nowadays all the waste, produced in Malé, is shipped to the neighbour island Thilafushi. Figure 11 shows the location of this island.

Figure 11: The location of Thilafushi (Google Earth)

In the year 2014 more than 250.000 tons of waste were shipped from Malé to Thilafushi, whereof more than 200.000 tons were domestic and the rest industrial waste (Waste Management Section / Malé City Council, 2015). Comparing the years 2014 and 2013, the volume of industrial waste has decreased 60% and the domestic waste has increased over 100% (National Bureau of Statistics, 2015). These numbers show that the waste problem will definitively be rising and therefore, a waste to energy plant can be the best solution.

4.3.2 Technical Potential

The International Renewable Energy Agency (IRENA) identified in a pre-feasibility analysis that a waste to energy plant on Thilafushi, dimensioned to a rated power of 8 MW, can be ready for generating energy in 2025 (Journeay-Kaler & Taibi, 2015). A minimum throughput of 15 tons' waste per day is required for running the plant.

There are different systems thinkable for a waste to heat plant. The direct combustion plant is the most likely method. There, the waste is burned and directly converted into steam, which is running a turbine. It is also possible to install a combined heat and power system. Also, technologies with a heat exchanger for flue gas cooling are possible (Ministry of Environment and Energy Republic of Maldives, 2012).

4.3.3 Degree of Sustainability

The impact of waste management to future generations is important. Therefore, a waste to energy plant can have two important positive impacts. The first one is the generation of power, without being depended on petrol imports. The second one is, that Malé gets rid of the waste. Storing the waste is always difficult for island states, especially for such a small state like Malé. Nowadays the waste is just shipped to the neighbouring island. There, the waste just lays for years.

A negative impact of the plant are the emissions provided by the burning of the waste. Even if modern filters are used, the burning of the solid waste entails emissions. Summarised, the ecological footprint of the waste to energy plant will be better than the footprint of the garbage dump, due to contamination of the island and even of the sea. Nevertheless, recycling should be the first option if it is possible.

4.4 Ocean Thermal Energy Conversion Potential

Written by: Sören Wieck, 548168

Ocean thermal energy conversion (OTEC) is a technology that converts thermal energy from the ocean to electricity by using the temperature difference between surface water and deep ocean water. As the surface temperature in the potential OTEC areas is not varying between day and night and only slightly between summer and winter, OTEC-Systems are capable of operating 24 hours a day and all year long. (International Renewable Energy Agency, 2014) Although OTEC technologies are still under development and it has to be examined if OTEC plants can be cost competitive in the future, the OTEC potential for Malé should be analyzed.

4.4.1 Availability of OTEC-Resources

Potential OTEC locations need to have a difference in temperature between the warm surface water and the cold deep ocean water of at least 20° C. Figure 12 shows the monthly average ocean temperatures of the Maldives. With surface temperatures between 28° C and 30°C and relatively constant water temperatures of about 6° C in a depth of 1000m the ocean region around the Maldives seem to meet the necessary conditions for OTEC in every month of the year. (O'Connell, 2013, p. 6) Other studies confirm these results (Owen, Kruijsen, Turner, & Wright, 2011). Nevertheless, further site-specific bathymetry investigations should be carried out in order to gain comprehensive knowledge about local climate characteristics that may affect the water temperatures. (Owen, Kruijsen, Turner, & Wright, 2011, p. 13)

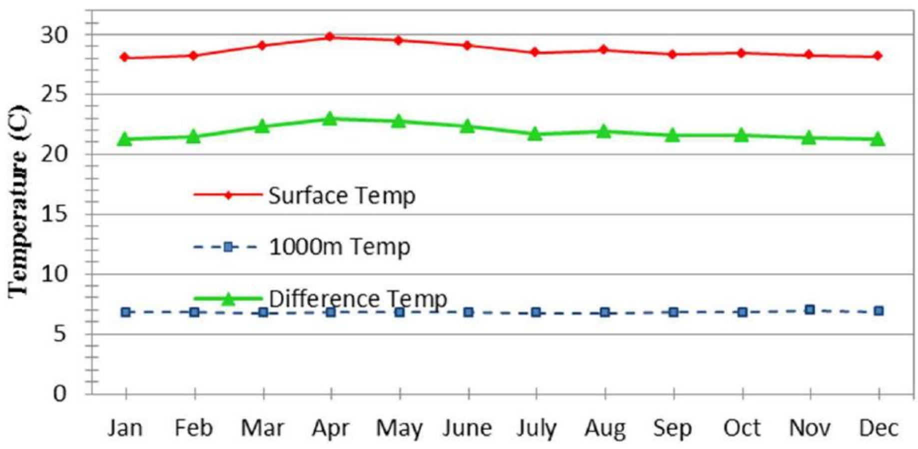

Figure 12: Ocean temperature profile of the Maldives (O'Connell, 2013)

Another essential element when selecting the location of an OTEC plant is the distance between the shore and the regions where the depth of the ocean is between 800 m and 1,000 m with temperatures of 8° C or less. This distance determines the length of the water pipe for cold water which can be very expensive for long distances. Therefore, the distance should not exceed a length of 25 km for OTEC plants with a capacity of more than 10 MW and 3 km for OTEC plants smaller than 10 MW to be economical. (Owen, Kruijsen, Turner, & Wright, 2011, p. 18) In Figure 13 the bathymetrical map of the area around Malé is depicted. It shows that water depths of 1000 m are located approximately 4,5 km from shore. Thus, under the assumed circumstances a OTEC system with at least 10 MW power is theoretically feasible.

Figure 13: Bathymetrical map of Malé (openseamap.org)

Despite these prospects, it is necessary to conduct detailed bathymetrical studies of the potential OTEC site because the system reacts very sensitively to any temperature fluctuations. Even a small decrease of the temperature difference can affect the energy yield significantly. (Owen, Kruijsen, Turner, & Wright, 2011, p. 13)

4.4.2 Determining the Potential

On the assumption that the given bathymetric and thermal conditions allow a OTEC feasibility, the ocean offers an almost infinitely large energy generation potential. For the future scenario to be analysed the size of the OTEC plant is dimensioned to the most economical capacity. This can be done by using a bottom-up approach.

Figure 14 shows the multifunctionality of an open cycle OTEC system. Besides a constant electricity supply OTEC offers the opportunity to use the pumped up cold water for sea water air conditioning (SWAC). Furthermore, OTEC plants can be combined with revers osmose desalination plants and produce desalinated water. Especially island nations as the Maldives are exposed to water scarcity and have to import big amounts of drinking water. (International Renewable Energy Agency, 2014, pp. 8-9)

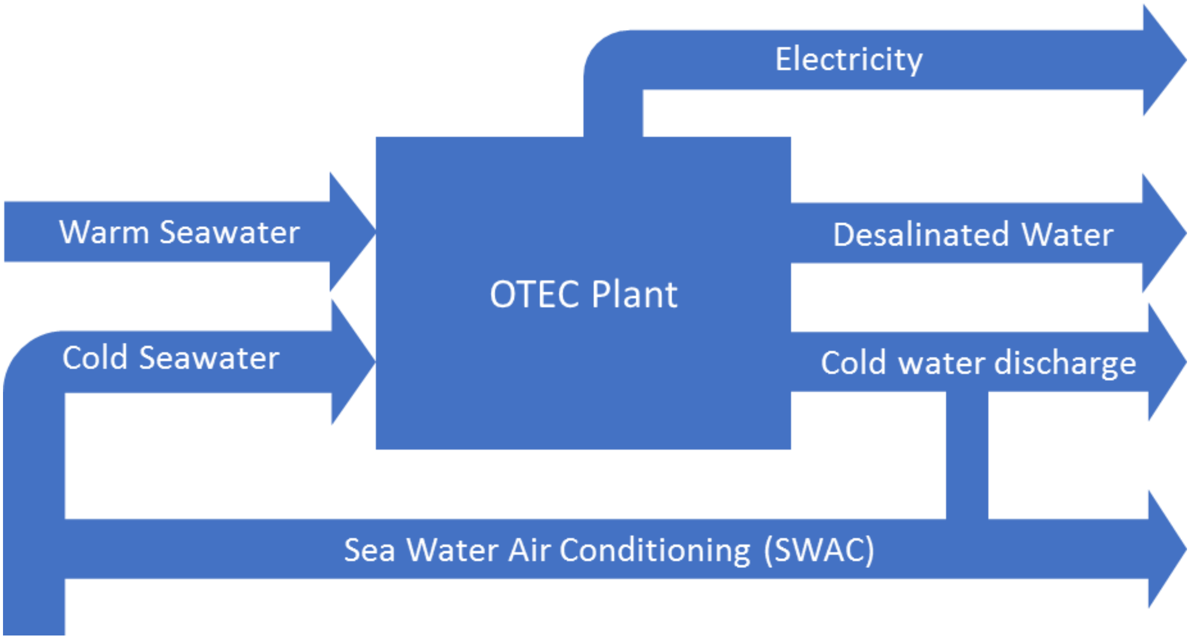

Figure 14: Multifunctionality of an OTEC plant (International Renewable Energy Agency, 2014)

In order to make the most effective use of these secondary functions the OTEC plant is dimensioned on the basis of the air conditioning demand and the demand for fresh water. In Table 4: Determining the OTEC Capacity based on Air Conditioning Demand the OTEC capacity which is required to cover the air conditioning demand is determined. The calculation is based on the predicted electricity demand of the year 2037 (See chapter 3.4). According to Figure 4 53 % of the electricity consumption is spent by the residents. 31 % of the consumed electricity by residents is used for cooling which is a demand of approximately 76 GWh in 2037. With a continuous cooling load over the entire year the theoretical required capacity of a generator would be 8,70 MW. By taking into account a seawater flow rate per ton of refrigeration of 5,4 m^3/h (Surroop, 2013) and a water flow of 10,000 m^3/h per installed OTEC MW (International Renewable Energy Agency, 2014) it results in a required OTEC capacity of 1.34 MW.

Table 4: Determining the OTEC Capacity based on Air Conditioning Demand

Electricity Demand 2037 (own calculation)	464	GWh
Share of residentials (Maldives Energy Authority, n.d.)	53	%
Share of cooling	31	%
Calculated SWAC potential	76	GWh
Calculated theoretical cooling load	8.70	MW
Cooling load in refrigeration tons	2,474	RT
Required seawater flow rate for cooling	13,359	m³/h
Calculated OTEC capacity	**1.34**	**MW**

The next step is to determine the needed OTEC capacity to cover the demand for fresh water. This is shown in Table 5: Determining the OTEC Capacity based on Desalination. According to Male' Water & Sewerage Company Limited (2016) an amount of 5,700,000 l of water were consumed on Malé in 2015. By dividing this value through the specific fresh water production per installed OTEC capacity and considering a capacity factor of 0.9 it results in a required OTEC capacity of 11.905 MW.

Table 5: Determining the OTEC Capacity based on Desalination

Water demand 2015 (Male' Water & Sewerage Company Limited, 2016)	5,700,000	m³/year
Desalinated water production per installed OTEC capacity (International Renewable Energy Agency, 2014)	532,000	m³/year/MW
Capacity factor (International Renewable Energy Agency, 2014)	0.9	-
Calculated OTEC capacity	**11.905**	**MW**

In the further analysis, the OTEC capacity rounded up to 12 MW. The usage of these secondary functions leads to a reduction of the electricity demand. The effect on the demand is discussed later in chapter 7.

4.4.3 Degree of sustainability

OTEC plants with capacities of more than 10 MW need pipe diameters of 4 m or more and can affect the coastal structure. However, the main impact of to the environment is caused by the substantial amounts of pumped up cold water. To avoid that the cold-water discharge affects the warm surface temperature that is needed for power production the water effluent is discharged in a curtained depth. Nevertheless, the cold water intakes will influence the temperature and density of the water in the area. This can change the local currents. Furthermore, the water chemistry and pH-level is influenced by the high nutrient content of the transferred water. The impact on marine life is difficult to predict as the ecosystem is of a complex nature. Further long-term studies are required to investigate the effects of large scale OTEC systems on the environment. (Vega, 2003 ; Owen, Kruijsen, Turner, & Wright, 2011)

5 Storage potential

Written by Jan Lukas Hillendahl 548132

A system running with 100 % renewable energy requires a back-up system, due to volatile energy production of solar and wind. In a 100 % renewable system, it is thinkable to use biodiesel generators as a back-up, but the demand on biodiesel cannot be produced in Malé. Therefore, Malé would still be dependent on imports. To be 100 % renewable and independent, it is necessary to store the overproduction of the renewables and provide this energy again at underproduction.

5.1 Theoretical Potential

Due to the size of the island and due to topographic reasons, pumped-storage hydro power stations are no storage possibility on Malé. Alternative storage technologies can be battery storages, power to x, or underwater compressed air energy storages (UWCAES).

The most important requirements of the 100% renewable system are, a high capacity and the possibility of fast charging and discharging. As already mentioned, the limiting factors are the topography and the space on the island.

Analysing the advantages and disadvantages of the three mentioned technologies, it turned out that battery storages can fulfil the requirements of fast charging and a high capacity. The only disadvantage of battery storages is the high investment cost in large scale installations. Power to x can mean power to gas or power to hydrogen. Both of them can have a high storage density and no storage losses. But a huge disadvantage of these methods is the low efficiency of transforming electricity into gas or hydrogen. The big advantage of the underwater CAES is, that most of the components are underwater, so that the construction is not visible and doesn´t need much space on the island. Disadvantages are, that the technology is still in development status. This status includes, that the impact of the technology on the marine life is not finally investigated. Furthermore, the storage capacities of the normal scale are not enough for the requirements (Sterner & Stadler, 2014).

5.2 Technical Potential

After the theoretical potential analysis of the storage technologies, it can be said that battery storages are the best fit for Malé. Also, the underwater CAES can be a good fit, but due to the lack of development and experience, this technology will not be analysed in this part.

Battery storages have the big advantage of being not bounded to some topographic conditions. Usually, large scale battery storages consisting of a bound of batteries, quartered in containers. So, they are easy to install and scale. These containers can for example be stored in available cellars. The possibility of building floating platforms for the batteries also exist. So, the lack of space on Malé can be solved by building floating battery storages. The only disadvantage, the high investment costs, can maybe overcome by the technological advance through the years.

5.3 Degree of Sustainability

With the help of storages, peak load generators can be replaced. Therefore, the future generation would no longer be dependent on imports of diesel or biodiesel. Furthermore, battery storages are not emitting any kind of emissions.

Disadvantages in terms of sustainability are, that the lifetime of batteries is not the same as the lifetime of any pumped-hydro storages. So, the depollution of the batteries can be a worry, especially for such a small island. Summarised, the battery storages seem to be the best option for the future to deal with peak loads and overproduction.

6 Sustainable Mobility Concepts

Written by Jan Lukas Hillendahl 548132

Due to the overpopulation on Malé, the citizens have to deal with congestions. Therefore, an intelligent and sustainable mobility concept is very useful to decrease the traffic jam and of course, to decrease the emissions of the vehicles. Nowadays the traffic on Malé is based on 86 % motorcycles and 11 % cars. The total kilometres of motorised vehicles on Malé are nearly

260.000 km. More than 200.000 km are driven by motorcycles. The emission reduction potential in this sector is huge. Calculating with 100 gCO_2/pkm for motorcycles (DEFRA, 2011) and 142 gCO_2/pkm (Umweltbundesamt, 2017) for cars, the CO_2 emissions per year are ca. 270,000 kg of CO_2 equivalent. The easiest way is just to replace every of them by electric equivalents. As already mentioned this would increase the demand of electricity of 39 GWh in 2037. Therefore, there is a big potential to save demand of electricity.

The short distances and the high population density are suggesting that public transportation systems can be a perfect add for the island. Sustainable public transportation systems have the potential to decrease the congestion and the demand of electricity. It is possible to build up such a system based on electrified busses or on electrified trams. The electricity supply can be provided by a trolley system or by charging the vehicles during the longer holding time (e.g. in the nights). The implementation of the system includes a plan to convince people to switch to public transportation. Therefore, the public transportation needs to obtain acceptance. Possible measures by the government are to establish a well organised timetable with enough stops. Furthermore, the system has to provide reliability and simultaneously offer good prices for being a better alternative. Another way to persuade the citizens can be a programme which inform the people about the need of a sustainable mobility. More measures the government can do are to give the public transport systems the right of way, so that they can go faster than other vehicles.

Another way to reduce the traffic on Malé is, to promote the ways for bicycles and pedestrians. With the help of well-constructed bicycle and pedestrian ways it is possible to replace a lot of motorcycles and cars. The small size of the island makes it possible that every corner of the island can be accessible by bike or even by foot.

Concepts of bike sharing or subsidies for bikes can motivate the people to drive by bikes. The implementation of pedestrian and bike zones can facilitate the locomotion of the people. Nevertheless, there will always be a need of trucks for deliveries to shops or stores, but they can run by electricity.

7 Energy Saving Potentials & Demand Site Management

Written by: Sören Wieck, 548168

Before scaling up the capacities of renewable energy sources the preliminary step towards a 100 % renewable energy system for Malé should be a reduction of the total energy demand. If the energy demand decreases the costs of the entire energy systems will decrease because less capacities of renewables are needed to cover the demand. In addition, this lead to a reduction of the environmental impact and thus to a higher acceptance of the residents for the change of the energy system. It is therefore crucial to improve the energy efficiency. (German Advisory Council on the Environment, 2011, p. 219)

7.1 Appliances and Lighting

Analyzing the energy saving potential of Malé, the first step is to investigate the primary areas of electricity demand. As already mentioned in chapter 3.4, residents consume 53 % of the total energy consumption on Maé. The highest shares of energy consumption are used for appliances, cooling and lighting. (Maldives Energy Authority, 2013; State Electric Company Limited, 2016)

For island states like the Maldives it is often difficult or extremely expensive to buy appliances that correspond to the latest state of technology because all products must be imported. The purchase of energy efficient electric appliances is associated with great effort and high expenses for the consumer. (Hohmeyer, 2017) For those reasons, the energy saving potential from replacing appliances and lighting by more efficient ones is estimated to be low. Thus, those efficiency measures are not considered in the analyses of future scenarios. However, the simulation model has the option to enter efficiency improvement rates.

7.2 Sea Water Air Conditioning

Cooling offers additional energy saving potential through sea water air conditioning which is a secondary product of OTEC. As described in chapter 4.4 the SWAC potential can be determined by calculating the share of residential demand and the share of cooling from the total electricity demand (See Table 6: Determining the SWAC Potential).

Table 6: Determining the SWAC Potential

Electricity Demand 2037 (own calculation)	464	GWh
Share of residentials (State Electric Company Limited, 2016)	53	%
Share of cooling (Maldives Energy Authority, 2013)	31	%
Calculated SWAC potential	**76**	**GWh**

In this calculation, it is assumed that the extra energy demand of the SWAC function is already considered in the capacity factor of the OTEC plant. Hence, in the future scenario analysis it is assumed that the complete SWAC potential equals the energy savings.

7.3 Desalination

Another by-product of OTEC is sea water desalination. Due to the high population on Malé the water consumption is also rather high. As already mentioned in Chapter 4.4.2 the billed water consumption on Malé amounted 5,700,000 l/a in 2015. This quantity of water is currently produced by inefficient desalination plants and can be covered by the desalination system of the OTEC plant in the future scenario. Additional 1,400,000 l/a mineral water were imported. (Male' Water & Sewerage Company Limited, 2016) Due to a lack of information, it is assumed that the imported water cannot be substituted by desalination because there is a specific demand for mineral water. Thus, it is not considered in the calculation of the OTEC capacity.

As there is no data available about the energy consumption of the existing desalination systems of Malé, the potential energy savings in this sector are not considered in the future scenario analysis. However, information about the production costs of desalination is available. According to the data of O’Connell (2013) the annual cost savings due to the substition of the desalination systems can be calculated to 19,095 US $ per year (see Table 7: Calculating the cost saving through desalination with OTEC). These additional savings can contribute to a cost efficiently operating OTEC system.

Table 7: Calculating the cost saving through desalination with OTEC

Production costs of current desalination systems (O'Connell, 2013)	3,65	US $/ t
Generation Costs of Desalination with OTEC (O'Connell, 2013)	0,3	US $/ t
Annual water production (Male' Water & Sewerage Company Limited, 2016)	5,700,000	l/ a
Annual cost savings (calculated)	**19,095**	**US $/ a**

7.4 Demand Side Management

Beside saving energy through efficiency measures, demand side management is another option to optimize an energy system and reduce the cost. By shifting the demand from times with a small energy production due to the fluctuation of the renewable energy sources to times with a high energy production, the energy plants can be designed in a smaller size. The same applies for a system with energy storages as demand side management function in the same way like a storage.

As already explained in chapter 6 the transition of the transport sector to a 100 % electrified vehicle fleet leads to an additional electricity demand of 39 GWh per year. However, the charging times of the electric vehicles are flexible and thus can be shifted to times of energy overproduction. The simulation model offers the possibility to choose between different charging patterns. The options are:

1. Manual input of the charging times;
2. Load oriented charging pattern;
3. Sun oriented charging pattern.

In the further analysis of the future scenarios, it was decided to select the sun oriented charging pattern because the solar radiation determines the times of the highest overproduction. An additional argument for this selection is the greater predictability compared to wind.

8 Simulation Model

Written by: Pascal Jess, 547960

This chapter shall give first information about the created simulation model and the way how the scenario results has been calculated.

Simulation models are the best solution for getting fast calculated results. Furthermore, simulation models offer reproducibility, thus results can easily be validated.

The simulation model is programmed with the spreadsheet program Microsoft Excel. This program is very common and easy to use, so that the reader is able to understand the model very quickly and can use it for own simulations.

The simulation model is used to simulate energy systems with the main idea that the energy system is supplied by renewable energies. Electable renewable energies in the simulation model are wind, photovoltaic, waste to energy, OTEC and biodiesel. As a storage system, a lithium-ion based battery storage can be activated. At the last level of the model, it contains diesel generators as a backup system. Furthermore, for an experienced excel user it is easy to integrate other renewable energies or storages. Overall, the simulation model is used to define and simulate different scenarios and comparing them among each other.

Besides the numerical results, the simulation model provides a lot of curves and graphs for the energy generation as well as for the electricity demand.

For the model handbook and a detailed explanation of the simulation model, please see the Appendix - The model handbook.

9 Renewable Energy Scenarios

Written by: Matthias Fischer, 548103

After analysing the potential of different energy carriers and storages, the renewable energy system for Malé can be designed. Therefore, several scenarios are defined and examined to find the most suitable technology combination.

For all of the renewable scenarios, the aim is to design a 100 % renewable energy supply while finding the lowest possible LCOE in each scenario as well. Furthermore, a business-as-usual (BAU) scenario is developed for a comparison basis.

The scenario year is set to 2037. Starting in 2017, 5 years of studies and political changes is assumed. Afterwards, the results are evaluated for 2 years whereupon 3 years planning follow. The construction itself is assumed to last around 10 years, so that in 20 years from now, the renewable energy supply is at 100 %.

All meteorological data, which the following results are based on, are provided by meteoblue.com.

In Appendix A1, an investment and operation & maintenance (O&M) cost overview is provided as used in the calculations. For the fuel based technologies Bio Diesel and Diesel, additional fuel costs have to be considered. At a current price for Diesel of 0.67 $/l and Bio Diesel of 0.82 $/l, these values are calculated with an inflation rate of 4 % for 2037 which results in 1.48 $/l for Diesel and 1.79 $/l for Bio Diesel in 2037. (U.S. Departmend of Energy, 2017) To calculate the levelized cost of energy (LCOE) for each technology and carrier, the investment costs are transferred to annuities with an interest rate of 6 %. In sum with the O&M costs, the yearly costs can be computed.

In Figure 15, a comparison of all LCOE for the different energy carriers is shown. All the shown values are based on the assumption, that the whole possible electricity generation is used. Hence, no curtailments are considered and the yearly costs are divided by the maximum possible generation from the meteorological data.

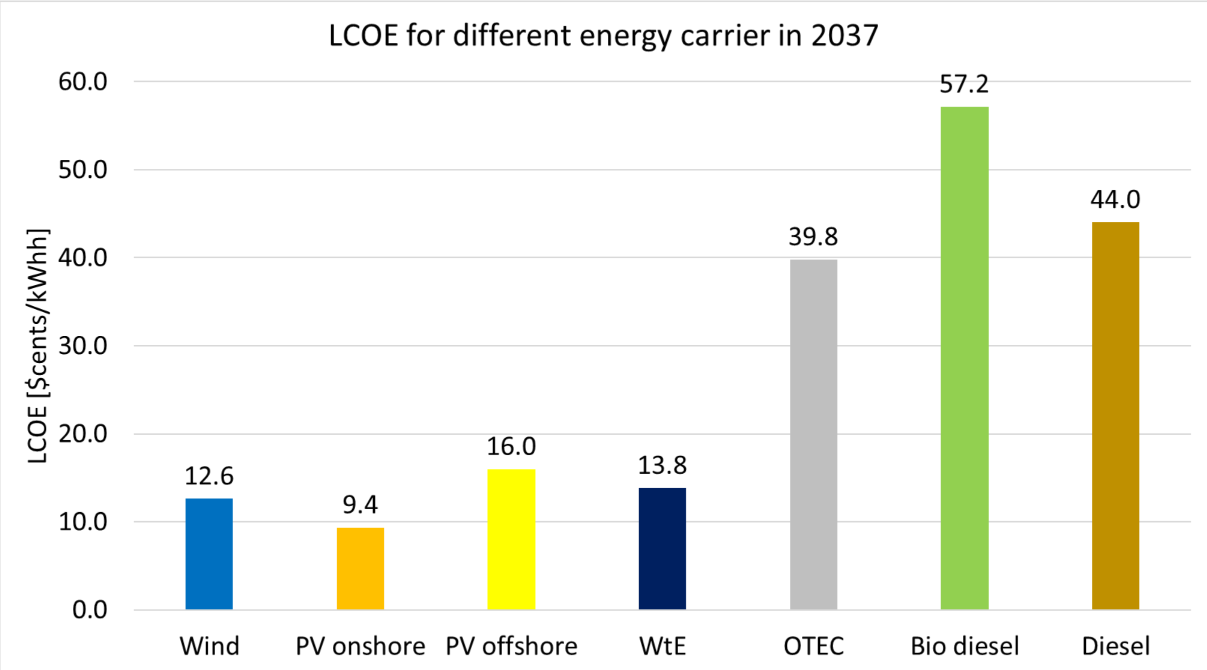

Figure 15: LCOE comparison for different energy carrieres in 2037

The lowest LCOE can be found at PV onshore. As already mentioned, space is very limited in Malé wherefore the maximum capacity of PV onshore is 18 MW. To use the potential of solar energy, offshore PV panels are considered which have a clearly higher LCOE due to a more difficult installation and additional underwater cable cost. Wind has the second lowest LCOE in this comparison. As the wind turbines are placed on uninhabited islands in the atoll, additional costs for underwater cables are considered as well with an additional 10 % investment cost share. Electricity from the Waste-to-Energy (WtE) plant is produced at comparatively low costs of 13.8 $cents/kWh in this comparison. As OTEC is still a developing technology, high investment and O&M costs are considered which lead to a LCOE of nearly 40 $cents/kWh. Solely the electricity generation from generators have higher LCOE due to the high fuel costs in 2037 as explained before. Accordingly, Bio Diesel shows higher LCOE than Diesel. In the case of the generators for Bio Diesel and Diesel, no additional investments are considered in the calculation of the LCOE in Figure 15. The already existing 61 MW of generator capacity is used and sufficiently dimensioned in the renewable scenarios. When considering additional generator capacity, the LCOE will change which is also implemented in the simulation model.

As a demand base for 2037, the already explained demand forecast is used whereby for the renewable scenarios, the gas cooking demand and also the E-mobility demand is considered. The gas cooking demand is assumed to be electrified until 2037 as no fossil fuels will be used.

For the E-Mobility demand, the existing vehicles are assumed to be electrified and a sun-oriented charging pattern is applied. This leads to an overall demand of 562 GWh/a with 464 GWh/a from the electricity sector, 59 GWh/a from the electrified gas cooking and 39 GWh/a from the E-Mobility.

9.1 Business-as-usual Scenario

Written by: Matthias Fischer, 548103

For a comparison, a business-as-usual scenario is developed and calculated. In this scenario, the demand base changes as it is expected that the gas cooking demand will still be fulfilled by gas and no E-Mobility is introduced. Therefore, only the demand of the electricity sector with 464 GWh/a is considered.

The technology combination in this scenario is shown in Table 8.

Table 8: Technology Combination, BAU scenario

	Capacity [MW]	**Fuel consumption [l/a]**
Wind	-	-
PV onshore	0.74	-
PV offshore	-	-
Waste-to-Energy	8	-
Battery storage	-	-
OTEC	-	-
Diesel generators	96.56	117,297,769

In the BAU scenario, only the already existing 740 kW of PV onshore are considered in the PV sector. As the Waste-to-Energy plant with 8 MW is already planned as explained before, it is also considered in this scenario. Business-as-usual involves no changes in the current energy production mix, therefore no capacity in wind energy, PV offshore, storages or OTEC is considered. Additional to the 61 MW installed generator capacity in 2017, 35.56 MW of generator capacity is needed in 2037 to meet the demand. As no changes in the supply are assumed, these generators are fuelled with Diesel. Therefore, about 117.3 Million litres of Diesel need to be imported per year which leads to emissions of 310,839 t CO_2 per year at a specific emission of 2.65 kg CO_2/l. (Alt, 2015)

The LCOE in the BAU scenario result to 40.18 $cents/kWh which is the comparison base for the following renewable scenarios to evaluate possible cost savings through renewable energies.

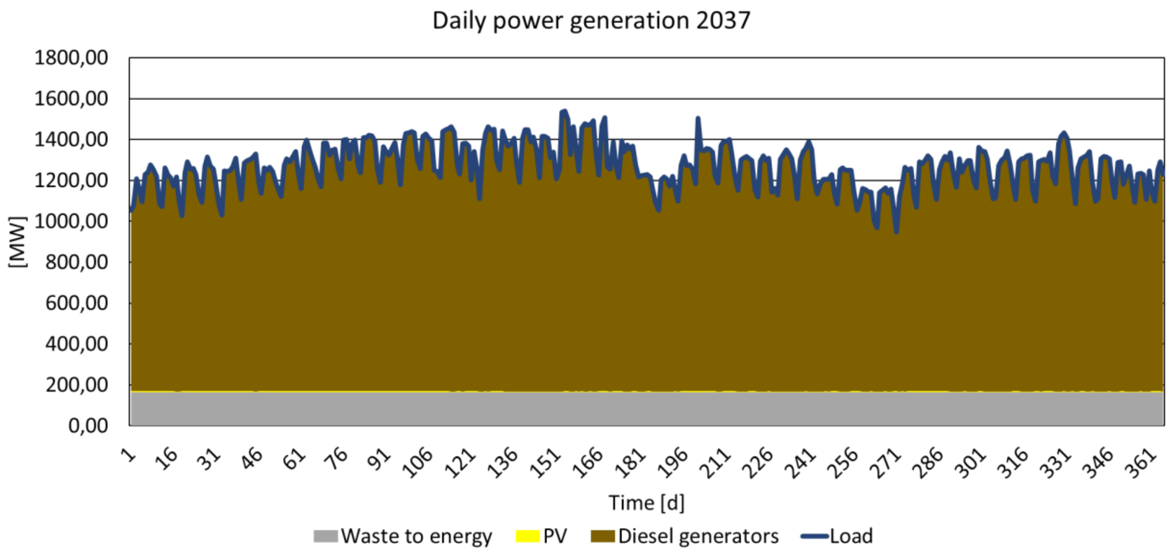

Figure 16: Daily power generation 2037, BAU scenario

In Figure 16, the daily sums of the power generation for the BAU scenario are shown for the year 2037. In grey, the waste-to-energy plant is assumed to run constantly. Barely visible in yellow, the onshore PV panels contribute to the electricity production as well. Obviously, the Diesel generators account for the greatest part in the electricity generation with a share of about 87 %.

Summed up, the electricity sector in Malé will mainly rely on fossil fuels in 2037 if nothing is changed. This leads to heavy emissions not only in the electricity but also in the transport sector which is not included in this scenario.

9.2 Low-Cost Scenario

Written by: Matthias Fischer, 548103

As a first renewable scenario, a low-cost scenario is developed. The name of this scenario already hints the aim to find the lowest possible LCOE with the available technologies and restraints. As OTEC and battery storages have comparatively high investment costs and accordingly high LCOE, they are not included in this scenario.

The demand base now changes compared to the BAU scenario. As already explained, the gas cooking and E-Mobility demand is included now.

Table 9: Technology Combination, Low-cost scenario

	Capacity [MW]	Fuel consumption [l/a]
Wind	252	-
PV onshore	18	-
PV offshore	57	-
Waste-to-Energy	8	-
Battery storage	-	-
OTEC	-	-
Bio Diesel generators	61	20,343,989

In Table 9, the needed capacities for this scenario are listed. 60 wind turbines are needed with a capacity of 252 MW. Furthermore, the 18 MW onshore PV potential is completely used. Additionally, 57 MW of offshore capacity is considered as floating PV panels. The planned 8 MW Waste-to-Energy plant contributes to the electricity generation in the renewable scenarios as well. As a peak load and backup technology, Bio Diesel generators are needed. In the renewable scenarios, the generators are fuelled with Bio Diesel and the existing 61 MW generator capacity is sufficient to meet the demand. The consumption amounts to about 20.3 Million litres whereby Bio Diesel does not lead to any emissions. Hence, the energy system in the low-cost scenario is emission-free. This includes emissions from gas cooking and the transport sector as these demands are included in the simulation.

This combination of technologies leads to an overall LCOE of 21.14 $cents/kWh in the low-cost scenario.

Since space is a limiting factor in Malé, wind and PV facilities are placed offshore respectively on uninhabited islands. While this space is limited in the end as well, the needed amount of wind turbines and the area requirement for offshore PV is mapped in Figure 17.

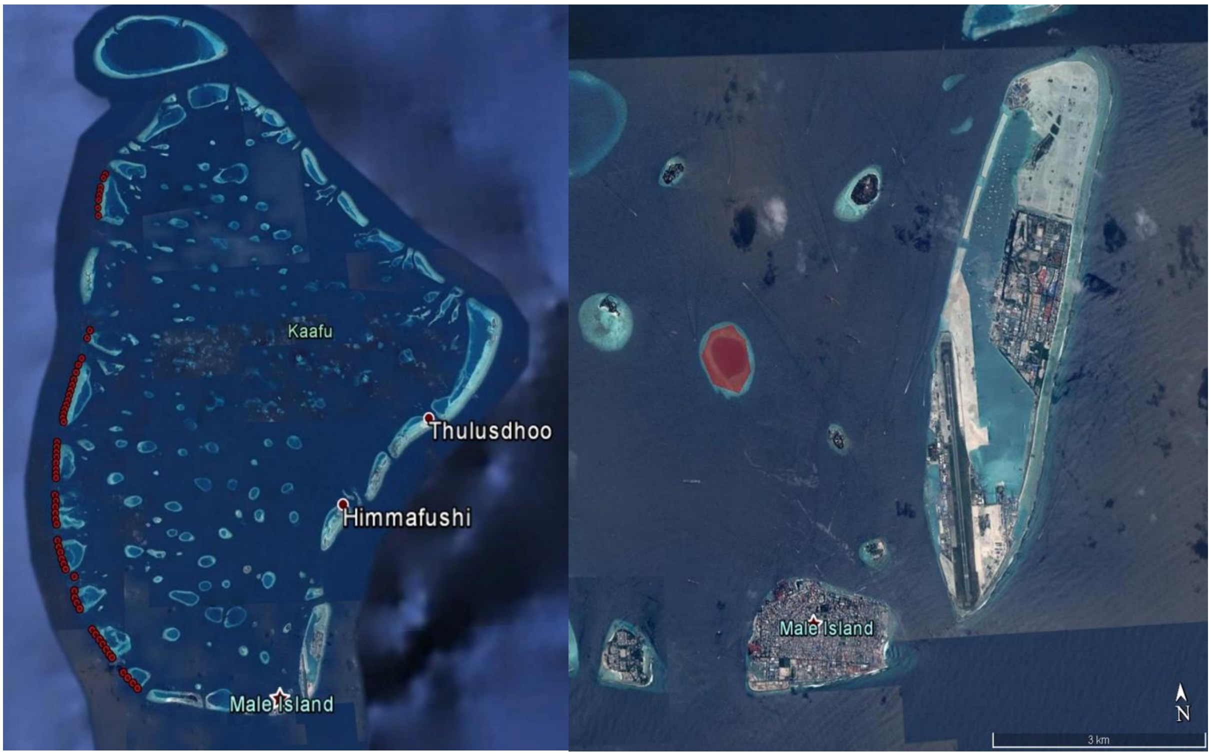

Figure 17: Wind turbine placement (left) and offshore PV are requirement (right), Low-cost scenario , Source: Google Earth

The 60 wind turbines are placed alongside the western coastline of the Malé-Atoll. As West is the main wind direction, this placement reduces wake effects and the maximum possible energy is used. The distance between the wind turbines is set to five times the rotor-diameter in main wind direction and 3 times in auxiliary-wind direction. From the most northern wind turbine to Malé in the south of the atoll, the linear distance is about 50 km. From this figure, the impact on the visual landscape can be estimated. The right illustration of Figure 17 shows the impact of offshore PV panels on floating platforms. This extract shows a zoom into the south-east of the atoll with Malé in the south. With a specific area requirement of 7.84 m^2 per kW (see chapter 4.2.2.2), the total area requirement is about 0.447 km^2. As seen on the map in red, an area close to Malé would fulfil this requirement in a distance of about 3.5 km. Indicated by the brighter colour, the ground elevation level of the ocean is comparatively high in this area. Hence, the fixture of floating PV panels is technically easier. Furthermore, marine traffic is not disturbed as this is an unnavigable area.

To examine the interaction of the chosen technologies in the simulation, a typical day is shown in Figure 18.

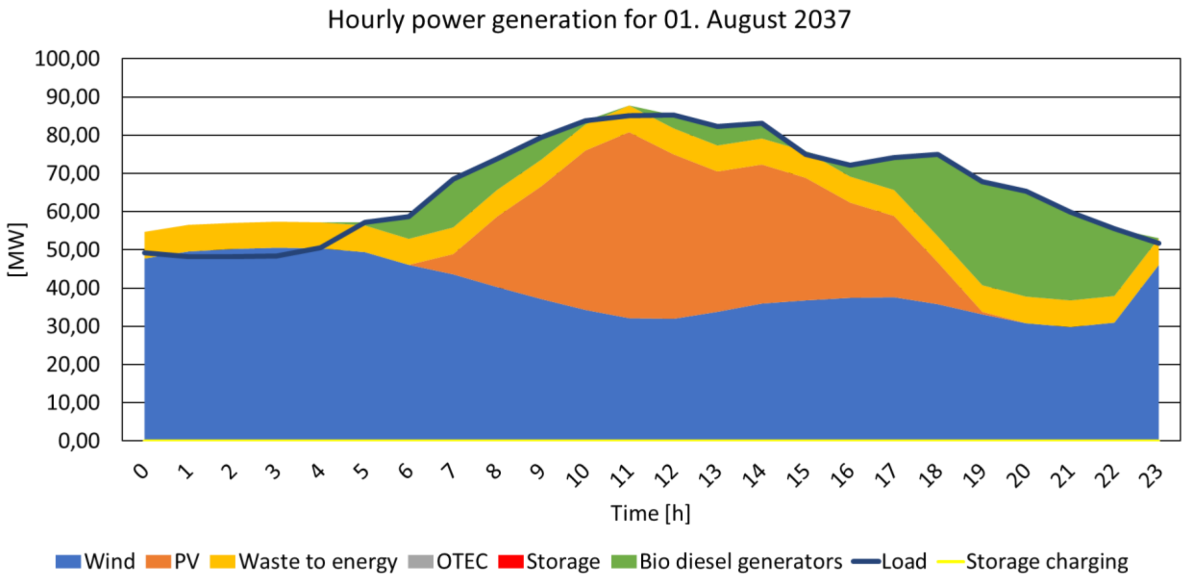

Figure 18: Hourly power generation for 1st August 2037, low-cost scenario

In the early morning hours, wind production in blue exceeds, together with the waste-to-energy production, the load curve which would lead to curtailments in wind turbines. During the later morning hours from 5 a.m. to 10 a.m., wind production decreases while the sun rises and solar production starts. Nevertheless, additional electricity production from Bio Diesel generators is needed to fulfil the demand indicated in green. At around 11 a.m., the solar radiation reaches its maximum leading to a shutdown of the generators. In the course of the day, solar production decreases according to the hours of sunlight. Hence, the generators have to fill the gap to meet the demand.

Naturally, a larger number of wind turbines and additional offshore PV capacity would lead to a reduced use of Bio Diesel generators. Since the optimization aim of all renewable scenarios is to find the lowest LCOE with the chosen technologies, this extension leads to an increase of the overall LCOE. Accordingly, the shown combination optimizes the LCOE.

In comparison to the business-as-usual scenario, the low-cost scenario of course implicates a 100 % renewable supply with a 100 % reduction in emissions not only in the electricity, but also in the transport and gas cooking sector. Furthermore, the lowest possible LCOE are provided as this is the aim of the scenario. The small PV offshore area requirement is also positively observed.

A disadvantage is found in the still existing dependence on imported fuels. Although the fossil Diesel imports are substituted by renewable Bio Diesel imports, the dependence remains constant. However, the amount of imported fuels is reduced by over 82 %. As seen in Figure 17, the influence on the visual landscape due to 60 wind turbines alongside the west coast of the atoll can be remarked as a negative aspect.

9.3 Storage Scenario

Written by: Matthias Fischer, 548103

The storage scenario is designed to substitute the use of Bio Diesel by considering an energy storage. In consequence, this leads to an independent energy supply without any imports of fuels. As the energy storage potential analysis pointed out, only battery storages are suitable for the Malé energy system.

As possible technologies, wind, PV, Waste-to-energy and storage are considered while excluding OTEC and generators. Generators are not taken into account due to the mentioned aim of an independent energy supply while OTEC is not considered because it is examined in an extra scenario.

Again, the overall aim of an optimized and therefore lowest possible cost structure still applies wherefore a small-sized storage system is targeted with respect to the prevailing costs of battery storages.

Furthermore, the demand base includes gas cooking and E-Mobility.

Table 10 lists the results of the technology combination according to the simulation.

Table 10: Technology Combination, Storage Scenario

	Capacity
Wind	667.8 MW
PV onshore	18 MW
PV offshore	142 MW
Waste-to-Energy	8 MW
Battery storage	552.28 MWh
OTEC	-
Bio Diesel generators	-

In the storage scenario, 159 wind turbines are needed with an installed capacity of 668 MW. Besides 18 MW onshore PV, 142 MW offshore PV is needed. Similarly to the other scenarios, 8 MW waste-to-energy is considered as well. Exclusively in this scenario, a battery storage is used. Its capacity is calculated to around 550 MWh at a power of 100 MW. According to the aim, no Bio Diesel generators are included in this scenario.

The described combination of technologies result in an overall LCOE of 44.90 $cents/kWh. Interesting in this scenario is the LCOE of the battery storage system as these costs vary according to the utilization ratio. With reference to the outgoing energy, hence the kilowatt hours fed into the grid, the LCOE of the battery system is 5.63 $/kWh. Compared to LCOE of other technologies listed in Figure 15, this value is many times higher even than the highest LCOE of Bio Diesel generators. Thus, the optimization for the smallest possible storage size is reasonable.

Furthermore, an emission reduction of 100 % compared to the business-as-usual scenario is once more achieved.

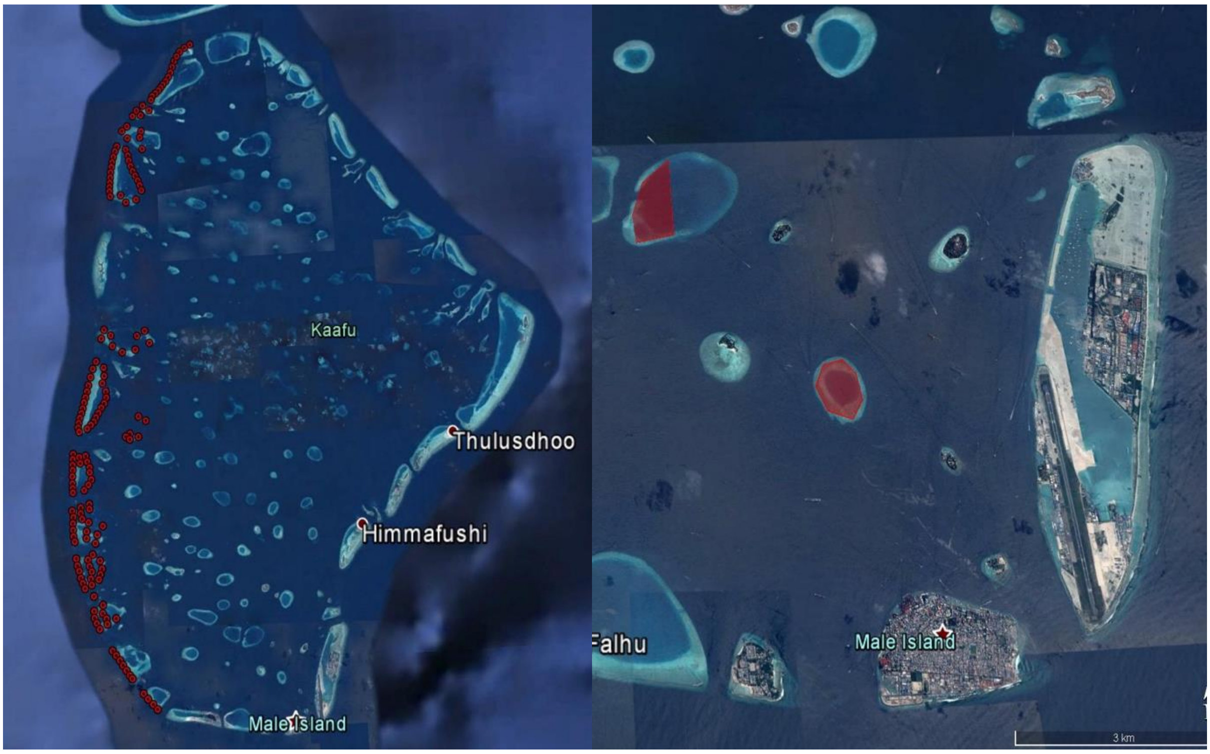

Figure 19: Wind turbine placement (left) and offshore PV are requirement (right), Storage scenario , Source: Google Earth

In Figure 19, the calculated amount of wind turbines and the area requirement for offshore PV is displayed for the storage scenario. Compared to the low-cost scenario, now more than 2.5 times the quantity is needed which clearly changes the distribution of wind turbines in the atoll. The entire western coastline is covered with wind turbines and even the second and sometimes the third coastal line is needed to place 159 wind turbines. Hence, the impact on the visual landscape is much higher in this scenario.

For offshore PV, the area requirement amounts to 1.113 km^2 which is again about 2.5 times the area needed in the low-cost scenario. However, this increase is not as visible as the increase in the number of wind turbines. Additional to the area close to Malé from the low-cost scenario, the half of another high ground elevation level area is needed in the north-west which is still close to Malé with about 7.5 km distance.

In the next step, the interaction of the technologies is examined again shown in Figure 20.

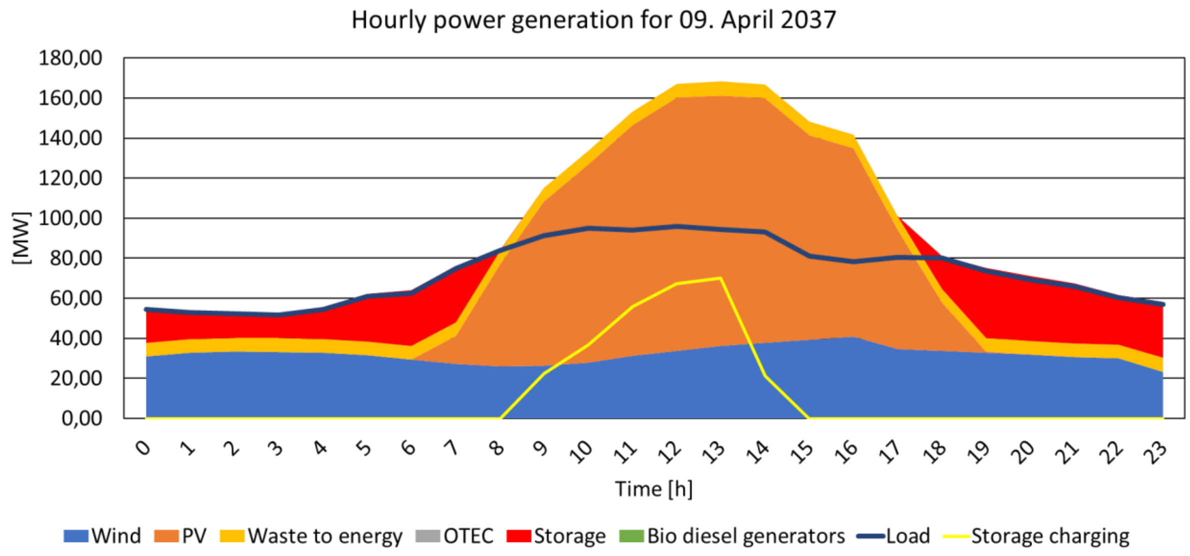

Figure 20: Hourly power generation for 9th April 2037, storage scenario

New in this figure is the storage activity in red. In the morning hours, there is some underproduction which is compensated by the battery storage to fulfil the demand. After 8 a.m., the solar production starts and the overall production is high enough to meet the demand and even exceed it. This surplus energy is used to charge the storage again which is indicated by the yellow line. The storage charging continues until the storage is completely charged at around 3 p.m. In the evening hours from 6 p.m. onwards, the production again falls below the demand line wherefore the storage fills the gap again. This pattern is typical for days where the storage is active in the energy system. To figure out how often the storage is active and therefore needed to balance the grid, Figure 21 depicts the hourly storage level for the whole year 2037.

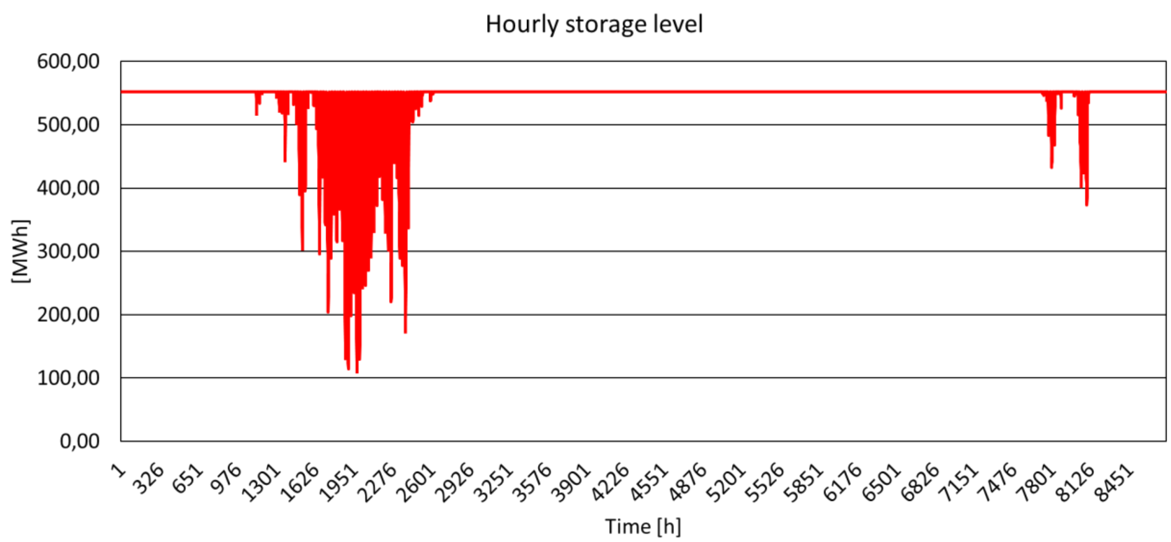

Figure 21: Hourly storage level, storage scenario

The graph shows clearly the inactivity of the storage for most hours of the year. However, in spring time and in November and December as well, the storage is needed. Also visible in this graph is the implemented 20 % minimum charging level of the storage to ensure a longer lifetime which also is a limiting factor during optimization in this scenario. In addition, an efficiency of 95 % is also included in the simulation model.

The main advantage of the storage scenario is the 100 % independent energy supply without any imports of fuels. Again, a 100 % renewable and emission-free energy supply is achieved as well.

Negatively remarked is the comparatively high LCOE which is even higher than in the business-as-usual scenario and the heavy influence on the visual landscape due to 159 wind turbines covering the western coastline of the atoll.

In summary however, the possibility of a 100 % renewable and independent energy supply has to be highlighted as this is the aim of the simulation.

9.4 OTEC Scenario

Written by: Sören Wieck, 548168

The OTEC scenario includes an Ocean Thermal Energy Conversion plant which is not considered in any other scenario as this technology is still under development and commercial plants were not realized yet. However, as soon as the technology has reached an appropriate state of development it can provide a large renewable energy potential.

In this scenario, the secondary function of OTEC, sea water air conditioning, is included. As a result of this, the electricity demand is reduced by 76 GWh/a due to the substitution of cooling appliances. This leads to a total demand of 486,2 GWh in 2037 which includes the demand for cooking and E-mobility. As explained before, energy savings through desalination is not considered due to the lack of information. Nevertheless, it should be mentioned that the substitution of the existing inefficient desalination plants leads to additional energy and cost savings.

Beside the OTEC technology, all feasible technologies except of battery storages are considered. As the overall target is again to achieve an optimized and therefore lowest possible cost structure, the battery storages are excluded.

Table 11 shows the combination of installed technologies.

Table 11: Technology Combination - OTEC scenario

	Capacity [MW]	Fuel consumption [l/a]
Wind	160	-
PV onshore	18	-
PV offshore	43	-
Waste-to-Energy	8	-
Battery storage	-	-
OTEC	12	-
Bio Diesel generators	61	12,538,448

Just like in the scenarios before, 18 MW PV onshore and 8 MW waste-to-energy are needed. In addition, 43 MW of PV offshore and 38 wind turbines with a total installed capacity of 160 MW are required. As already mentioned, a OTEC system with a capacity of 12 MW which was dimensioned based on the fresh water demand is included in this scenario. The existing 61 MW diesel generators are kept in order to function as a back-up for peak loads. In this scenario, they are operating on bio-diesel and need 12,538,448 l per year to meet the demand which is a lot less than in the low-cost scenario. Hence, the energy system in the OTEC scenario is emission-free.

The composition of this technologies leads to total levelized costs of energy of 22,5 $cents/kWh. The greatest price driver is the OTEC system with investment costs of 23 Mio $/MW and operation and maintenance costs of 430,000 $/MW*a.

As before, the impact of the renewable energy installations on the visual landscape should be discussed. Figure 22 shows the placement of the wind turbines (left) and the area requirement of PV offshore. As only 38 wind turbines are required, this scenario has the lowest visual influence on the affected area. With an installed capacity of 43 MW offshore PV only 0.34 km² of the high ground elevation level area is required. This demonstrates that the energy system of this scenario has by far the smallest impact on the visual landscape of the atoll.

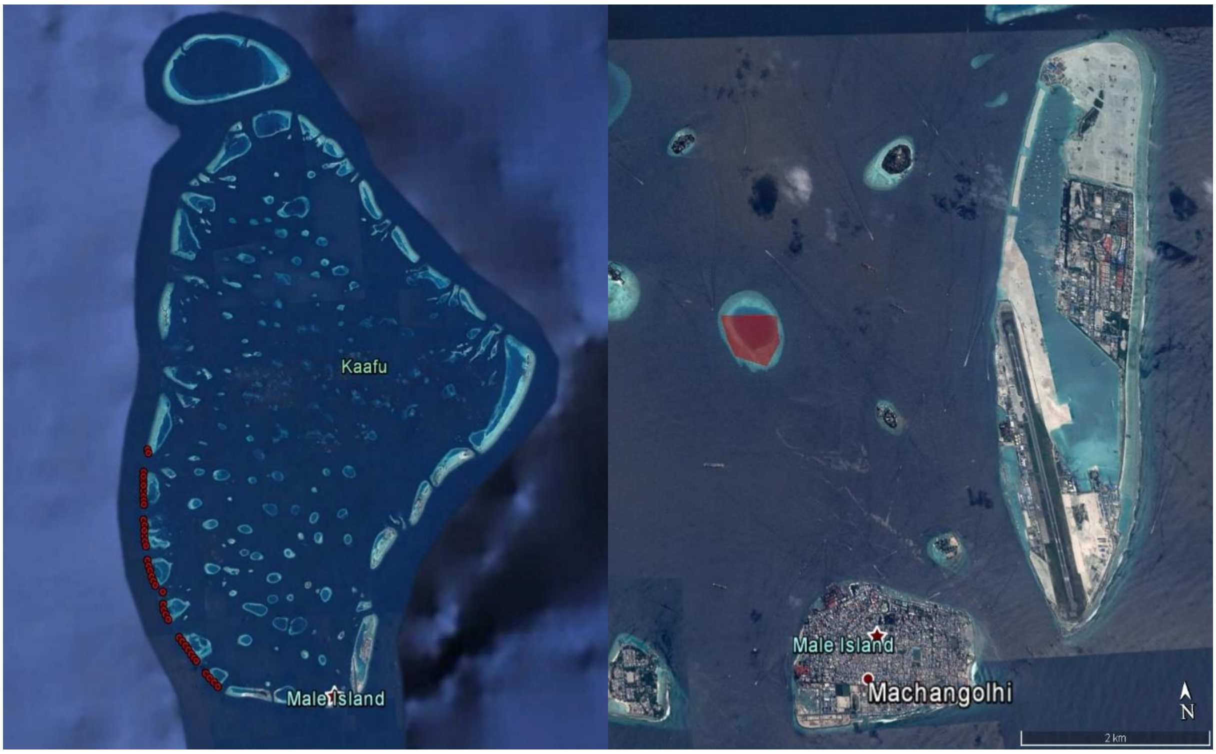

Figure 22: Wind turbine placement (left) and offshore PV are requirement (right), OTEC scenario

However, the OTEC plant also requires an area for operation which can be realized on an undeveloped site in the south east of Malé. In Figure 23 it can be seen that there are around 10,000 m² of free space that can possibly used for the onshore station of the OTEC system. In addition, this place has the advantage to be the closest location to the identified deep-sea area in a distance of approximately 4.5 km.

Figure 23: Space requirements of OTEC plant

Next, the interaction of the selected technologies is analysed again. Figure 24 shows the simulated hourly power generation of the 1st August of 2037. The OTEC system and the waste-to-energy plant produce constantly electricity over the day. In the night hours, when the demand is low, there is an oversupply of energy so that the wind turbines would be curtailed. During the morning, the demand rises as well as the power production from PV. There are again times of underproduction where the biodiesel generators must fil the gap to cover the demand. Nevertheless, the generators show a clearly lower activity than in the low-cost scenario. This observation is consistent with the fuel consumption of the generators.

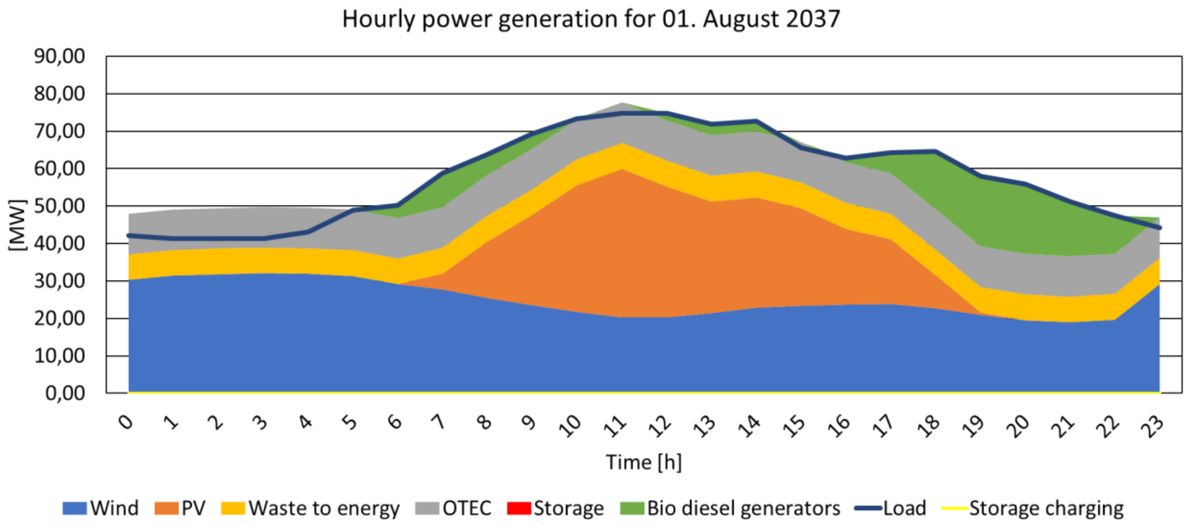

Figure 24: Hourly power generation for 1st August 2037, OTEC scenario

The OTEC scenario brings just like the storage scenario and the low-cost scenario the advantage of 100% renewable energy supply. The LCOE of this scenario is not as low as the one of the low-cost scenario but at a similar level. Additional advantages are associated with the secondary functions of the OTEC system. Due to the use of SWAC the electricity demand can be reduced. Desalination in combination with OTEC also reduces the demand and lead to an independent drinking water supply for Malé. Furthermore, it was illustrated on the maps that the wind and solar installations of this scenario have the least impact on the visual landscape. Despite the fact that the fuel consumption is the lowest compared to the other scenarios, the dependence on imported biofuel is a negative aspect. The greatest obstacle of this scenario is the lack of experience of the OTEC technology. The development of the technology and costs are a significant factor of uncertainty. Furthermore, the impact on marine life have not been adequately researched yet and another obstacle that should be considered.

9.5 Scenario Comparison

Written by: Matthias Fischer, 548103

After evaluating all simulated scenarios, the results can be compared. As a comparison basis, the business-as-usual scenario is selected to show the possibilities in cost reduction through a renewable energy system.

Table 12: Scenario LCOE comparison

	LCOE [$cents/kWh]	Deviation to BAU
Business-as-usual scenario	40.18	-
Low-cost scenario	21.14	- 47.39 %
Storage Scenario	44.90	+ 11.74 %
OTEC scenario	22.62	- 43.70 %

In Table 12, the LCOE results for all scenarios are listed as well as the deviation of the renewable scenarios to the business-as-usual scenario. In the low-cost scenario, the LCOE can be lowered by about 47 %, the storage scenario displays a 12 % LCOE increase in contrast. This increase mainly comes from the high investment costs of battery systems. The OTEC scenario on the other hand can lower the LCOE by about 44 % compared to the business-as-usual scenario.

In two of three simulated renewable scenarios, the LCOE are clearly decreased by the substitution of fossil fuels through renewable energies. Thus, besides the advantage of an emission-free energy supply, the electricity bill of Malé can be lowered by a huge percentage. Furthermore, the transport sector is included as well which leads to additional emission reductions. These results reveal the chances and problems of renewable energy based systems. The chances of lower costs and emission reduction have been clearly outlined. Problems in the case of Malé is the storage possibility. Through volatile energy production from wind and solar, energy needs to be buffered. As the only currently available possibility for Malé is a battery storage system, the costs pose a problem as seen in the storage scenario. Since the development of battery systems is proceeded in the next years, updated cost calculations are recommended and easily conducted with the simulation model.

Considering the present results stated above, the OTEC scenario fits best for the energy system of Malé. The potential of a close-by deep ocean with constant surface water temperatures is recommended to use. In this scenario, the least influence on the visual landscape is expected which also increases the acceptance of an energy transition. In the first step, biofuel imports are needed which later can be substituted by a storage system if investment costs decrease.

However, OTEC is still a developing technology with limited utilization around the world. It has been researched for a few decades still waiting for the breakthrough and distribution of the technology. Thus, it is questionable if OTEC will experience its breakthrough in the next decade.

Nevertheless, all scenarios have a share of wind and PV in common. These technologies are highly developed and can be installed immediately. Hence, a robust strategy is to implement wind turbines and PV panels until a decision has to be made for storages or OTEC. Furthermore, current capacities of generators can run as long as possible by simply substituting Diesel with Bio Diesel.

The impact on the visual landscape through several wind turbines has also been discussed in this chapter. This impact cannot be argued away but equally the impact of not participating in an energy transition cannot be argued away. As Malé and the whole Maldives only have a height slightly above the sea level, they will be one of the first victims affected by a rising sea level through climate change. Hence, an impact on the visual landscape is recommended to be accepted.

10 Policy and Action Plan

Written by: Sylvia Schimanek, 547945

To realise big changes like the adjustment to a 100 % renewable energy system, an elaborate and sophisticated policy is essential. In the following chapter a few expectable difficulties are pointed out and possible opportunities for action submitted. Since a detailed research on the policy in Malé exceeds the aim of the report, it needs to be said that recommendations are exemplary and not complete.

The government of Malé already has the intention to change the system and introduced some measures to diversify the energy mix to for instance introduce renewable energies. The Maldives want to demonstrate international leadership and has declared a policy commitment. This includes national energy policy as well as a national energy action plan. (Ministry of

Environment and Energy, 2012, p. 21) The plan lasted from 2009 – 2013 to focus on more energy efficiency, reduction of CO_2 and conservation awareness (Ministry of Environment and Energy, 2012, p. 22) Furthermore there are policies to encourage private investments in the energy sector. This includes a zero import duty for renewable energy related merchandise (Ministry of Environment and Energy, 2012, p. 21). Even though, there is still a lot potential, this shows first acceptance and that the government of the Maldives is interested in change.

Another challenge would be the sustainable transport system and changing the habits of motor bike and car users. In the short term biofuels in transport would be an option, as about 15 % ethanol can be used without modifying the vehicles (Fenhann & Ramlau, 2014, p. 67). To increase mitigation efforts, the introduction of incentives, like reduced tax for efficient vehicles and introduction of vehicles standards based on their emissions would be options. Also promoting the use of push bikes for example with bicycle lanes are another example for improving a more sustainable transport system (Fenhann & Ramlau, 2014, p. 66) as already pointed out earlier.

In the end, even the most effective measures cannot be realised, if the government does not have the budget. Therefore, an investment plan is essential. The SREP requires an investment plan and uses SREP resources and co-financiers to support the implementation of renewable energy systems in the Maldives. Specific examples for Malé are:

- Funding energy efficiency opportunities from the governmental budget, the Multilateral Development Banks and maybe the Maldives Green Fund
- Solar PV investments funded by the SREP, Government of Maldives, International Development Association, World Bank Group and private fundings
- Waste to energy supported by SREP, International Finance Corporation and also private

(Ministry of Environment and Energy, 2012, pp. 24, 59)

And last but not least, the SREP would contribute money for a renewable power system integration. (Ministry of Environment and Energy, 2012, p. 59)

The following action plan gives should be seen as recommendations for a pathway for a transition to a 100 % sustainable energy system. As already pointed out at the beginning of this chapter, more concrete measures need further researches and studies.

Technical Aspects:

1. Conduct exact measurements of the wind and planning of wind energy locations at the west coast of the Malé-atoll
2. Analyse possible contribution of rooftop and floating solar PV installations
3. Expand the PV area, by roofing all sport fields
4. Conduct proper planning of the preferred water surfaces for solar energy sites in the north of the island (in the middle of the Malé-atoll)
5. Develop utilities to upgrade, manage power infrastructure, improve efficiency
6. Introduce RE-based charging stations for transport

Policies:

7. Introduce measures to diversify energy
8. Start a feed-in tariff system for wind and solar energy and give it guaranteed priority access to the grid
9. Promote demand side management, focussing on main energy usage at night (conditioning, fridge, street lighting)
10. Promote electricity production, distribution and usage via workshops involving stakeholders
11. Set up technical grid connection rules for the connection of wind and solar energy systems
12. Set annual targets for the capacities of wind and solar energy to be installed
13. Promote energy conservation and efficiency (Air conditioning, appliances, cooking)

Financial Aspects

14. Develop a strategy in order to mobilise international funding
15. Encourage national and international investments to develop and sustain energy
16. Introduce incentives to power sector developers

Transport Sector

17. introduction of vehicles standards of incentives reduced tax for efficient vehicles
18. Incentives to promote public transport, bicycles and push bikes (bicycle lanes and other preferences)

Social Aspects

19. Introduce incentives to encourage greater use of electric vehicles by establishing charging station using RE sources
20. Facilitating and promoting research opportunities for locals and international parties

Back-up

21. Keep the existing diesel generators as back-up for as long as possible
22. Analyse the quality requirements for biofuels to be burned in the existing generators without technical problems

11 Conclusion

Designing a 100 % renewable energy supply for Malé poses special challenges due to its heavily overpopulated structure. Currently, the electricity supply is nearly 100 % diesel based. The limited space and further topographical constraints have a crucial impact on the renewable energy potential.

Analysing the climate, optimal conditions for solar energy and sufficient conditions for wind energy are found. On the Malé island itself, only a limited PV potential is identified while wind energy is only possible on outer uninhabited island in the atoll. To extend the PV capacity, offshore installations become an apparently good solution to overcome space problems. Furthermore, an OTEC potential is revealed as well as a waste-to-energy plant.

In order to balance volatile renewable energy production, an electricity storage is necessary. As many storage technologies have to be excluded due to the mentioned topographical constraints, battery storages fulfil the electrical and space requirements and thus are seen as the best solution for Malé.

Besides a renewable energy transition in the electricity sector, the transport sector offers potential for improvements as well. Currently, this sector is dominated by fossil fuels based motorcycles. A possible solution is the electrification of all vehicles then powered by a renewable energy supply. As limited space is a problem in other mentioned affairs, it can be an advantage for a new sustainable mobility concept as only short distances have to be considered. It is possible to implement a sustainable and intelligent public transportation system and well-constructed cycle lanes. By this, not only a lot of petrol based vehicles can be substituted but also the congestion in the city is lowered.

Before scaling up the capacities of renewable energy sources, the preliminary step towards a 100 % renewable energy system for Malé should be a reduction of the total energy demand. Due to the island status, the energy saving potential from replacing appliances and lighting by more efficient ones is estimated to be low. However, the secondary functions of OTEC systems, SWAC and desalination, offer a huge energy saving potential. Demand side management is another option to optimize an energy system and reduce costs. Adjusted charging patterns of electric vehicles shift electricity consumption to times of overproduction and therefore reduce curtailments.

For an hourly examination of a renewable energy system for Malé, a simulation model is developed considering aforementioned technologies. With the help of the model, different technology combinations can be easily analysed. To simulate the reality as good as possible, real data of wind speeds and solar irradiation for several years are implemented into the model. Furthermore, the model contains an hourly load curve for Malé which has to be balanced with the chosen technologies. With a few adjustments in the input parameter section, new scenarios can easily be developed. The provided curves and graphs ensure a meaningful comparison between different scenarios.

In this report, three renewable energy scenarios are developed and evaluated. With their results, the possibility of a 100 % renewable and emission-free energy supply is verified. In comparison with the business-as-usual scenario, the cost effect of renewable energies is proven as well. In two of three scenarios, the LCOE can be lowered by an energy transition. The existing potential of OTEC should be further investigated and used if possible. As all scenarios have a certain share of PV and wind generation in common, the focus is to be set on these well-engineered technologies in the first step. With future achievements in storage systems and OTEC, the impact of changes in their parameters can be examined using the hourly simulation model.

To enhance its data base, local measurements are recommended to be conducted as a first policy measure. A reduction of taxes on imports of renewable energy systems can support the technical realisation of a renewable energy supply. Further steps include an implementation of a feed-in-tariff system for wind and solar energy as well as implementing annual targets for capacities of wind and solar energy. For an energy transition in the transport sector without directly forcing the residents, a political instrument is to reduce taxes on the electric vehicles.

Nevertheless, to realise all these projects one of the most important aspects in the policy is to acquire national and international financing options. At this point, it needs to be mentioned that on Malé, corruption is a problem which can pose difficulties in the implementation of new policies.

In summary, the overall results show a possible transition from the current fossil fuel based energy system towards a 100 % renewable energy supply including the transport sector as well. Despite the predominant areal and topographical constraints, appropriate technologies with different combinations are found. The realization now lies with the government of Malé.

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A1. Appendix - Investment and operation & maintenance (O&M) costs for different technologies

Appendix A: Investment and operation & maintenance (O&M) costs for different technologies

	Investment costs	O&M costs	Lifetime [a]
Wind	1,567,940 $/MW [1] + 10 % cable costs [2]	59,133 $/MW*a [1] 4.48 $/MWh [1]	20
PV onshore	1.68 Mio$/MW [8]	16,000 $/MW*a [8]	20
PV offshore	3 Mio$/MW [7]	16,000 $/MW*a [8]	20
Waste2Energy	9,519,639 Mio $/MW [3]	18,480 $/MW*a [3] 25.76 $/MWh [3]	20
Battery Storage	519,000 $/MW (PCS) [4] 890,000 $/MWh [4]	8,000 $/MW*a [4] 2 $/MWh [4]	15
OTEC	23,060,000 $/MW [5]	430,000 $/MW*a [5]	20
Generators	300,000 $/MW [6]	10 $/MWh [6]	30

[1] (DEA, 2016)

[2] (ISE, 2007, p. 11)

[3] (DK, 2012, p. 18)

[4] (Zakeri & Syri, 2014, p. 591)

[5] (O'Connel, 2013, p. 10)

[6] (Adefarati, Papy, Thopil, & Tazvinga, 2017, p. 73)

[7] (Swimsol, 2015, p. 11)

[8] (NREL, 2017)

A2. Appendix - The model handbook

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In this chapter, the basic functions and the operation of the created simulation model "energy simulation model Malé" are explained. The simulation model is programmed with the spreadsheet program Microsoft Excel. This program is very common and easy to use, so that the reader is able to understand the model very quickly and can use it for own simulations after the handbook has been read.

The simulation model is used to simulate energy systems with the main idea that the systems is supplied by renewable energies. Electable renewable energies are wind, photovoltaic, waste to energy, OTEC and biodiesel. As storage system, a lithium-ion based battery storage can be activated. At the last level of the model, it contains diesel generators as a backup system. Furthermore, for an experienced excel user it is easy to integrate other renewable energies or storages. Overall, the simulation model is used to define and simulate different scenarios and compare them among each other.

But beware, the simulation model is programmed for Malé and it needs some major adjustments to use it for any other location. Furthermore, if the user changes the programming or values which aren't input values, there is no guarantee for the validity of the results. So, it is highly recommended to check every result for their validity.

If there are any questions regarding the simulation model, feel free to contact the developer pascal.jess@studierende.uni-flensburg.de.

The further structure of the model handbook is guided by the different worksheets of the simulation model.

A2.1 Overview

The first worksheet "1. overview" gives an overview of the structure of the model and shows a table with all worksheets of the model. The same table can be seen in Figure 25. The "1. overview" worksheet also contains information about the developer and general facts of the simulation model. Furthermore, there is a table named "cell & colour explanation". It defines the function of the coloured cells. So, the following cell explanations apply for all other worksheets. The green coloured cells are input cells. The user can change the input values of these cells to adjust values as needed for own simulations and different scenarios. The golden coloured cells are output cells. Values in this cells are computed results and it is highly recommended not to change such cells. The last defined cells contain fixed values. In some cases, these cells are also output cells. It's easier and clearer not to colour all cells containing computed results in gold.

To the right of the worksheet, a picture shows the general calculation steps of the model. This picture gives the user a first and better understanding how the simulation model works. A step by step explanation of the functionality takes place in chapter A2.3 Model.

Worksheet	Name
2	Input & output
3	Model
3.1	Graphs
4	Electrical load curve
4.1	E-mobility
4.2	Load forecast
5	Wind energy prognosis
5.1	Wind data
6	PV energy prognosis
6.1	PV data
7	Waste to energy
8	OTEC
8.1	SWAC
9	Battery storage
10	Diesel generators
11	Appendix

Figure 25: All worksheets of the simulation model (own illustration)

The worksheets from the figure above can be seen in the bottom edge in the simulation model. There, one worksheet is coloured in green. The green colour means that values on this worksheet can be changed. All the other worksheets are coloured in grey and provide specific information like detailed results and graphs. It is highly recommended not to change any values on these grey sheets.

A2.2 Input & Output

The worksheet "2. input and output" is the most important sheet of the simulation model. All inputs have to be set in this sheet. The sheet also provides key results of the simulation.

The input side is to the left. To the right side, the user finds the mentioned key results. And again, due to possible mistakes by the user, it is highly recommended to change only the green coloured input fields.

In the following, the specific input fields are explained.

Input:

Scenario year: The first input field expects the specification of a year, which is the year of the scenario. The input happens by a dropdown list.

Demand: It follows a table with some out and inputs. Here, the electricity demand can be adjusted. The left side of the table shows the composition of the demand. The first cell gives the electricity demand of 2017. This is the reference year. The cell below contains the demand forecast of the chosen scenario year. The value is based on the worksheet "4.2 load forecast" and is explained in more detail later on.

The next cell gives the increase/decrease of the demand compared to the reference year. The "SWAC" cell shows the energy saving potential due to seawater air conditioning. The option can be turn on/off right next to the "SWAC" cell. SWAC is immediately dependent on the installed capacity of OTEC.

The two cells below give the demand reduction due to efficiency measures and possible deviations from the demand forecast. They are changed with the two input cells to the upper right. The cell "Deviation from load forecast" can be used to adjust the demand forecast. The value of the input option "Efficiency measures" gives the saving potential due to efficiency measures in percentage.

The "E-mobility" cell displays the electricity demand of the electrified transportation sector. Settings regarding the e-mobility can be made to the right under the cell "E-mobility". Here are four possible input fields. With the first one, the e-mobility can be switched on/off. The next cell is again a dropdown list where one of three charging modes can be chosen. For a detailed clarification of the charging modes, please read the paper "Sustainable Energy Systems in Male". The last two input fields belong to the charging mode 'specific time'. The start and end time are set to give the simulation model a time frame when vehicles can be charged.

Supply: The next five tables follow the same structure. Each table stands for one energy source. The user can choose between the following energy sources: wind, photovoltaic, waste to energy, OTEC and biodiesel/diesel.

The settings of the input fields are shown in an exemplary way by reference to wind, because all settings for the energy sources work on the same principle.

With the first input field to the upper right in the table “wind”, the energy source can be switched on/off. Then, the table is subdivided into “technical parameters” and “financial parameters”. The technical parameters influence directly the energy generation. In the case of a wind turbine, the higher the hub height the higher are the reached wind speeds. Here, the input is set by a dropdown list. Accordingly, the shear factor is used to calculate the wind speeds at hub height. The input field “Power turbine” is a fixed value, because it is not possible to change the type of the wind turbine. Finally, the installed capacity can be adjusted with the value of “Number of turbines”. For all other following energy sources, the installed capacity is a direct input field.

The right part of the table consists the financial parameters that are used for the energy cost analysis. Here, typical input parameters are the lifetime of the “plant”, costs for this energy source subdivided into investment costs and operating and maintenance costs (o&m costs). Sometimes, there are two types of o&m costs, fixed and variable costs. As the wind turbines are located at sand banks, extra cable costs are assumed.

The input of the “diesel/bio diesel generators” is a bit different to the other energy sources. Here, the user can’t key in the installed capacity, because it is calculated automatically as it operates as back up if there is a gap between the energy generation and demand. Furthermore, the fuel can be changed between bio diesel and diesel. Accordingly, fuel costs are needed which are entered in the section “additional economic data”.

Storage: In this part, the storage system is defined. Due to geographical restrictions and space problems, the only selectable and programmed storage option is the battery storage. The storage input fields follow the same structure like the ones of the energy sources. With the first option to the upper right, the storage can be switched on/off. Then, below the “technical parameters the storage capacity has to be chosen. The minimum capacity of the battery meaning the maximum depth of discharge is calculated with the percentage given in the input field “depth of discharge” times the storage capacity. For the “capacity first day” it is assumed that the battery is fully charged. Furthermore, the efficiency and the maximum dis-/charging power can be typed in.

At the right side of the table, the financial parameters can be defined. It follows the same structure like before for the energy sources. Just one last hint: The abbreviation “PCS” stands for power control system.

Additional economic data: The first part of the economic data is about costs for resources, namely the costs for diesel and bio diesel. Here, the prices for diesel and bio diesel have to be put in. The reference year is 2017 and the model automatically calculates the values for the chosen scenario year.

The exchange rate for euro to US-dollar is fixed, because we used this rate to convert costs for the energy sources in US-dollar which were given in euro. Furthermore, the exchange rate for US-dollar to Maldives Rufiyaa has to be set, because the cost analysis for the energy generation in this model is calculated in US-dollar and there is function to convert the cost analysis from US-dollar to Maldives Rufiyaa.

The last two input fields are the interest rate and the inflation. The inflation is used to compute the costs of diesel and bio diesel in the chosen scenario year. The interest rate is important for the costs analysis, because the rate is part of the formula to calculate the annuity.

Output:

Now, the right side of the worksheet “2. input & output”, the output side is explained.

The first table shows an overview about the **installed capacity** for the scenario. More precisely, it’s a summary of the chosen installed capacity of the energy sources from the input side. Furthermore, the table separates the existing capacities in the reference year 2017, the installed capacity in the scenario year and additionally, the new installations from 2017 to the scenario year. Moreover, the table shows the chosen installed capacity of the battery storage.

To the right, the **key facts** of the simulation can be seen. The first two values show the maximum peak of the electricity demand and the total installed capacity of the energy sources. A total installed capacity smaller than the maximum peak of the electricity demand wouldn’t be reasonable. The following two results indicate the total electricity demand and the total energy generation. This could be a first hint, if the energy system is sufficiently dimensioned to cover the electricity demand. The next two output fields are highlighted dependent on an open demand. An open demand is visualised by red and the other way around, a covered demand is visualised in green. So, it’s clearly and fast visible if the simulated scenario can cover the demand. Additionally, the share of renewable energy of the total energy generation can be seen. Finally, this table ends with the result of the levelized cost of electricity (LCOE) for the scenario and a comparison to the business as usual scenario.

An interesting function provides the input field “results in MVR” (Maldives Rufiyaa). Hereby, the user can switch all values from US-dollar to MVR.

In the next table **different scenarios**, the user can type in the results of his simulated scenarios to save the results and to compare the scenarios among each other. As the LCOE in the year 2017 and in the business as usual scenario for 2037 are fixed values, they are already predetermined.

The next table that will be explained is the **balance of the grid**. Here, the user gets an overview about the details regarding the energy generation and energy demand. At the first level in this table, the electricity demand can be seen which is separated into the electricity demand and the demand for the e-mobility. There are five columns that show the yearly sum of the electricity demand, the minimum and maximum load during the year, the average of all loads and also, if this is not the case for the demand, the overproduction.

For the first stage of the energy generation, wind and photovoltaic is used. Again, the annual energy generation, the minimum generated power, the maximum generated power as well as the average generated power can be seen. The same outputs apply for the further two stages of energy generation and the battery storage.

The residual load is the difference between demand and generation. A positive value for the residual load and a red coloured cell means that the demand is still open. Vice versa, a negative value and a green coloured cell means that the demand can be covered by the energy generation. After every stage of energy generation, a residual load is calculated. Finally, residual load 4 should be highlighted in green, otherwise the energy system would still need energy to be balanced.

To the right, the table **overproduction** shows more precisely the overproduction in the chosen scenario. Besides the share of overproduction, the table consists the hours of overproduction.

In the last table of the output side, the **cost analysis** for the chosen scenario can be seen. Here, in the first column the total investment costs for the chosen energy sources are calculated. The annuity in the next column allocates the investment costs to the corresponding lifetime of the energy sources. The next two columns show the operating and maintenance costs and the fuel costs. Fuel costs can only arise for the diesel/bio diesel generators. The following column "total costs" exhibits the yearly costs for every energy sources of the scenario. Below the column, the sum of the yearly costs can be found. The most interesting results are in the last two rows of the cost analysis table. Here, the user sees once the results of the LCOE (specific costs) of the scenario and also the LCOE without any curtailment. Additionally, the user finds the specific costs of each chosen energy source to the right of the column "total costs".

A2.3 Model

In the worksheet "3. model", the total electricity demand meets the energy generation from the single energy sources. To simplify the explanation of the exact calculation, Figure 26 shows the calculation steps of the simulation model. And by this figure, the procedure of the model is explained.

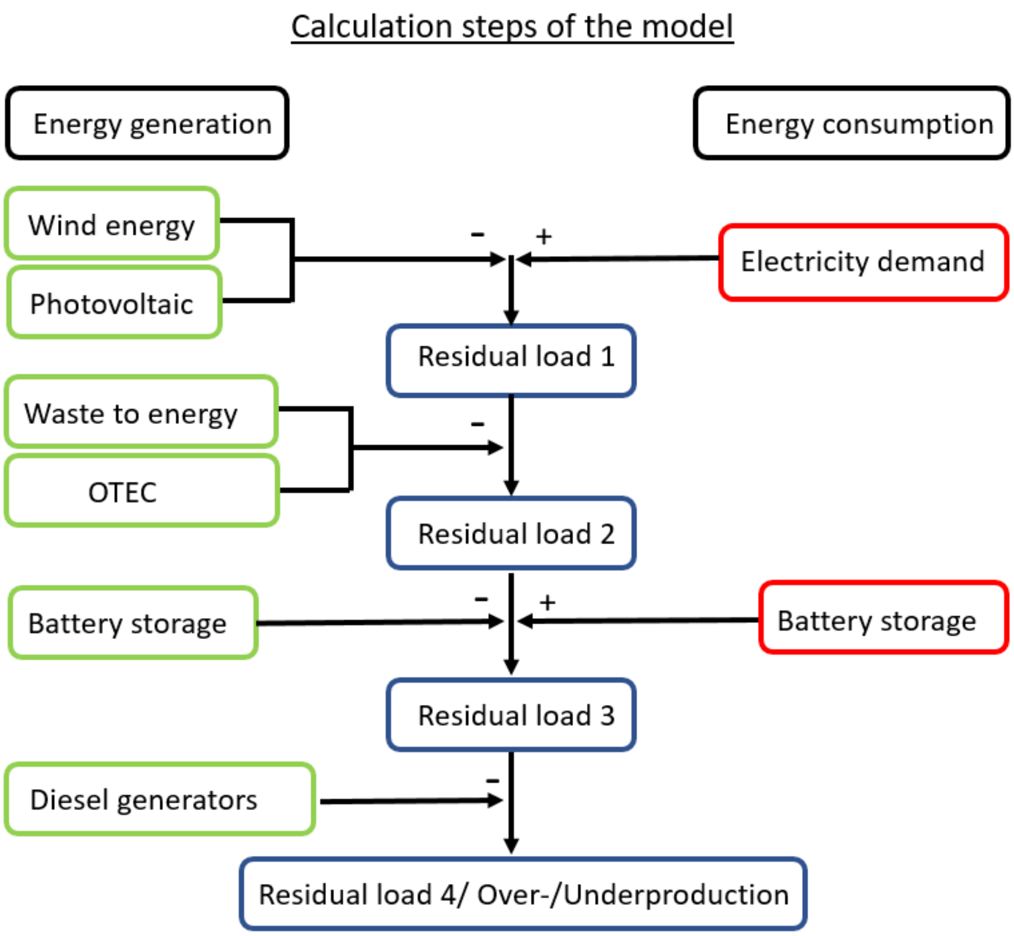

Figure 26: Calculation steps of the simulation model (own illustration)

For every hour in the year, the electricity demand has to be covered. At the first level, wind and photovoltaic try to cover the demand. Every time energy is generated, it is treated as a negative value. Vice versa, an energy demand is treated as a positive value. So, as a result out of the electricity demand, wind and photovoltaic residual load 1 can either be positive or negative. If residual load 1 has a negative value, the demand is covered and an overproduction occurs. If residual load 1 has a positive value, the system still needs energy to cover the demand.

Next, waste to energy and OTEC are considered and residual load 2 is calculated. The next component in the simulation model is the battery storage. It stands on each side, because a battery storage can consume and supply energy. Then, residual load 3 is determined. At the last level of the energy generation, the model uses the existing diesel generators as a backup system. In the end, residual load 4 is calculated. If residual load 4 contains only one hour with a positive value, the energy system isn't sufficiently dimensioned. The model contains four residual loads because it's easier to analyse the generation and the user can simply see where and when is a possible energy shortage.

Since the basic calculation steps of the model are clear, let's turn back to the worksheet "3. model". Here, the described calculation steps can be seen in detail for every hour of the year. Additionally, for every 24 h a sum is computed.

Now, some results at the top of the single columns are explained. The "total electricity demand 2037" column contains in its first three rows results for the maximum, minimum and average load of the 8760 values of the electricity demand. The fourth row shows the total electricity demand. The blue colour is just used to indicate a load/demand and to get a better overview. The same structure can be seen for the wind energy generation. Only the total demand is substituted by the total energy production.

In the case of a column with a residual load, the first four rows show values for the total energy surplus, the total energy shortfall, the maximum power surplus and power shortfall. The total energy surplus indicates the unused energy and vice versa, the total energy shortfall indicates the open demand. The maximum power surplus shows the highest overproduction per hour and the maximum power shortfall indicates the highest underproduction per hour.

Moreover, the depiction of the battery storage is considerable, because it contains four columns. For the calculation, only the column "balancing" is considered. The other three columns give the user information about the charging, discharging and status of the storage level.

A2.3.1 Graphs

The next worksheet summarizes and visualises the results of the previous worksheet "3. model". The graphs to the left show the hourly power generation for five different days in the chosen scenario year. Next to the right, the results of the residual loads are depicted in daily values. Residual load 1 contains only wind and pv. Waste to energy and OTEC are added in residual load 2. Then, in the graph of residual load 3 the battery storage appears additionally. Residual load 4 contains all chosen energy sources.

Furthermore, the user finds two additional graphs. The hourly storage level graph depicts the status of the storage level for the whole scenario year. The pie chart shows the share of every single energy source at the total energy generation.

A2.4 Electrical load curve

In this worksheet, the real load curve for Malé in 2017 is integrated which can be seen in column “hourly electrical load” that contains only fixed values for every hour of the year. So, this is the base for the load curves in other scenario years.

The single loads in the column “hourly calculated electrical load” are calculated as follows: Every single load of 2017 is divided by the total demand in 2017 and after that the resulting value is multiplied by the forecasted total demand of the chosen scenario year. Hereby, the forecasted total demand is the result of the forecasted demand minus saving potentials like SWAC and efficiency measures.

Moreover, the user sees the resulting hourly load curve in the scenario year for the whole year, the month April, one week in April and one specific day in April.

A2.4.1 E-mobility

Here, the electrical demand for the mobility is more specified and dependent on the chosen charging mode converted to a load curve. For the charging mode “all-day”, the hourly load is calculated as described for the electrical load curve. The curve becomes the same behaviour like the electrical load curve. The charging mode “sun oriented” is calculated in a same way, the e-mobility demand is oriented towards the behaviour of the pv energy generation. In the charging mode “specific time” the demand is equally divided between the start and end time for the charging. The needed inputs are taken place at the worksheet “2. input & output”. The value of the total demand for the e-mobility comes again from a load forecast. And additionally, the resulting hourly load curve for the e-mobility for the whole year, the month April, one week in April and one specific day in April can be seen.

A2.4.2 Load forecast

This worksheet is the source of all forecasts regarding the electricity and e-mobility demand. As an additional feature, the development of the total electricity demand is shown in a graph.

An explanation of the load forecast calculation can be found in the paper **“Sustainable Energy Systems in Malé”.**

A2.5 Wind energy prognosis

In the worksheet "5. wind energy prognosis" the calculation of the energy generation can be seen in detail. The values for the "mean wind speed" column come from the worksheet "5.1 wind data" and is explained in the next chapter. The next column shows the wind speed at hub height. This wind speed is the decisive factor for the energy generation and it is calculated with the mean wind speed, the hub height, the height of the wind measurement and the shear factor. To calculate the power of the turbines, the wind speed at hub height is applied in the power curve of the Enercon E-141.

The needed inputs are taken place on the worksheet "2. input & output". The results of the column "outputs" show the total installed capacity, the total energy generation and with the full load hours and the capacity factor two comparison figures of the wind energy branch.

Furthermore, the resulting hourly energy generation for the whole year, the month April, one week in April and one specific day in April can be seen.

A2.5.1 Wind data

Here, the collection of the wind data from 1985 until 2016 for Malé and its evaluation takes place. Due to the overview, the user sees only the years 2010, 2015 and 2016. As the result of the large wind data collection, the mean wind speed is calculated. To the right the hourly mean wind speeds are shown for a whole year.

The wind data is provided by meteoblue,

A2.6 PV energy prognosis

Here, the exact energy prognosis for photovoltaic can be seen. The first column shows the mean irradiance of the sun. It comes from the worksheet "6.1 pv data" and is explained in the next chapter. With the mean irradiance, the onshore and offshore pv energy generation is calculated by multiplying the mean irradiance with the installed capacity, the area requirement and the system efficiency. The column "total" shows the sum of the energy generation for pv onshore and offshore. The required inputs are taken place on the worksheet "2. input & output".

The outputs from this worksheet are the sun hours (corresponding the full load hours) and the annual energy generation. Moreover, the hourly energy yield is depicted in four graphs showing the whole scenario year, the month April, one week in April and one day in April.

A2.6.1 PV data

Here, the collection of the pv data for Malé and its evaluation takes place. Due to the overview, the user sees only the years 2010 and 2016. Out of the data collection of the irradiance, the mean irradiance is determined. To the right, the hourly irradiances are figured for a whole year.

The data of the irradiance is provided by meteoblue.

A2.7 Waste to energy

This worksheet is kept very simple. The hourly values are calculated by multiplying the installed capacity of the waste to energy plant with the capacity factor. The required inputs are typed in on the worksheet “2. input & output”. And finally, the hourly energy generation is pictured in four graphs for a whole year, one month, one week and one day.

A2.8 OTEC

As the worksheet is like the worksheet “7. waste to energy”, see for further explanations the chapter before.

A2.8.1 SWAC (Seawater Air Conditioning)

On this worksheet, the possible saving potential for SWAC is determined and the minimum required OTEC capacity to use this potential is calculated. The demand is dependent on the chosen scenario year. Then, the SWAC potential follows from the share of residentials and the share of cooling. For the simulation model, it is now assumed that the potential can be split in equal shares to the whole year. With the stated conversion rate, the refrigeration tons can be calculated. An estimated seawater flow rate per ton of refrigeration and a possible flow rate of 10,000 m^3/h per installed OTEC MW leads to the minimum required OTEC capacity to use the saving potential of SWAC.

A2.9 Battery storage

In this worksheet, the first column shows the residual load 2. The residual load indicates if the battery storage can be charged (negative value for the residual load) or discharged (positive value). The column “storage balance” is the interface of the storage with the energy system. A negative value indicates a discharging and vice versa a positive value means a charging. The actual charging or discharging is calculated in the identically named columns. The “storage level” shows always the status of the storage level. As in some worksheets before, the storage level is pictured for the whole scenario year, the month April, one week in April and a day in April.

The required input parameters are entered in the worksheet “2. input and output”

A2.10 Diesel generators

The first column shows the residual load 3, because the diesel generators are applied as a backup system. That means, they should only provide energy to the system, if the residual load 3 is positive (= underproduction). The diesel generators generate the exact open demand until its installed capacity is reached. The required inputs are typed in on the worksheet “2. input & output”. The resulting outputs are the full load hours, the needed liters of diesel and the annual energy yield.

A2.11 Appendix

This worksheet is only used to calculate daily values for the demand and the energy generation out of the hourly values from the worksheet “model”. The daily values are utilized to create the residual load graphs in the worksheet “3.1 graphs”.