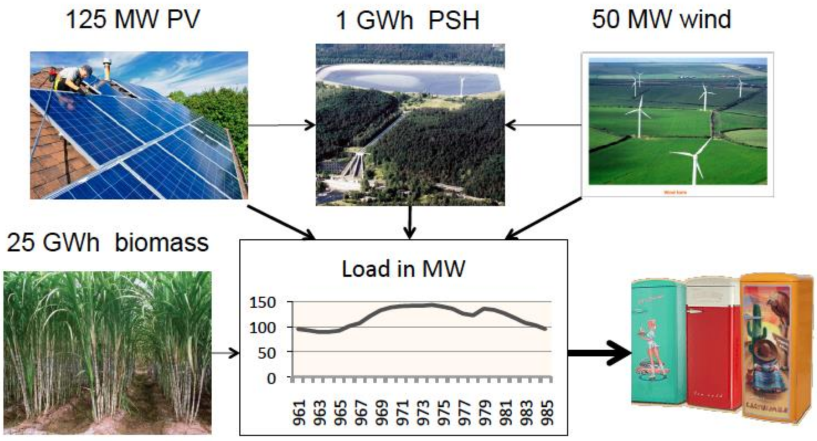
CENTER FOR SUSTAINABLE ENERGY SYSTEMS (CSES/ZNES)
System Integration Department

A 100% renewable Seychelles

A plan to change the Seychelles' power supply to 100% renewables, its costs and possible benefits

Report 1: Mahé



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0. Executive Summary

This report is based on some first simulation of the power systems of Mahé based on the hourly demand data for 2014, wind data from Mahé airport and internationally available solar data (NASA 2016) used for a coordinate close to Mahé (4.5°S / 55.625°E).

As the subject is of great interest to key players from the civil society and from government, and as the issue is of great importance for the Seychelles’ energy future and its economy, the author has attempted to give a written account of the main arguments in a form that should be understandable to a lay person interested in the subject. A corresponding scientific publication in a peer-reviewed journal will be published based on more complete data at a later point in time.

0.1 The Problem

Although the Seychelles enjoy a reliable high quality power supply they have experienced massive power price fluctuations during recent years due to the sole reliance on crude oil products for electricity generation. Out of a total electricity production cost of 2.33 SCR/kWh (in 2014) fuel costs alone made up a share of 2.08 SCR/kWh (data based on actual cost statistics of PUC for 2014). These high fuel costs have lead to high electricity bills for private households and enterprises as well as to a massive drain of hard currency from the Seychelles’ economy in the order of 650 million SCR/a in 2014 (PUC 2016, personal communication) for Mahé alone. Even after oil prices have dropped from the high levels reached in 2014, the oil based power supply will remain a major economic burden on the Seychelles’ economy and private households as well as a major risk to the Seychelles’ future economic and social development.

At the same time it is obvious that the Seychelles, together with the other small island countries, enjoy very favourable conditions for wind and solar energy production, two domestic energy resources, which are hardly used so far. Solar energy enjoying conditions twice as good as in Germany, the home country of the author, and wind conditions being at least comparable. Germany has installed just about eighty thousand Megawatts of wind and solar energy systems by the end of 2015. With roughly twice the energy output from solar energy systems compared to the German situation the cost of the produced solar electricity is cut in half in the Seychelles. Together with low cost wind energy the available renewable resources make for very attractive economic conditions for the production of renewable energy based electricity.

On the basis of his more than thirty years of professional experience in the field of energy supply and the use of renewable energy sources the author has analysed the situation of the power supply of the three main granite islands of Seychelles’ and a possible development towards a 100% renewable power supply. This work was done on invitation by the government of the Seychelles after a first discussion of the issue in December 2015.

0.2 Aim of the report

This report summarises the findings of the analysis that the author performed in preparation for his second stay in the Seychelles in order to make them available to policy makers and the general public of the Seychelles. It was drafted as a first input into the discussion on the future development of the Seychelles' power supply and the possible transition to a 100% renewable electricity future.

0.3 Results of the analysis – the case of Mahé

Based on an annual total electricity demand (including system losses) for Mahé of 320 GWh and a scenario with 50 MW of installed wind power capacity, 125 MW of installed solar energy (PV) capacity, an assumed liquid biomass volume of 25 GWh/a equivalent to 5 000 t of biodiesel and a pump storage hydro plant with a storage volume of 1 GWh it can be shown that Mahé can easily be supplied with electricity from renewable energy sources every hour of the year. Thus, a 100% renewable power supply is technically feasible for Mahé.

A 100% renewable power supply will cost about 2.3 SCR/kWh, which is approximately 10% higher costs than Mahés' fuel costs for power production of 2.08 SCR/kWh in 2014. These additional costs amount to about 50 million SCR per year. Nevertheless, compared to the average electricity rate charged to the customers of 3.85 SCR/kWh (NBS 2015, p. 95), the full system costs of the 100% renewable system amount to just about 60% of the average rate charged.

With the 100% renewable energy strategy Mahés' fuel imports for electricity production can be reduced by about 650 million SCR per year. At the same time renewable energy technology worth approximately 80 million SCR/a would need to be imported on averaged over the twenty year lifetime of the equipment, assuming a local production share of 20% of the investment. Thus, the average net import reduction amounts to about 570 million SCR/a.

As the import reduction stops the drain of hard currency from the country and at the same time increases the spending power of the citizens of the Seychelles, the change of the energy system creates a double boost to the economy. Imports are reduced and the spending for energy produced locally is increased, while the energy bill is only marginally higher.

In addition the tax income of Mahé can be increased by more than 150 million SCR/a, as more money stays on the island and is kept in the economic cycle of production, earnings and spending. Just in the first round of spending the 570 million SRC/a will induce an additional tax income of 85 million SCR/a assuming an average tax rate of 15% on money which presently leaves the country to buy the imported oil and is unavailable for taxation in the Seychelles.

Once an appropriate planning and policy framework is set up, it is feasible that the transition to a 100% renewable power supply can be achieved in as little as five to ten years. This is less a technical or economic problem but induced by the substantial lead time necessary to set up a solid policy and regulatory framework to enable the transition.

Once this transition is achieved the system can be enlarged to generate enough renewable electricity to power all private cars, small trucks and busses, assuming the present fleet is gradually exchanged with electrical vehicles.

The transition to renewable energy based electric transport can save another 400 million SCR/a in fossil fuel imports and lead to net import savings of about 350 million SCR/a. Such development would boost Mahés' economy even further.

To prepare for the transition it should be possible to use the instrument of a so called NAMA (Nationally appropriate Climate Change Mitigation Action), which would allow the Seychelles to draw on substantial international climate funds to finance the upfront costs for the preparation of the transition to 100% renewable power supply for Mahé.

As oil prices fluctuate widely it is suggested that the political risk of temporarily low oil prices is compensated by an international climate fund, guaranteeing that the domestic electricity rate of the Seychelles, once setting its policy to achieve a climate friendly 100% renewable power supply, will never be above the power price of the incumbent mineral oil based power price.

0.4 Recommendations

It is recommended to pursue the target of a 100% renewable power supply as soon as possible in order not to loose more money than necessary on the import of expensive fossil fuels and to stop the drain of hard currency from the country as fast as possible. This should be coupled to the drive for an international clean power price guarantee fund.

In order to allow such development, a number of (preparatory) steps/considerations need to be taken:

- Improve the grid quality and the high voltage grid coverage to the entire island of Mahé in order to establish a solid grid infrastructure as backbone of the future development of renewable power up to 100%
- Use of the NAMA framework or similar mechanisms to secure up front financing for all preparatory measures e.g. the planned GCF project
- Conduct a proper site assessment for the location of larger solar installations and onshore wind parks to avoid conflicts of interest with other land uses and nature preservation
- Conduct a detailed assessment of the hourly wind speeds on the island at hub heights between 80 and 100 m in the prime locations for onshore wind power and derive a wind atlas for Mahé from it
- Extend the present analysis by more in depth studies of the costs of the different renewable energy options under the specific circumstances found in Mahé to lay the basis for future FIT rates
- Perform a thorough site and underground assessment for the location of the pump storage plant
- Conduct a more in depth analysis of possible 100% renewable power supply scenarios
- Set up a policy (FIT) and regulatory framework (specific ordinances) to guide the smooth development to the target
- Set up the policy framework in a way that the investment in the new renewable power technologies is generated on the island in order to keep the income generated from renewable power production in the Seychelles' economy

- Use a policy for wind and solar power that enables a broad local participation in the investment in order to generate additional income for as many Seychellois citizens as possible
- Involve as many citizens in the planning and development of wind and solar energy as possible to spread the idea as widely as possible (i.e. explore the use of a community investment model)
- Conduct an electrical grid integration study of a full 100% renewable future and the likely transition pathways towards this future energy system
- Set up technical grid connection rules for wind and solar systems (e.g. 'fault ride through' rules as opposed to 'fault shut down' rules
- Improve the grid capacity and quality in those locations foreseen for larger renewable power production sites and the site of the pump storage hydro power plant
- Ensure that only high quality products are installed in order to have a well functioning and reliable power supply system
- Keep the existing power generation facilities as back-up as long as possible, as they complement the expansion of renewable power supply very well
- Analyse the quality requirements for biodiesel to be burned in the existing diesel generators without technical problems
- Don't build the storage facilities too early, as they will sit idle before you have not reached at least 50% of renewable power production.
- Build up a specialised labour force for planning, construction operation and maintenance of the necessary technologies and their full scale system integration
- Secure experienced independent scientific, technical, economic and policy advise for the entire process. Try to avoid expensive short term consultancy contracts on the core issues, as the expertise needs to be available throughout the entire process.

1. Mahé's present power supply

Unlike many other non-highly industrialised countries Mahé enjoys the service of a reliable electricity system, which services practically every citizen and has very few downtimes. The total annual electricity demand is in the range of 320 GWh/a including system losses (PUC 2016). With a maximum load in the range of 51.6 MW (PUC 2016) the installed capacity of about 74 MW (PUC 2016) allows a considerable reserve margin for unscheduled downtimes due to equipment failure as well as downtimes for scheduled equipment maintenance. All 14 generation units are diesel generators with a wide age span (PUC 2016).

Besides some urgent technical maintenance issues at the power plant concerning the inspection of circuit breakers, the greatest challenge of Mahé's power supply is the urgently needed grid expansion at the high voltage level (33 kV), which would allow to increase the coverage and reliability of the grid substantially by moving from single high voltage power lines to a mashed grid with the necessary redundancy to facilitate a far higher security of Mahé's power supply in all parts of the island.

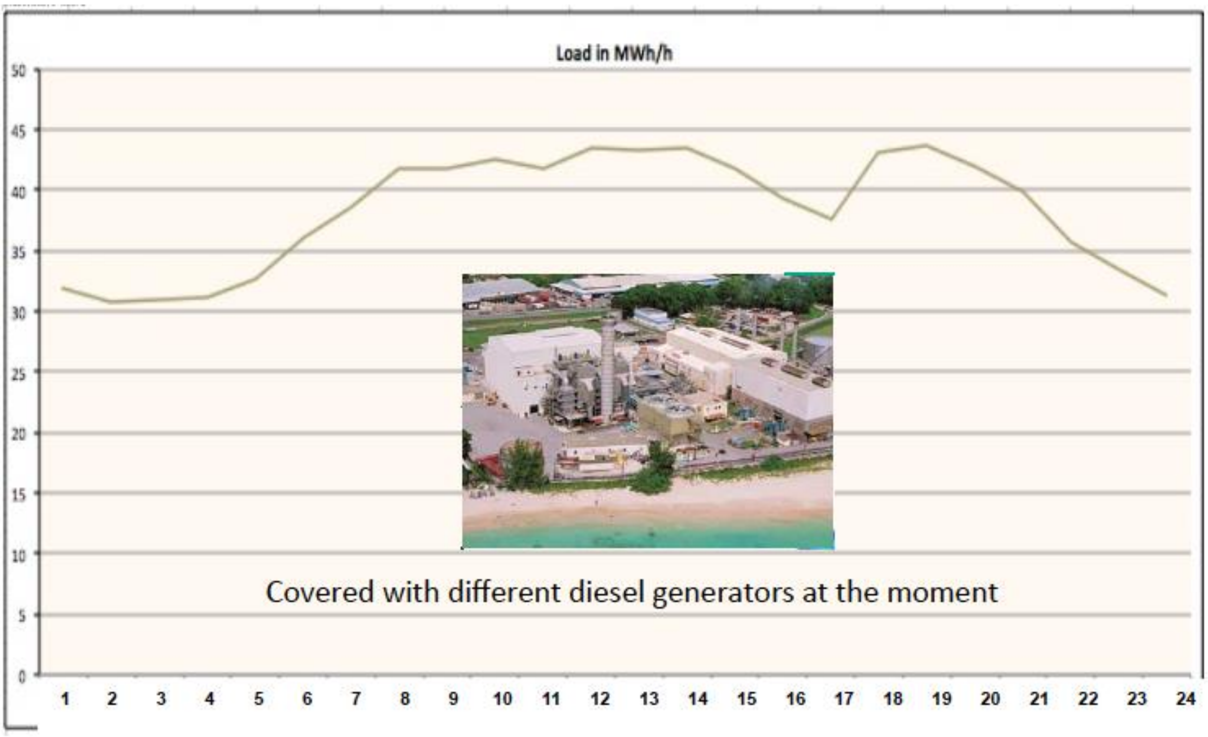
A major advantage of the power generation technologies presently used on Mahé is the high degree of flexibility of all units. All units should need only a few minutes from start to full production. In contrast to this situation large base-load power plants, forming the backbone of many national power systems of industrialized countries like Germany or the US, normally take a number of hours (coal fired power plants) or even days (in the case of nuclear reactors) to get from start to full load operation. These long reaction times make it very difficult to use large shares of wind and solar energy in most established electricity systems. In Germany this lack of flexibility of the existing stock of power plants will lead to stranded investment in the case of a further fast development of renewable energy sources in the country and can be seen as the major reason for the large utility companies strongly objecting a faster build up of the renewable generation capacity.

Currently the flexibility of Mahé's power system is only needed to meet the change in the daily load (demand for electricity), which is ordinarily highest around noon and lowest between midnight and the very early morning hours, before people start to work. As Figure 1 shows, the changes in the load, to which the production needs to adapt, are rather slow and less than 50% of the maximum load during the course of the day or less than 15% during the hours of the fastest changes, while the system could accommodate a load change from 0 to 100% in well under 30 minutes.

Besides the changes in load during the day, there are differences between weekdays and weekends, which typically show a lower load as many businesses are closed. In addition there may be seasonal variations in load due to higher air conditioning demand or changing levels of tourism. Nevertheless, all these changes are rather slow and can be predicted. Thus, Mahé's power system is only exposed to fast or sudden load changes in the case of equipment failure of large single units with a maximum size of 6.5 MW.

In the case of growing shares of electricity from wind or solar energy, which are changing fast with variations in wind speed and solar radiation or cloud cover, the flexibility of the existing production units may prove to be of great value. These existing conventional units can easily complement the rapidly changing production from wind and solar energy to meet the power demand, assuming this is forecasted well on the basis of detailed and timely weather reports.

Figure 1: Typical daily Mahé load curve for a day in May (22nd) (Source: graph based on PUC 2016)



Unfortunately Mahé's current sole dependence on mineral oil products leads to an extremely strong sensitivity to crude oil price increases on the electricity generation cost on Mahé. This has lead to the situation that the fuel costs per kilowatt-hour (kWh) made up almost 90% of the total power generation costs in 2014 (2.08 out of 2.33 SCR/kWh). Although crude oil prices are declining at the moment, Mahé's power generation remains expensive and extremely vulnerable with regard to crude oil price changes.

The volume of the present (2014) fuel import for electricity production has withdrawn approximately 4% of the Seychelles' national income (gross domestic product) per year creating a major burden on the economy. What is more, together with the imports of transport fuels more than 5% of the national income has to be used every year to pay this fuel bill with hard currency. This poses a major threat to the economic development and stability of the Seychelles. Thus, the present electricity system, although supplying power quite reliably, cannot be sustained in the long run without jeopardising the Seychelles' future economic development.

2. The possible contributions and costs of wind and solar energy

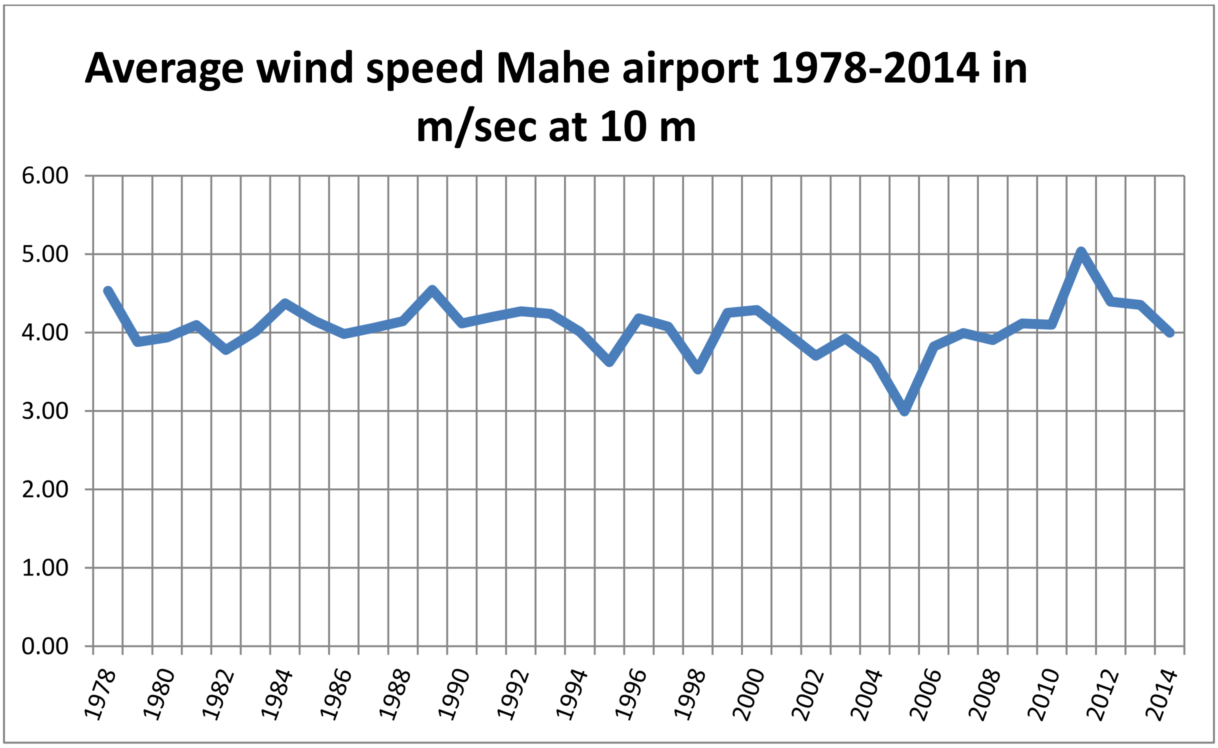
To the visiting energy expert the Seychelles displays a stunning picture. On the one side it uses a high share of its national income to pay for imported mineral oil products to run its electricity production, while on the other side it enjoys very good wind and excellent solar resources. Thus, it is very likely that a major part of the expensive present electricity production can be replaced by the use of domestic renewable energy resources. Which will be the cheaper future energy source in the long run anyway.

To analyse the possible contribution of renewable energy sources to the Seychelles' long term energy supply, the resource potential and the costs of utilising the different renewable energy resources need to be assessed. Besides accounting for the capacity of renewable energy technologies that can possibly be installed on Mahé, the hourly availability of wind and solar energy needs to be taken into account, as the storage of electricity over long periods of time is expensive and the possible volume of storage will most likely be limited.

3.1 Wind energy

For the calculations performed hourly wind speed data for Mahé airport reported as knot (miles per hour) figures rounded to full knots available for the years 1978 to 2014 (SNMS 2016). The wind speeds for Mahé are fair with a long term average (1978-2014) of 4.04 m/sec at 10m and display a high degree of annual variation with a very good wind year in 2011 (124% of the average) and with a very bad wind year 2005 with only 73.7% of the long term average. Figure 2 gives the long term wind speeds measured at Mahé airport at 10m height.

Figure 2: Average annual wind speeds from 1978 to 2014 measured at Mahé airport (10m) in m/sec (calculation based upon SNMS 2016)



Comparisons with the wind speed data from the global (NASA 2016) 2 data set for the coordinate 4.5°S / 55.625°E and measurement data from eight existing wind turbines at the inner harbour of Mahé and data from a measuring campaign with four different meteorological measuring masts, which are all available for a period in April 2010 (9.-26.4.2004), show a very good agreement of the airport data and the MERRA 2 data, displaying average values within 2% of each other. At the same time the measurements for the four locations Inner Harbour, Tea Factory, Four Seasons and La Misere show that different sites on Mahé can have very different wind speeds, with the Inner Harbour displaying 4% less than the airport, the location Tea Factory shows slightly higher wind speeds 3% above the airport average, while the Four Seasons location has substantially higher wind speeds 32% above the airport average and the highest wind speeds being measured at la Misere 45% above the airport values. At the moment it is no quite clear, at which heights above ground these measurements have been taken. Thus, the comparability is not fully given, as this would require measurements at the same height above ground.

Across the year the comparison of the MERRA 2 data to the airport data shows a higher deviation as the period in April. In 2010 the MERRA 2 data display an average wind speed of 5.14 m/sec at 10 m height (NASA 2016) while the airport measurements have an average of only 4.1 m/sec. It seems likely that preferable locations on Mahé will display higher wind speeds as the airport. In order not to overestimate the output from wind turbines the wind data from the airport for 2010 have been used for the scenario calculations, as they represent a long term average year (101% of the 1978-2014 average). Figure 3a shows the distribution of the wind energy output from an installed capacity of 50 MW based on the wind speeds at Mahé airport in 2010. It is quite obvious from the graph that Mahé displays a rather strong fluctuation in wind energy with some periods of rather low output from wind turbines in the first part of the year, while the output seems to be relatively high during the winter month and early spring. During the summer month the output can fluctuate widely.

For the month of May Figure 3b shows that even during a month with higher wind speeds there are a number of hours and days with very low output from the installed wind energy capacity. Furthermore the graph shows that the output from wind turbines can change by 70 or 80% of the maximum output within only a few hours.

Figure 3a: Output from 50 MW installed wind capacity across a year based on the 2010 wind data from Mahé airport (80 m hub height, shear factor 0.2) (calculations based on SNMS 2016)

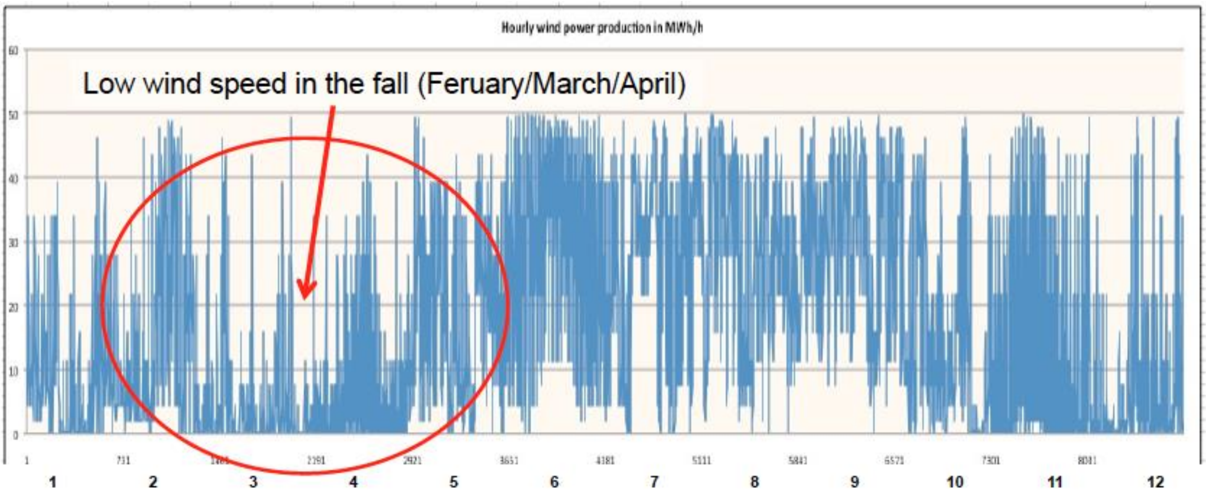
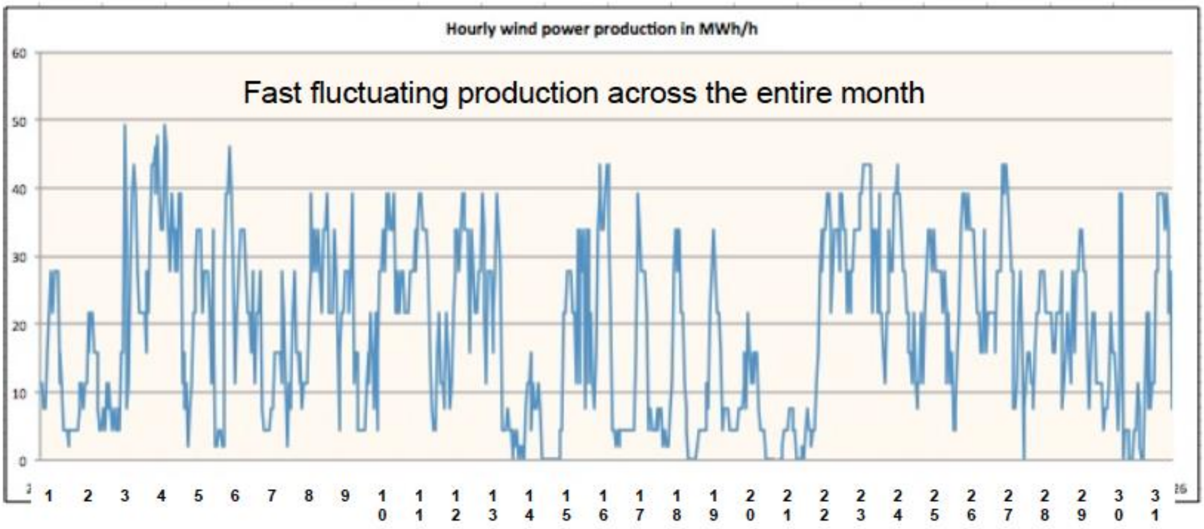


Figure 3b: Output from 50 MW installed wind capacity for the month of May based on the 2010 wind data from Mahé airport (80m hub height, shear factor 0.2) (calculations based on SNMS 2016)



The theoretical wind energy potential of Mahé with a size of 152 km^2 is about 1.5 GW, if the entire area of the island would be used. A first very rough estimate of the wind power capacity of Mahé suggest a potential of well over 100 MW. Thus, the assumed 50 MW installation should not cause any problems for finding suitable sites for the necessary turbines (about 25 turbines of 2 MW each). Nevertheless, one of the next steps towards a more substantial wind energy development are the computation of a wind atlas for the island and a mapping of the available areas for wind turbine deployment (white are mapping) based on the minimum distances to dwellings, streets, areas of nature conservation and other areas to be taken into account in proper wind energy planning. Special care needs to be taken of the accessibility of possible sites with respect to the transport of rotor blades of up to 50 m of length and almost 5 m diameter at the root. Once the best areas for wind turbine installations are identified there needs to be a dedicated measuring campaign as basis for the design of an appropriate tariff for wind energy and as a basis for bank loans necessary to finance the investment. Unfortunately, - to the knowledge of the author - hardly any data has survived the last measuring campaign using four meteorological masts around the island.

Taking the given hourly wind energy data for Mahé airport and scaling these to a hub height of 80 m for modern 2.5 to 3 MW standard wind turbines and assuming investment costs of 1,330 US$/kW installed (1,050 €/kW), 5% of the investment costs as annual operation and maintenance costs, a life time of 20 years for the wind turbines and an interest rate of 6%/a results in specific wind electricity costs of 0.827 SCR/kWh or 0.055 €/kWh, which compares favourably to costal sites in northern Germany. The wind speeds taken lead to full load hour equivalents of about 2,600 h/a or a load factor of 0.30, which compares well with typical values for onshore wind energy in Germany where 2,200 h/a or load factors of 0.25 are reached at the better coastal locations.

0.5 Solar energy

For the calculation of solar energy production on Mahé internationally available MERRA 2 solar radiation data was used, which are available for 4.5°S / 55.625°E (NASA 2016). An annual total useful irradiation of 2,071 kWh/m^2 is reported for this coordinate. All calculations were performed for photovoltaic solar systems (PV).

With a size of 152 km^2, Mahé has a theoretical potential of 1,900 GW of solar capacity, if we assume a necessary area of 8 m^2/kW_p. This is more than 1000 times higher than the wind energy potential. But unlike the use of wind energy, the use of solar energy does only allow for agricultural use of the land, if it is installed in the form of solar shading and the island would need to be covered entirely by solar panels to realise this extremely high theoretical potential. An installed solar capacity of about 125 MW would only require an area of roughly 1 km^2 or 0.66% of Mahé's land area. A fair share of this could be installed as roof top installations or solar shading for some agricultural land.

The system efficiency was assumed to be 12.75% and the system costs to be 1,900 US$ or 27,500 SCR/kW_p. Annual operation and maintenance costs were taken as 5% of the initial investment costs. As in the case of wind energy the interest rate for loan financing was assumed at 6%/a. These assumptions lead to specific production costs of 1.49 SCR/kWh or 0.1 €/kWh. Figure 4 shows the typical fluctuation in the production of solar electricity across the year and Figure 3b shows the fluctuation during the month of May.

Figure 4a: Hourly output of solar energy for an entire year based upon an installed capacity of 125 MW on Mahé (solar radiation data of 2010) (calculations based on NASA 2016)

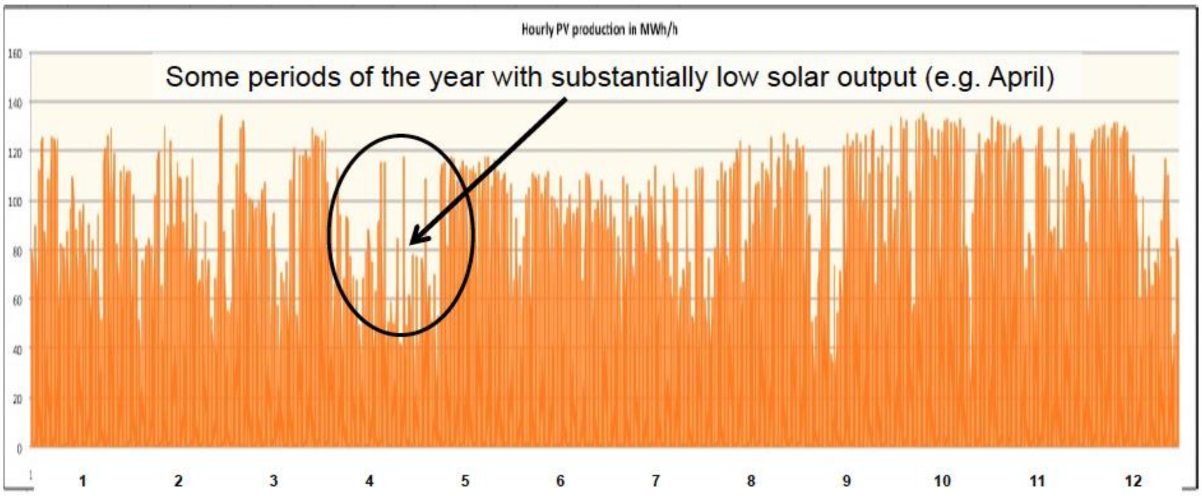
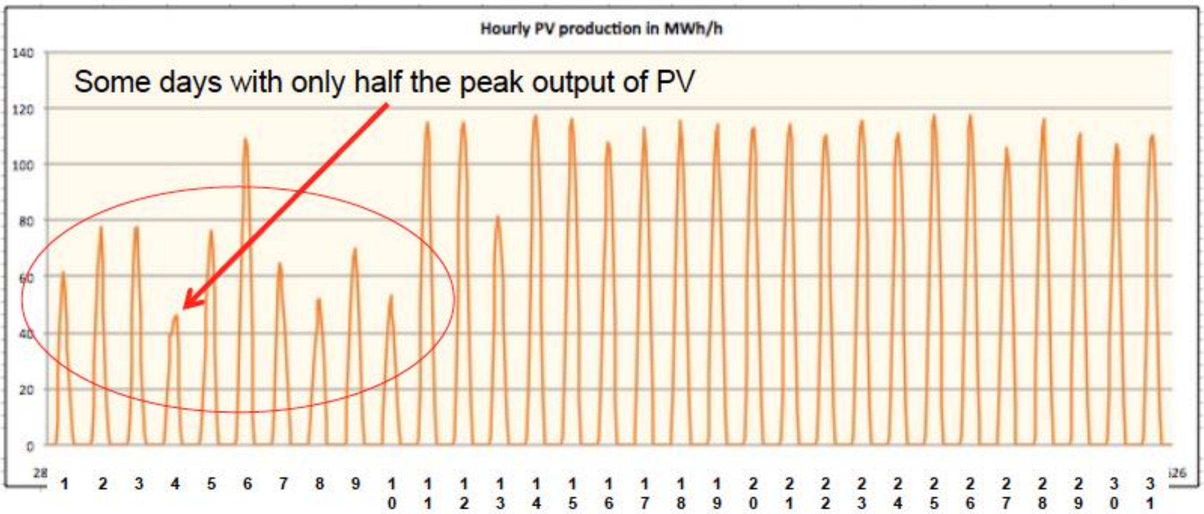


Figure 4b: Hourly output of solar energy for the month of May based upon an installed capacity of 125 MW on Mahé (solar radiation data of 2010) (calculations based on NASA 2016)



Even though Mahé is rather close to the equator the output from the solar installations varies substantially across the year due to different degrees of cloudiness, as the first week in May (Figure 4b) clearly shows. During some days the noon peak in output is reduced from about 120 MW on a bright day down to as little as 45 MW.

Simulation results show that the variations in the output from wind and solar energy seem to complement each other well. Thus, a concentration on one or the other renewable energy technology leads to substantially higher costs, as higher capacities would need to be installed to meet demand, while large volumes of power can not be used due to overproduction. As solar energy shows a higher degree of regularity the cost minimal combination has a higher share of solar energy (125 MW) than wind energy (50 MW), although the specific production costs of solar energy are about twice as high as those of wind energy.

3. Balancing a 100% renewable power supply

3.1 The concept of residual load

To understand how the energy demand can be met by using very large shares of wind and solar energy a new concept has to be introduced, the concept of residual load. While in conventional electricity systems the hourly demand, which we call electrical load, had to be met by different controllable production units like base load or peak load power plants, in the new electricity systems the controllable units don't have to follow the load but they have to match the difference between the load (demand) and the uncontrolled production of wind and solar energy, which produce as much electricity as possible as soon as they are installed. This is due to the fact that no money can be saved by turning these power plants down or running them at partial load. The difference between the hourly load and the hourly production from wind and solar energy, which can be positive or negative, is called residual load. Thus, it is the task of all controllable units to meet the residual load of the system. As Figure 5 shows the residual load changes far faster than the load. This requires that all controllable production units can change their production much faster than in a conventional electricity system.

As an example, Figure 6 shows the load and the residual load for Mahé employing wind and solar PV for May 22nd. We can see that the residual load can change by more than 30 MW (more than 50% of the maximum system load) up or down within an hour. This is far more than the change in the load during the entire day (12 to 13 MW). Furthermore, the structure of the solar energy output leads to a negative residual load from the morning to the afternoon. Although, the sum of wind and solar energy production of the day are sufficient to meet the total electricity demand of the day, it is quite clear that we will need substantial storage capacity to meet the residual load every hour of the day.

Figure 5: Hourly load, hourly production from wind and solar energy and the resulting residual load of a system with high shares of wind and solar energy (Source: Hohmeyer 2015, Figure 4)

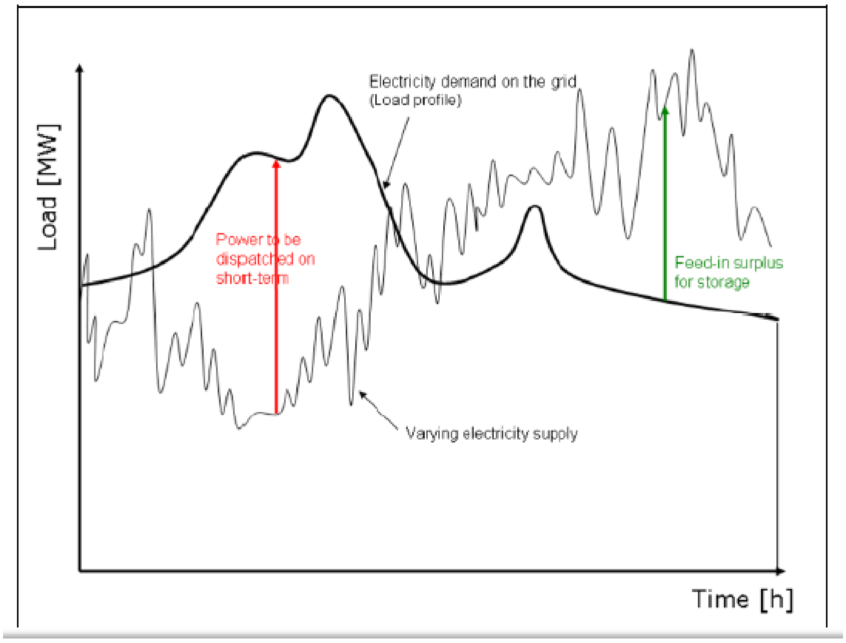


Figure 6: Load curve and residual load for Mahé on May 22nd with 50 MW wind and 125 MW of PV installed (Source: own calculations)

Figure 6a: Load curve Mahé May 22nd 2014 (source: graph based on PUC 2016)

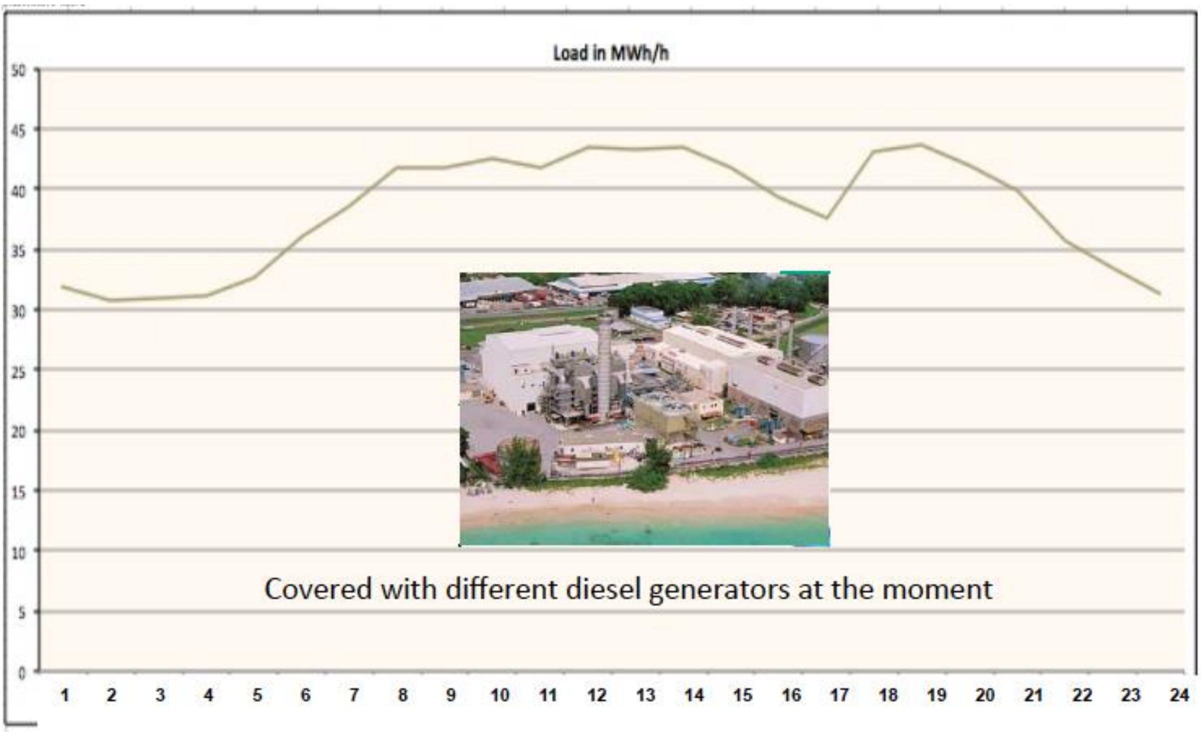


Figure 6b: Residual load curve Mahé May 22nd 2014 with 100% RE power generation

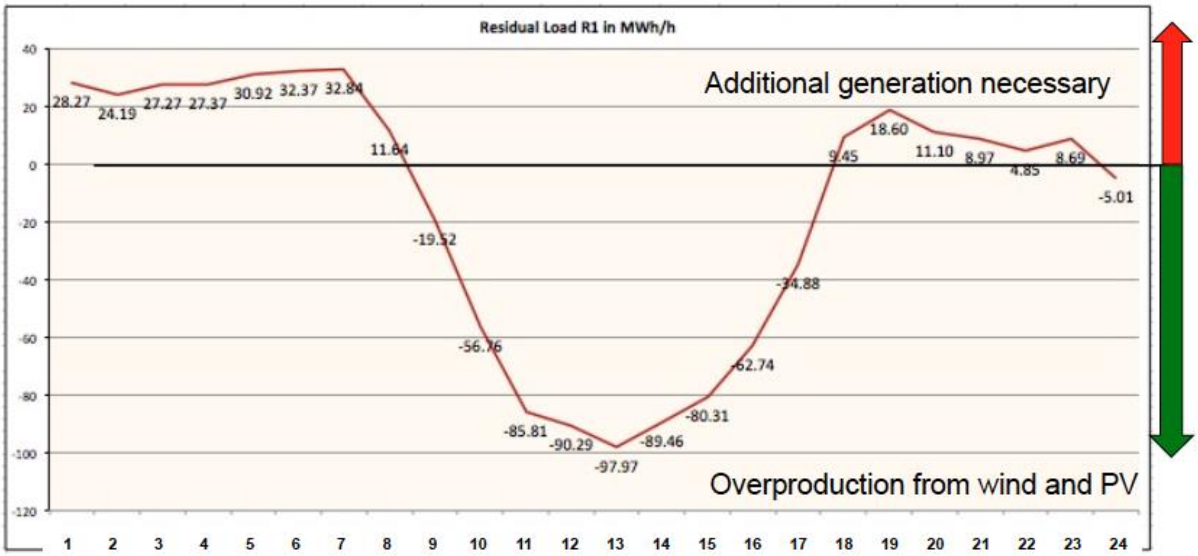
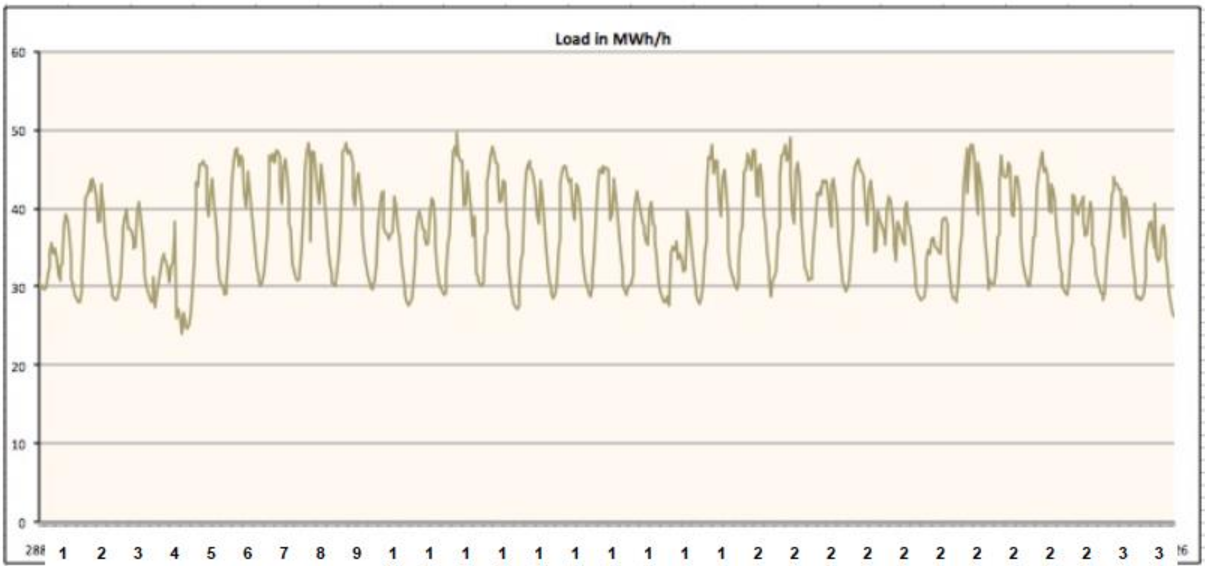


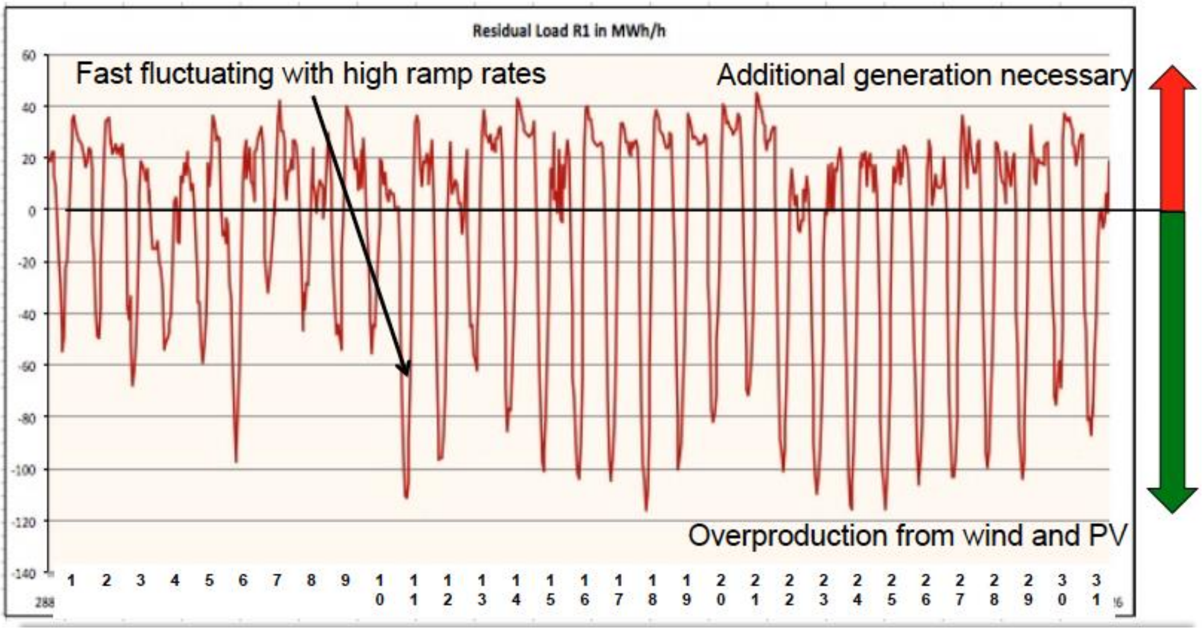
Figure 7a shows the daily and weekly pattern of the electrical load for the month of May, which needs to be met every hour of the month. Subtracting the wind and solar energy production of an installed capacity of 50 MW wind and 125 MW of solar energy leads to the fast fluctuating residual load shown in Figure 7b, which has to be covered by the controllable units of the system. The structure of the residual load suggests that Mahé will need substantial storage to balance the residual load in the case of a 100% renewable energy supply, if the availability of biomass is limited.

Figure 7: Load curve for the month of March (7.a) and resulting residual load with 50 MW wind energy and 125 MW PV installed (7.b) covering an increased electricity demand and load

7.a Simulated hourly load curve (Source: graph based on PUC 2016)



7.b Hourly residual load curve (Source: own calculations)



3.2 Biomass

Often the easiest use of biomass is the use of the solid biomass residues from agricultural production or biogas from liquid agricultural residues. In order to match the residual load remaining from a high share of wind and solar energy, the biomass has to be utilised in a very flexible form. For such purpose liquid biofuels are most useful. They can be used in combustion engines, which can be started within minutes and reach full load in less than ten minutes. Furthermore, liquid biofuels can easily be stored for longer periods of time. Thus, it seems to be most appropriate to analyse whether some form of palm or coconut oil can be produced on Mahé and converted into biodiesel. With the suggested configuration of the renewable power system an annual demand for about 5,000 metric tons of biodiesel would be needed to back up the system. At present it is not clear, whether such a production would be feasible for Mahé or whether it would be better to produce the biomass on other islands of the Seychelles or to import this energy from other countries with lower production costs.

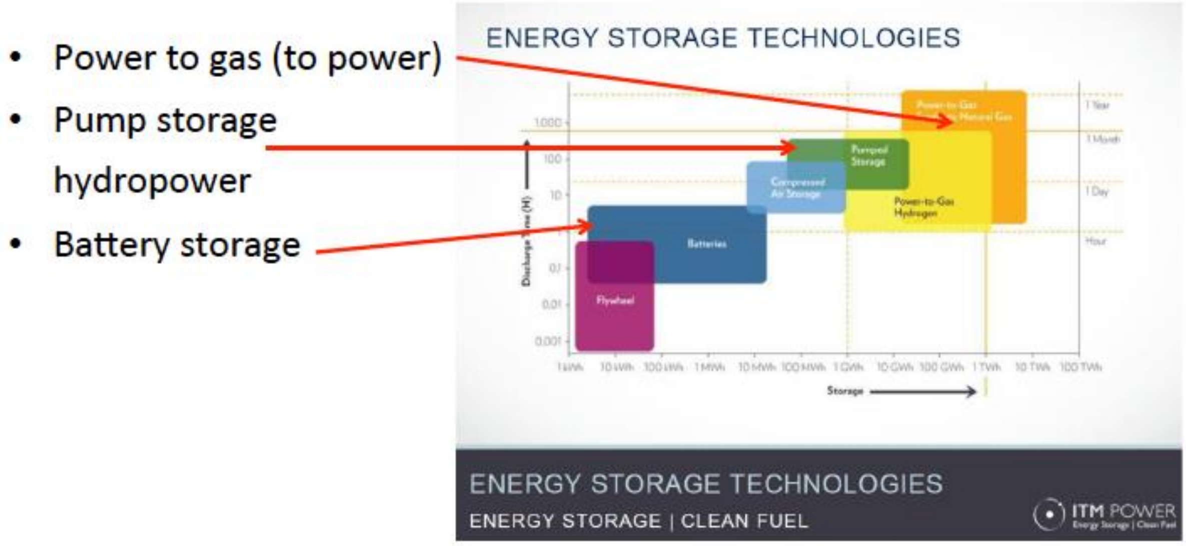
3.3 Storage

As a high share of solar and wind energy will lead to an electricity production which will at some hours be higher and at other hours considerably lower than the electricity demand, a power supply based solely on renewable energy sources will require substantial volumes of storage. The electricity produced by the storage should be available within a few minutes due to the fast changes in the residual load. The capacity of the power production from the storage needs to be equivalent to the maximum load of the electricity system and the storage volume should be in the order of at least twelve hours of demand. If affordable it might be in the order of the power demand of a number of days, depending on the load characteristics of the country being served and the specific cost of storage versus the cost of overproduction being down regulated. For the power supply of Mahé the storage needs to have a generation capacity of about 64 MW, a pump capacity of about 128 MW to make the best use of the available overproduction and a storage volume of about 1 GWh. These properties need to be taken into account in the selection of the most appropriate storage options.

As electricity demand from many households combined is far smoother than the demand of every single household and as the production from many solar installations and many wind turbines combined is far more regular than the production from each single operation, the storage demand for a connected electricity system is considerably less than the storage necessary to level the renewable energy production from a single solar installation with the demand from a single household (the summed up single home storage can easily be factor 5 to 10 the size of a centrally controlled storage). Thus, even if decentralised storage is used, it has to be operated on the basis of the storage needs of the entire system, not on the basis of the demand of single households. For this reason every storage installation needs to be centrally controlled ('dispatched' in the terms of power systems).

As Figure 8 shows, there are at least six different storage technologies that might be considered for use in Mahé's power system. Two of these options don't apply for technical reasons. First, flywheels, large rotating masses, which store kinetic energy, are not able to supply storage volumes in the necessary range. This storage option is limited to volumes of stored energy up to 50 kWh, while the capacity necessary for Mahé starts at 0.1 GWh or 100,000 kWh. Thus, flywheel storage is far to small for this application.

Figure 8: Different storage technologies for electricity with range of storage volumes and discharge times (double logarithmic scale) (Source: Hohmeyer 2015, Figure 8)



The second technology that does not apply here is compressed air storage (CAES). Compressed air storage needs very large underground salt formations to form caverns of a volume between 100,000 and 500,000 m^3. These are used to press air under high pressure into the caverns at times of overproduction of power. The maximum pressure in the cavern is brought up to about 150 bar. Whenever additional power is needed from the storage the compressed air is released through an air turbine to produce electricity. For this purpose the pressure is dropped to about 100 bar. Thus, the active storage is made up by the pressure difference between 100 and 150 bar. As the air is heated up in compression to temperatures in the range of 500 to 600°C and the salt in the cavern would melt at such temperatures, the air has to be cooled down to ambient temperature. On the return the air has to be heated up to temperatures between 400 and 500°C before it can drive an air turbine. Thus, it is strongly desirable to store the heat energy as well. Such combined air pressure and heat storage systems are called adiabatic air storage (adiabatic CAES). To the knowledge of the author there are no large salt formations under Mahé. If this holds true, CAES is not an applicable storage option for Mahé, although it could supply storage in volumes of up to 1 GWh.

Thus, four storage technologies seem to remain for an application in the case of Mahé, which can not be disqualified right from the beginning. These technologies are:

- Battery storage
- Pump storage hydropower
- Power-to-gas storage in the form of hydrogen
- Power-to-gas storage in the form of methane.

Battery storage is a rather mature technology and available in very different sizes ranging from batteries for single devices like calculators to large containerised battery storage applications for the stabilisation of weak electrical grids. The storage capacity goes up to volumes in the range of 50 MWh (50,000 kWh). As we will need storage volumes up to 1,000 MWh (1,000,000 kWh), battery storage appears to be falling short in the necessary storage volume. Nevertheless, it is far closer to the target range than the flywheel technology discussed above.

Figure 9: Pros and cons of battery storage (Source: adapted from Hohmeyer 2015, Figure 9)

Battery storage:

- Easy to install
- High efficiency
- Electricity loss over time
- Relatively expensive (500-600 US$/kWh storage)
- Too small for Mahé (MWh range)

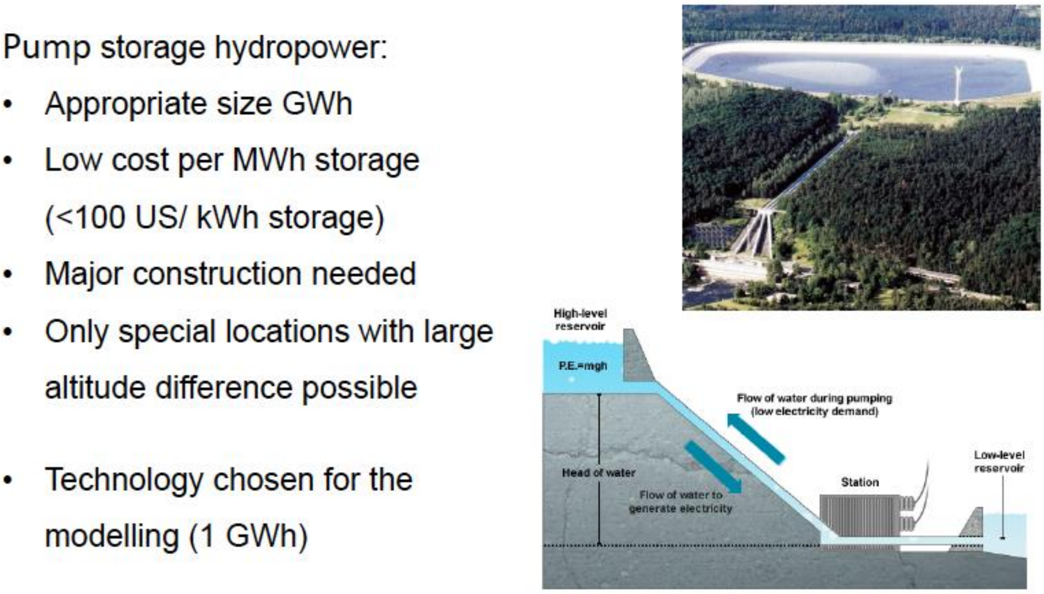
As battery storage can be bought 'off the shelf' in containers ready to be connected to a grid, it is very easy to install. It just takes the cabling and some foundations for the containers to set up this storage option. Figure 9 shows a picture of containerised battery storage and sums up the main pros and cons for battery storage.

Battery storage has a relatively high efficiency for the storage of electricity. In short term storage more than 90% of the energy stored may be retrieved from a battery, if it is used shortly after the energy has been stored. If a battery is used for energy storage over weeks it may loose a large share of the stored energy even without being used.

One of the major disadvantages of battery storage is its relatively high costs, which are in the order of 500 US$/kWh of storage volume. Thus, a storage volume of 1 GWh would cost about 500 million US$. At the same time batteries have a far shorter lifetime than pump hydro storage, even if they are very well maintained.

Another relevant option is pump storage hydropower. This technology has been used for more than a hundred years all over the world to back up and stabilise larger electricity systems. It uses the gravitational potential energy held by water at high elevations. A normal pump storage system consists of an upper and a lower storage lake, which exchange freshwater. If energy needs to be stored, water is pumped with the help of an electric motor (driving a pump) from the lower lake into the higher lake. Once the energy is needed for the electricity supply the water runs from the upper lake to the lower lake driving a turbine, which is connected to an electric generator producing the electricity needed. Figure 10 shows a picture of the upper lake and the power plant of a pump storage hydro plant, and a cross section of such an installation showing the basic principle. The altitude difference between the two lakes should be greater than 100 m, as the stored energy is directly related to the height difference (head) and the volume of the water stored

Figure 10: Pump storage hydro systems and their main advantages and disadvantages (Source: adapted from Hohmeyer 2015, Figure 10)



Pump storage hydropower:

- Appropriate size GWh
- Low cost per MWh storage (<100 US/ kWh storage)
- Major construction needed
- Only special locations with large altitude difference possible

- Technology chosen for the modelling (1 GWh)

Thus, the smaller the altitude difference of the two lakes, the larger the necessary storage volume for the same energy. Assuming an altitude difference of 600 m the necessary storage volume of each lake to store 1 GWh (1,000,000 kWh) is about 625,000 m^3. At an average water depth of 20 meters each storage lake would measure approximately 175 by 175 meters. As Mahé has substantial areas with an elevation around 600 m above sea level, the necessary storage volume can easily be estimated by multiplying each kWh of necessary energy storage by 0.625 m^3.

In the overall storage operation about 20 to 30% of the original electricity is lost. Thus, the efficiency of the storage is not as high as in battery storage, but it is far better than in the power-to-gas storage discussed below. As Figure 8 above shows, pump storage hydro is applied in a range of 50 MWh to 50 GWh (50,000 to 50,000,000 kWh), which easily covers the most likely size of the necessary storage for Mahé. Although the cost of a pump storage hydro system will vary considerably with the construction costs of the storage lakes and the pipeline or tunnel connections between them, the costs for such systems are most likely below 100 $US/kWh of storage volume. Which is about one fifth of the cost of battery storage. The function for calculating the pump storage cost is more complex and includes costs for the pumps and turbines as well as the costs for the storage volume.

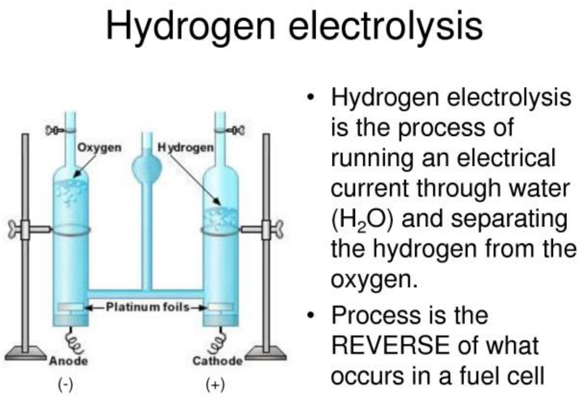
One of the historic reasons for including pump storage hydro systems in almost all major electricity supply systems is the ability to ramp a pump storage system from no operation to full load operation in about 90 seconds. Thus, such a system can change from full load operation for storage to full load operation for electricity production within three minutes (180 seconds). This capacity has rendered pump storage hydro systems ideal for dealing with all short term fluctuations in power supply systems. Under normal circumstances the relation between the storage volume, measured in GWh, and the electricity production capacity, measured in MW, allows for a full load operation of 4 to 6 hours. In conventional power systems the storage is filled by cheap electricity produced during low load hours during the night and electricity is produced during peak load hours of the day or to smoothen the production to exactly meet demand at every minute of the day.

Although it will be necessary to do a very detailed site assessment for the location of a pump storage hydro plant on Mahé, this technology seems to offer the right size and technical properties for the storage needed for a 100% renewable electricity supply for Mahé at comparatively low costs when compared to battery storage.

Before a final decision on the storage system to be used for the system simulation is made, the other options have to be looked at. These are the two so called power-to-gas technologies. In the first case the electricity to be stored is used to split water (H_2O) with electricity into its two components hydrogen (H) and oxygen (O) in a process called electrolysis. Figure 11 shows the basic principle of the electrolysis process.

In the electrolysis process the two produced gases (oxygen and hydrogen) have to be separated, because a mixture of the two forms a highly explosive gas (detonating gas). The energy is stored in the form of the hydrogen produced. As soon as this is recombined with oxygen from the surrounding air, the stored energy is set free. This recombination can be done in a combustion engine or in a fuel cell, which is just the electrolysis process in reverse. In this recombination process of hydrogen and oxygen the stored energy is set free in the form of electricity. Although there are a number of different fuel cell technologies, most of the technologies have not left the demonstration stage and are hardly available as robust commercial technologies.

Figure 11: Electrolysis: splitting water with electricity (Source: imagekid.com 2015)

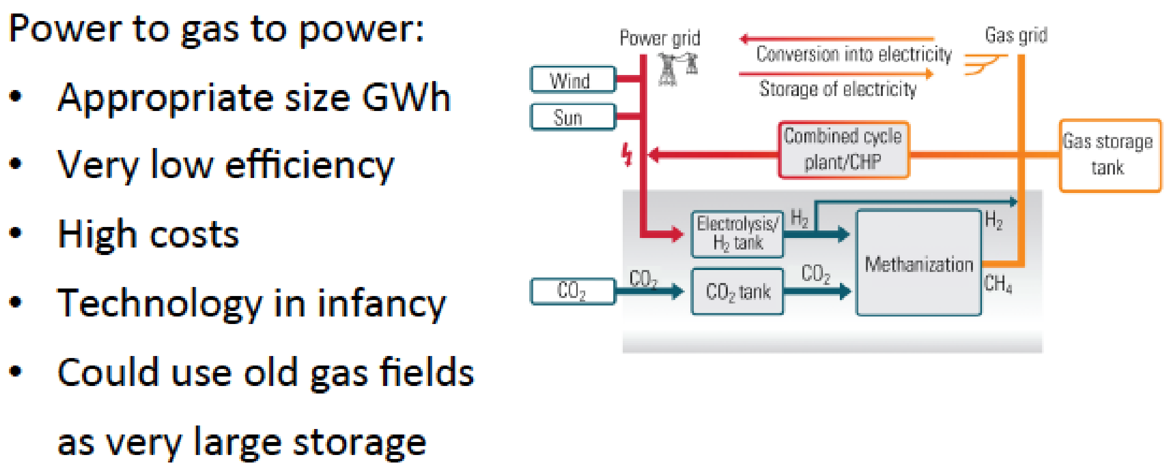


Hydrogen electrolysis

- Hydrogen electrolysis is the process of running an electrical current through water (H_2O) and separating the hydrogen from the oxygen.
- Process is the REVERSE of what occurs in a fuel cell

As hydrogen is relatively difficult and expensive to store the suggestion has been made to take this technology one step further to make storage much easier. This is achieved by using the hydrogen generated to produce methane (CH_4), which is the major part of natural gas. The idea is that methane can then be stored and distributed using the natural gas infrastructure, pipelines and storage, existing in many countries. This would reduce storage costs drastically. For the production of methane from hydrogen we need carbon dioxide (CO_2) to supply the carbon (C) necessary. This so called methanation process is a standard synthesis process in the chemical industry. Once the electricity is needed the methane can be used in combustion engines or turbines to drive generators to produce electricity. Figure 12 shows the principle of power-to-gas storage of electricity.

Figure 12: The principle of power-to-gas storage and its major advantages and disadvantages (Source: Hohmeyer 2015, Figure 12)



Power to gas to power:

- Appropriate size GWh
- Very low efficiency
- High costs
- Technology in infancy
- Could use old gas fields as very large storage

Due to the different conversion steps, 60% of the originally produced electricity will be lost in hydrogen storage. In the case of methane storage 70 to 80% is lost. Thus, for these types of storage 2.5 to 5 kWh of electricity need to be produced and fed into the storage system for every 1 kWh to be finally used after storage. The numerous conversion steps and the high losses lead to relatively high storage costs. As the technology is still in its early stages of development, actual cost figures for mature systems are not available.

Although power-to-gas storage covers the right size range of storage for Mahé it has not been used for the system simulation, as it is not clear how expensive such a system would be as the technology is still in its infancy and as the low storage efficiency would require substantially larger installation volumes of wind and solar energy systems.

As a result of this preliminary analysis of the different possible storage options, pump storage hydro systems have been selected for the simulation of a 100% renewable power supply system for Mahé as this technology offers potentially low storage costs, a relatively high storage efficiency, is available in the right storage size, is technically mature and offers great technical advantages for stabilising the electricity system.

4. Simulation of a 100% renewable power supply system for Mahé

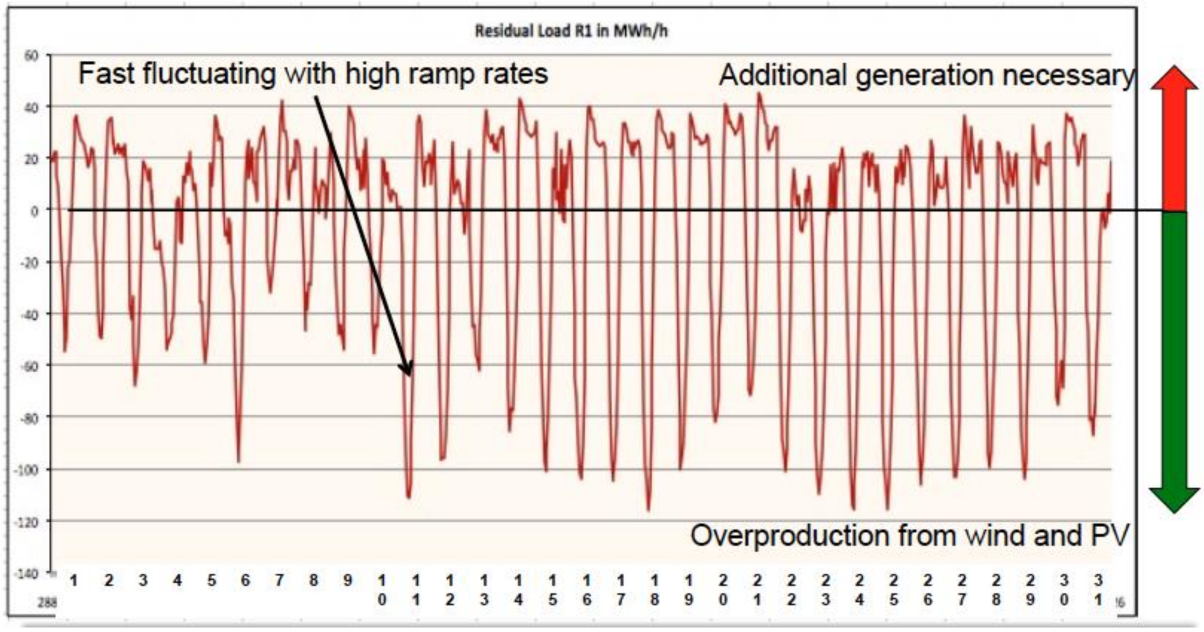
After the basic technology selection has been made we can analyse how Mahé's electricity demand can be met every hour of the year. For this purpose a simple simulation tool has been developed by the author and one of his colleagues (Sönke Bohm) at the University of Flensburg.

For the simulation an hourly load curve was derived from the available daily power production data for Mahé supplied by the PUC for the year 2014. This hourly load curve is shown for the month of May in Figure 7a above. The data supplied by the PUC is actually the most complete demand data set the author has worked with during his professional career.

The next input into the simulation was the hourly solar radiation and the hourly wind speeds for an entire year, which were taken from the hourly wind measurements at Mahé airport and the solar data from the international MERRA 2 data set for the coordinate 4.5°S / 55.625°E. MERRA 2 data are available for almost the entire world for coordinates in 0.5° steps of latitude and 0.625° steps of longitude. The chosen coordinate, which is about half way between Mahé and Praslin is the coordinate with the best representation for Mahé.

Based on the hourly wind and solar data the model calculates the energy output from a typical wind turbine (2 MW size) using a detailed power curve for the turbine and the energy output from a typical photovoltaic installation. The calculated hourly wind energy produced is shown for the wind year 2010 in Figure 2 above, while the hourly solar energy production for the solar year 2010 is shown in Figure 3 above. The installed wind and solar power can easily be put into the model, which then subtracts the wind and solar energy production from the hourly load to calculate the residual load, which is shown in Figure 13.

Figure 13: Calculated hourly residual load for Mahé in May (load 2014, wind and solar data for 2010) (Source: own calculations)



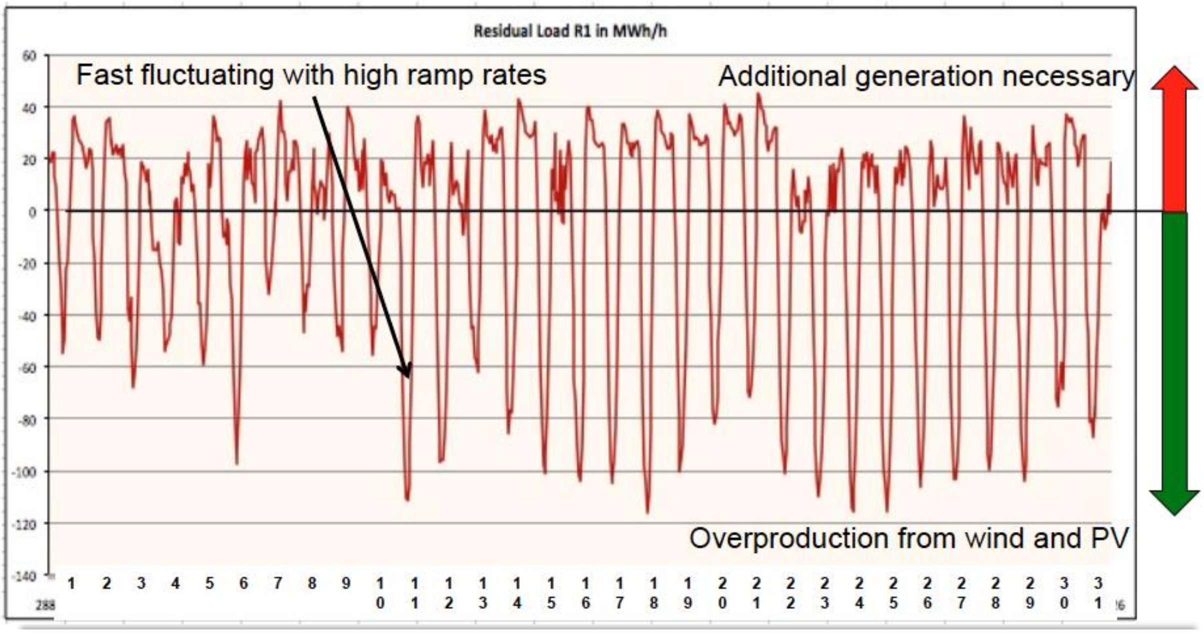
Whenever this residual load is positive we have demand not covered by the wind and solar power produced in this hour. This has to be met either by production from the storage or, if the storage is already emptied out, by electricity production from our liquid biomass in the form of biodiesel.

A detailed analysis of the data shows that the residual load is massively positive during the hours 1,400 to roughly 2,900. Thus, we will need to produce large quantities of electricity from storage or from biomass. During the winter month we find the residual load to be negative most of the time. Thus, for this time we can expect storage to be filled quite well, easily able to supply the necessary electricity to cover the hours of positive residual load.

Figure 14 shows the resulting operation of the pump storage plant for the month of May. A storage volume of 1 GWh (1,000,000 kWh) was chosen, resulting in a useful electricity generation capacity of about 64 MW and a pumping capacity of 128 MW.

During the entire month the storage is working quite actively in both directions. As the system is heavily driven by solar energy this reflects the fact that energy is overproduced and stored during the daytime and used for pump storage power production during the night hours.

Figure 14: The simulated hourly operation of the pump storage plant during May (Source: own calculations)



The filling level of the storage displayed in Figure 15 touches the bottom during the first days of May and the biodiesel back-up has to be used to fill in the gaps during the night time of the first three days of the month as shown in Figure 16. During the rest of the month the solar and wind conditions are sufficient to keep the storage from running dry. In the second half of the month the storage reaches its upper limit almost every day around noon time and Figure 17 shows the peaks of overproduction. Nevertheless, during the night time the storage level drops again and the system can absorb a substantial part of the overproduction of the next day.

Figure 15: Filling level of the pump storage system in MWh during May (Source: own calculations)

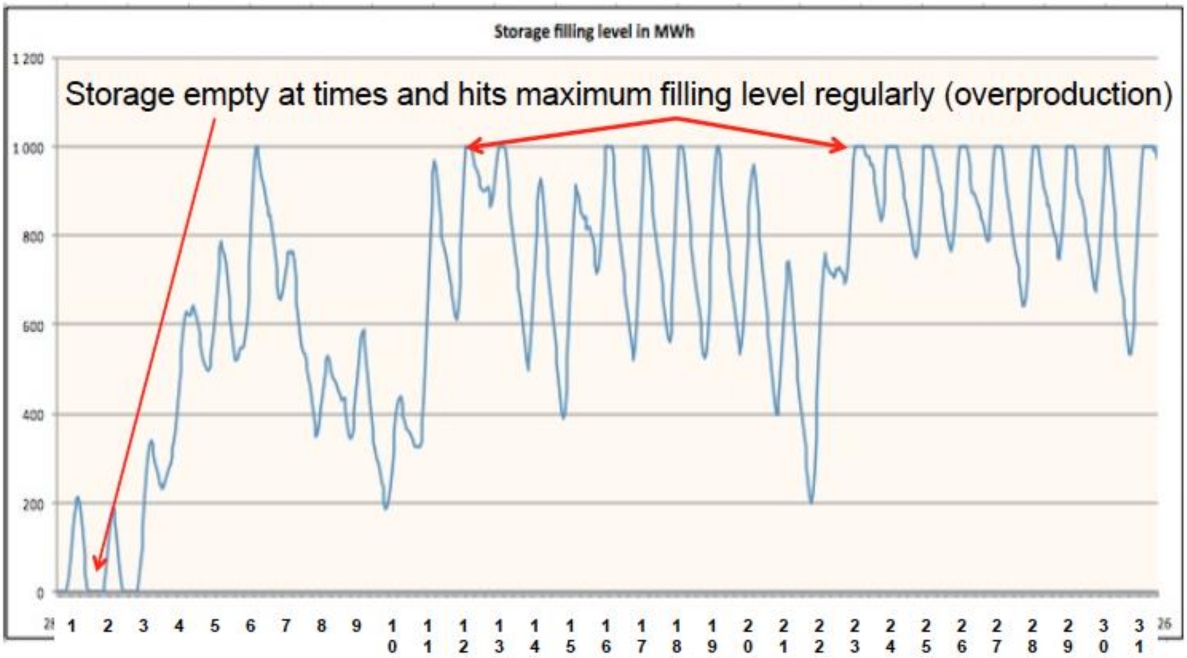


Figure 16: The use of biomass in March to meet the remaining the residual load after storage has been used (Source: own calculations)

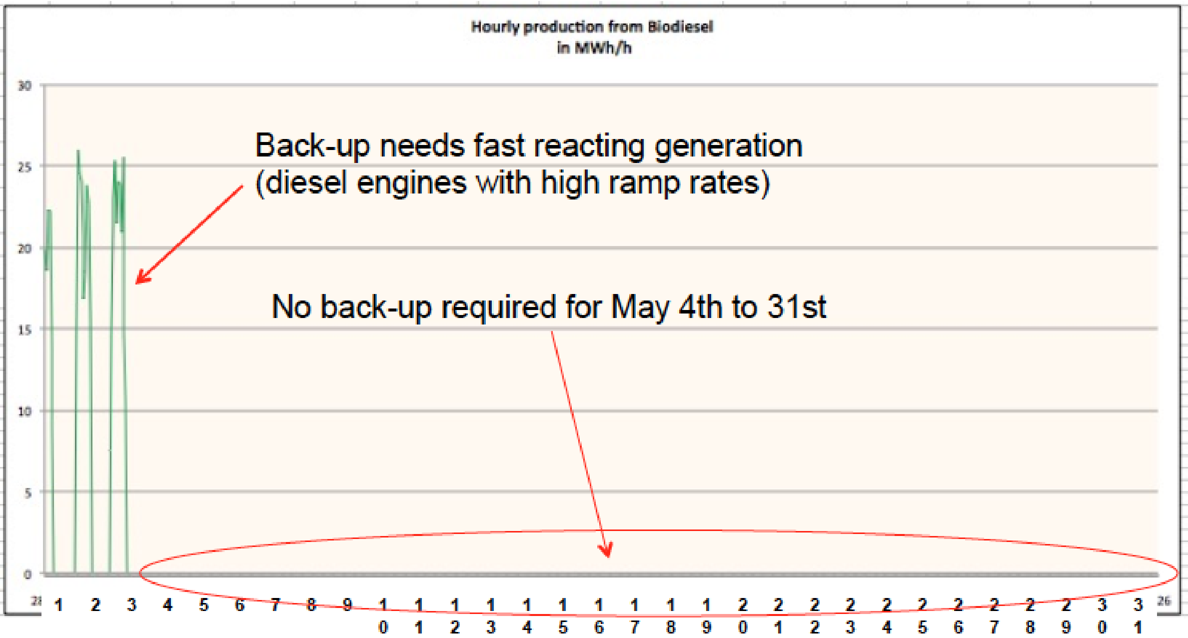
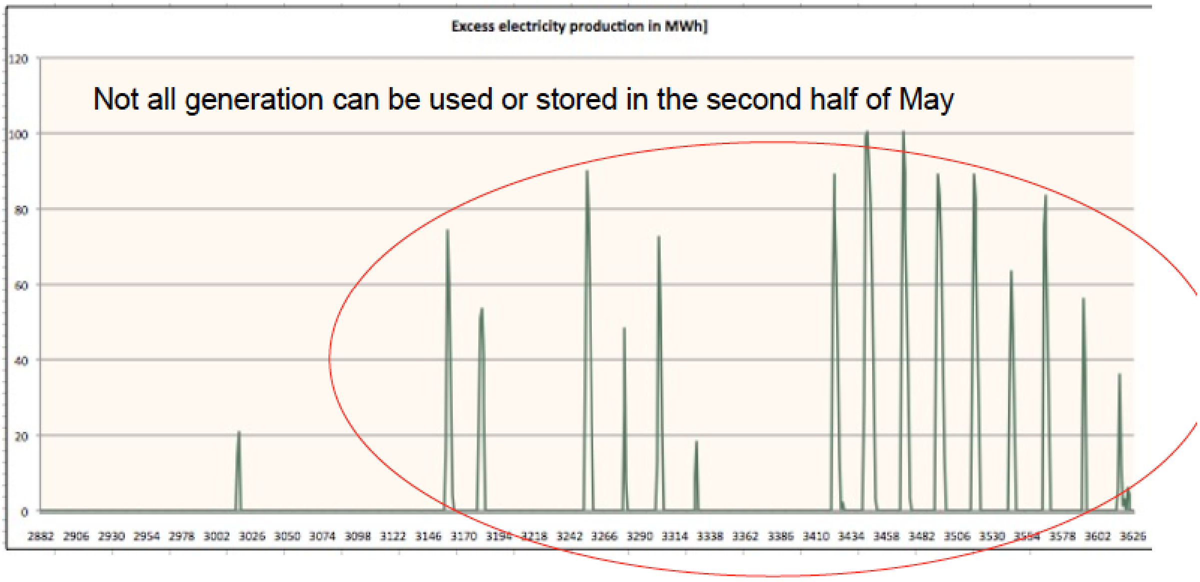
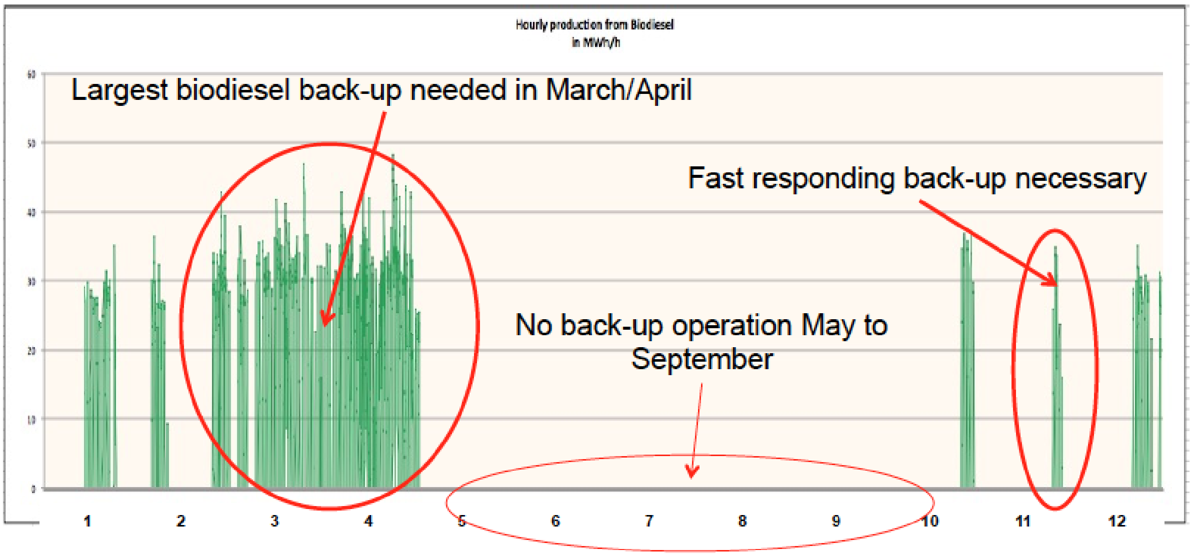


Figure 17: Overproduction of electricity from wind and solar energy in MWh/h (Source: own calculations)



The use of biomass is a very good indicator showing, when the system is at its limit. Figure 18 displays the necessary use of liquid biomass across the entire year. It shows that during the month of February to May there is a lack of wind and solar power to fully balance the system, while during almost the entire rest of the year the biomass back-up is not needed except for a few days in November and December.

Figure 18: The use of biomass during the entire year simulated (Source: own calculations)



5. A scenario for a 100% renewable power supply for Mahé

Once the six major parts of Mahé's future energy system have been specified for analysis (hourly demand, hourly wind energy production, hourly solar energy production, calculation of residual load, operation of storage and production of biomass to match remaining demand), Mahé's future power supply can be analysed under different scenario assumptions.

The starting point of a scenario is the volume of biomass available or accepted as imported biodiesel quantity. In a second step the volume of storage is set. On this basis the installed wind and solar capacities are varied until a cost minimum for covering the entire demand is reached. In a next round of iterations the storage volume is varied and combined with different solar and wind capacities to find the lowest cost combination of the three variables. This is not automated (it is actually a linear optimization process) in order to get a clear picture of the reaction of the system cost on different combinations of these variables.

For the scenario a number of technical and economic assumptions were made, which are summarised in Table 2.

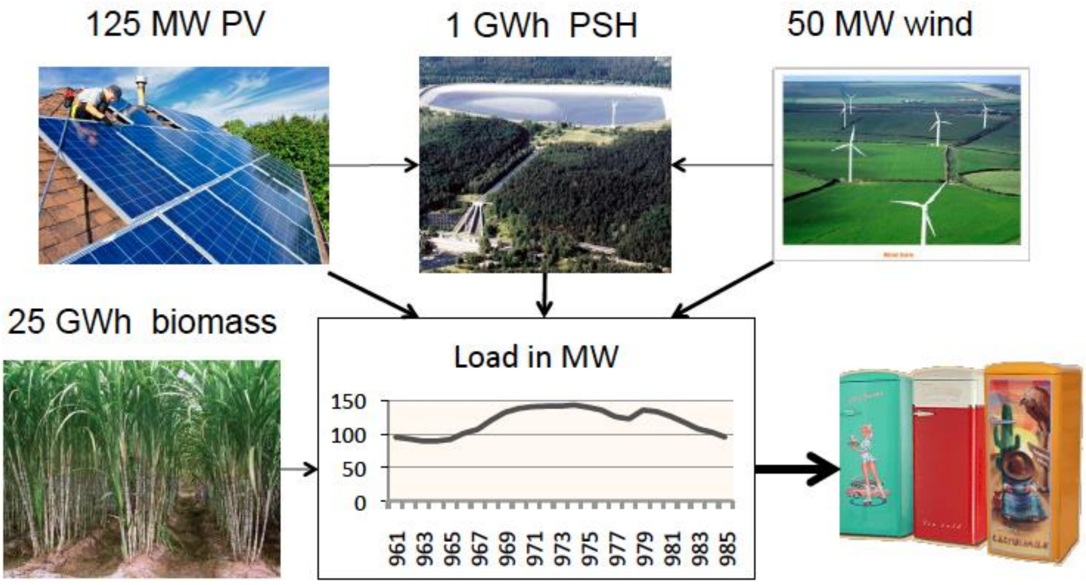
Table 2: Technical and economic assumptions made for the scenario presented in this report

Demand curve	- based on actual hourly operation data of PUC 2014	
Demand	- base year 2014	321 GWh/a
	- Peak demand	51.6 MW
Exchange rates	- Euro to SCR	15
All systems	- interest rate for financing	6%/a
Wind energy	- turbine size	2.5 MW
	- hub height	80 m
	- shear factor	0.20
	- investment costs	1,050 Euro/kW
	- operation and maintenance costs	5%/a of investment costs
	- hourly wind data	Mahé Airport 2010
	- measurement height of wind data	10 m
Solar energy (PV)	- solar radiation per year	2,071 kWh/m^2
	- module capacity	150 W$_p$/module
	- module size	0.125 m^2
	- system efficiency	0.1275
	- investment costs	1,500 Euro/kW$_p$
	- operation and maintenance costs	5%/a of investment costs
	- hourly solar data	MERRA 2 (4.5°S / 55.625°E)
Pump storage	- investment costs a) capacity	1060 €/kW of pump capacity
	b) storage volume	1300 €/MWh of storage vol.
	- operation and maintenance costs	4,000 Euro/MW pump capacity per year
	- altitude difference	500 m
	- turn around efficiency	0.75
Bio fuel	- fuel costs per metric ton	7 800 SCR/t
	- electricity cost from biodiesel	3 000 SCR/MWh

Starting from an assumed biomass availability of 25 GWh of liquid biomass (either imported or produced locally), the size of the storage was varied between 0.5 GWh and 10 GWh. A variation of the wind and solar generation capacities under each of these combinations showed that a storage volume of 1 GWh leads to the lowest costs. In the most extreme cases there was only wind or only solar power used, but in both cases this was far more expensive than all the mixed scenarios. To find the cost minimum, more than fifty different scenarios were simulated and analysed. Varying the installed wind and solar capacities lead to the cost minimum within the scenario family (25 GWh of biomass and 1 GWh of storage capacity) at an installed solar capacity of 125 MW and an installed wind energy capacity of 50 MW. This system configuration is depicted in Figure 19. This configuration is based on the energy consumption and peak load of the year 2014.

One technical result calculated by the simulation tool is the capacity of the generators and pumps of the pump storage hydro plant necessary to meet the task of the storage. These capacities were calculated to be 64 MW of generation capacity and 128 MW of pump capacity in the minimum cost scenario.

Figure 19: System configuration of the minimum cost scenario chosen for this report (Source: own calculations)



It can be concluded from the simulations that a 100% renewable power supply is technically feasible on the basis of wind and solar energy, if sufficient storage is built and some liquid biomass can be made available. Such energy supply would make Mahé entirely independent of future world market developments for crude oil products and at the same time reduce Mahé's net greenhouse gas emissions from electricity production to virtually zero.

The central economic result of the calculations was the cost per kilowatt-hour produced to meet the demand. This includes the costs for all kilowatt-hours produced, including those which can not be used due to overproduction, the generation costs of wind and solar energy, and the full costs of storage. The cost for biodiesel was taken as shown in Table 2 above. All costs include the investment costs as well as the operation and maintenance costs based on the assumptions summarised in Table 2. These costs do not include the costs for the operation of the electrical grid and general overheads of the Seychelles PUC.

The total costs of electricity production in the minimum cost scenario were calculated to be 2.299 SCR/kWh.

This figure can be compared to the **2014 fuel costs** of Seychelles PUC for the electricity generation in Mahé, which have been at **2.08 SCR/kWh** (PUC 2016a). As these do not include investment costs or operation and maintenance costs (besides fuel costs) for the present power generation facilities of PUC, these fuel costs can be taken as the minimum cost savings achievable by renewable electricity generation at the crude oil prices of 2014. This assumption allows us to keep the existing generation equipment to be used with the biodiesel, as these investment costs are already covered by the present overheads of PUC. Thus, the cost increase, which will result from renewable energy generation is 0.219 SCR/kWh compared to the fuel costs of 2014. This is a cost increase of about 10% as compared to the total electricity cost of 2014, which amounted to 2.33 SCR/kWh (PUC 2016a), but it should be compared to the average rate charged to the PUC customers of 3.85 SCR/kWh in 2014 (NBS 2015, p. 95). Figure 20 summarises the costs of the 100% renewable electricity supply and shows the cost changes compared to the present electricity costs.

Figure 20: Costs of a 100% renewable power supply for Mahé compared to present generation costs (2014) based on present prices for renewable energy technologies (minimum cost scenario) (Source: own calculations, data from Seychelles NBS and PUC)

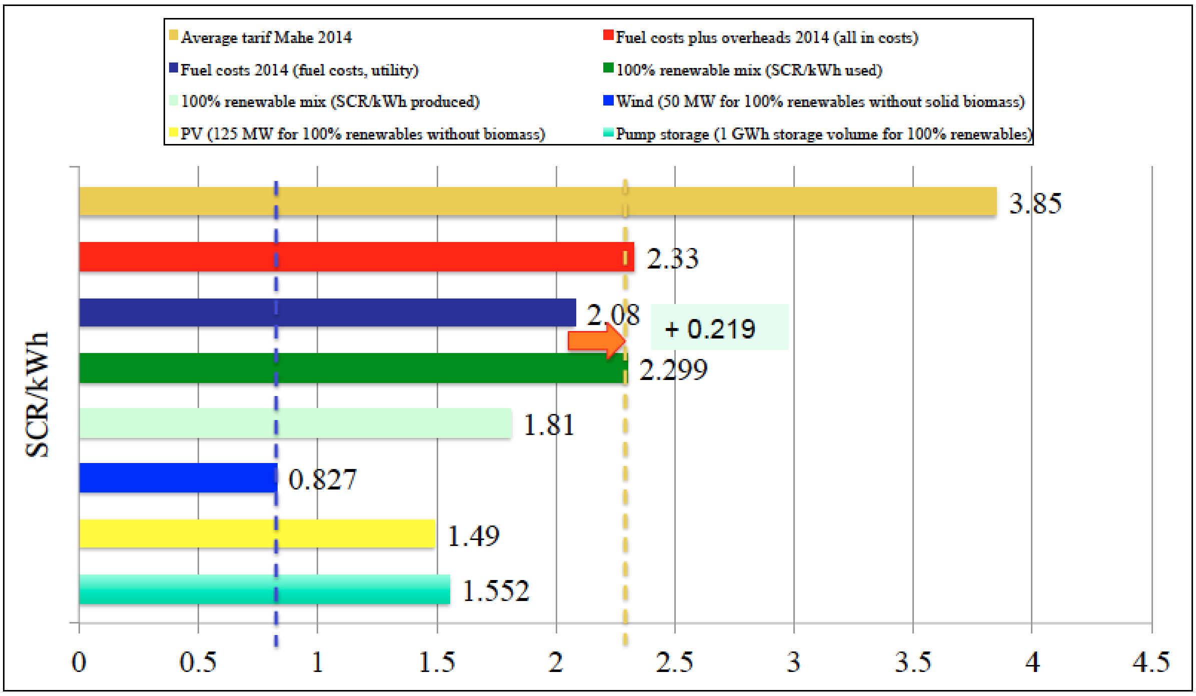


Table 3 summarises the economic results of the minimum cost scenario. It shows that the total electricity cost increase would have amounted to about 56 million SCR/a in 2014.

Table 3: The economic results of the minimum cost scenario(Source: own calculations)

Costs and Imports	
Mahé PUC electricity generation costs 2014 (all in costs) SCR/kWh	2.33
Mahé PUC Fuel cost 2014 only in SCR/kWh	2.08
Wind (50 MW for 100% renewables) SCR/kWh	0.827
PV (125 MW for 100% renewables) SCR/kWh	1.49
Biodiesel (25 GWh/a) SCR/kWh	3.0
Pump storage (1 GWh storage volume) SCR/kWh	1.552
100% renewable mix (SCR/kWh used) SCR/kWh	2.299
Cost increase compared to 2014 (renewable cost minus fuel cost) in SCR/kWh	+0.219
Electricity cost increase in % (of 'all in costs')	8,9%
Electricity cost increase per year in SCR/a compared to 2014	56 000 000
Import reduction in SCR over 20 years (570 Mill. SCR/a) in SCR	11 400 000 000

6. Impacts on the economy and taxes

The proposed change of Mahé's electricity production to a 100% renewable electricity supply will have a substantial impact the Seychelles' economy. The electricity cost increase of about 56 million SCR/a is equal to a small decrease in national spending power of 0.28%, if we assume a national GDP of about 19 881 million SCR/a in 2014 (NBS 2015, p.72).

In a 100% renewable energy future the entire fuel imports for electricity generation of 651 million SCR/a (2014) (source PUC 2016) can be eliminated. At the same time **net imports**, taking into account necessary new imports of about 80 million SCR/a for technical equipment for the use of renewable energy, **can be reduced by about 570 million SCR/a, which is equal to a GDP increase by 2.9%**. What is more, this import reduction saves the Seychelles from having to spend hard currency in the order of 43 million US$ every year.

If the money invested into renewable energy technologies can be raised locally then the long-term income generated will stay in the economy and maximise the positive economic impact.

As the renewable energy technologies to be employed are not manufactured in the Seychelles, about 80 million SCR/a will need to be spent on the necessary technology imports (e.g. wind turbines, PV modules, etc.) on average across the lifetime of the equipment. Further analysis is necessary to analyse which parts of the investment can be produced in the Seychelles; like the foundations for the wind turbines or the construction work necessary for the pump storage hydro power plant. The higher the share of local production the lower are the remaining imports and the higher are the possible employment effects during the construction phase of the new energy supply technologies.

Once the new energy technologies go into operation, most of the necessary labour will lead to additional employment in the Seychelles.

If Mahé is successful in moving to a 100% renewable electricity supply as one of the first small island countries, it has a great chance to create the highly skilled labour force needed to facilitate the transition processes in the other small island countries. This could lead to a substantial boost in employment for the Seychelles in the field of renewable energy systems.

The impact of the transition to a 100% renewable power supply on tax income has been a question of great concern to governments, as the reduction of the fuel imports can lead to a loss in import taxes. Although such tax losses are overcompensated by the additional taxation on the money kept in the country, the Seychelles are in the favourable situation that the fuel oil (diesel) used in the electricity generation is not subject to excise of import taxes (information from PUC). Thus, the switch to 100% renewable electricity is extremely attractive with respect to the taxes generated.

In the case of the conventional electricity generation the Seychelles had to pay about 650 million SCR/a for imported fuels in 2014, which were not taxed. Thus, this part of the GDP was lost from the tax base. In the case of **the 100% renewable energy transition** the country could even afford to exempt the imported equipment from import taxes and still increase its tax base by about 570 million SCR/a. Assuming that the present and the future electricity are subject to the general VAT of 15% nothing would change at the level of electricity sales, but the income of 570 million SCR/a generated from the operation of the new renewable power production system would be subject to the average income tax of 15%. This would amount to an additional tax income of 85.5 Million SCR/a. Assuming that the remaining income of (570 - 85.5 =) 484.5 will be spend in the Seychelles again and a VAT of 15% applies, this would lead to a second tax income of about 73 million SCR/a. The remaining income would then be taxable at 15% and so on. At the end the import substitution of just the 2014 volume **would lead to an additional tax income for the Seychelles treasury over 150 million SCR/a**.

Table 4: Net effect of a switch to a 100% renewable electricity production (Source: own calculations)

Net impacts on taxes (when you keep the money in the country)

• Taxes on diesel imports (0%)	- 0 Million SCR/a
• Taxes on reduced spending (15%)	- 7.5 Million SCR/a
• Taxes on higher electricity bills (15%)	+7.5 Million SCR/a
• Taxes on income from 570 Million SCR/a spending on the island (15%)	+ 85 Million SCR/a
• VAT on spending of remaining 485 Million income (15%)	+ 73 Million SCR/a
• **Net tax increase per year**	**+ 158 Million SCR/a**

(and there are more rounds for the money to go in the Seychelles)

7. Suggestions for a possible transition

The result of the preliminary analysis clearly shows that a 100% renewable electricity supply is possible for the Seychelles and that it can massively, reduce imports, stop the drain of hard currency in the order of 570 million SCR/a and increase the governments tax income by more than 150 million SCR/a at the same time.

In this situation the question arises, how the Seychelles in general and Mahé as its main island can achieve a transition to a 100% renewable electricity supply to reap the full benefits of such a 100% renewable energy supply? Although it is not possible to fully outline all of the steps for such a transition process, it is possible to confirm that such a transition can be achieved within a time frame of less than ten years. To complete the task by 2025 will require some decisive action soon, but it is certainly achievable. The transition will require a solid but not over 'engineered' policy framework, setting the targets, the economic and technical framework for the implementation of the renewable energy production, the necessary extension of the grid and the building and operation of the storage required to achieve a 100% renewable electricity supply. Fortunately, such policy framework can draw upon more than twenty-five years of experiences in countries like Denmark or Germany, which successfully started the diffusion of renewable energy sources in the 1980s (Denmark) and the 1990s (Germany), ramping up the share of wind and solar energy to more than 80% of the total electricity production during some hours of the year and to more than 100% in major parts of the national grid.

Based on the long-term experiences of the author, who started to work on renewable energy technologies back in 1979, the following measures should be taken to facilitate the process:

1. Conduct exact measurements of the wind speeds at hub height (80 - 100 m) around the island
2. Do a detailed analysis of all possible wind energy sites on the island taking into account the necessary minimum distance from inhabited buildings, natural conservation areas and other activities, on which wind energy might infringe (white area mapping)
3. Analyse the possible contribution of rooftop solar PV installations
4. Conduct proper planning of preferred wind energy locations around the island
5. Conduct proper planning of the preferred open field solar energy sites around the island
6. Lay down a feed-in tariff system for wind and solar energy and give solar and wind electricity a guaranteed priority access to the grid
7. Set up a tariff system for the additional biomass you will need in the system, with an extremely high emphasis on flexibility and dispatchability
8. Set up technical grid connection rules for the connection of wind and solar energy systems (e.g. 'fault ride through' rules as opposed to 'fault shut down')
9. Conduct an electrical grid integration study for 100% RE power production
10. Set annual targets for the capacities of wind and solar energy to be installed
11. Improve the overall grid on Mahé to allow for decentralised generation in all parts of the island
12. Especially strengthen the island electricity grid in those areas where substantial volumes of wind and open field solar energy will be supplied according to the planned build up of capacity
13. Keep the existing diesel generators as back-up for as long as possible (overhaul will be far cheaper than new equipment considering the few hours the back-up diesel will be run in the future)

14. Analyse the quality requirements for biofuels to be burned in the existing generators without technical problems
15. Do a very thorough site assessment for the pump storage facility (or facilities)
16. Start to build storage as soon as you have reached about 50% electricity production from wind and solar energy (it will not be economical before than). It will take a number of years to be completed
17. Develop a NAMA strategy (Nationally Appropriate Climate Change Mitigation Action) for the early stages of the implementation in order to mobilise international funding for the first realisation steps
18. Implement the NAMA strategy with the help of international climate funding
19. Ramp up the installed capacities to 100% renewable electricity supply within five years after the framework has been successfully implemented, tested and fine-tuned.

For most of the policies or the technical ordinances needed in the process there do exist rules and regulations, which can easily be translated and adapted from the German regulatory framework.

For further elaborations of the transition process the author will be available as an independent consultant to the government and the people of the Seychelles in the years to come if the Seychelles government sees the need for such support.

8. Switching to 100% renewables powered e-mobility

Once Mahé has switched to a 100% renewable electricity supply, it is possible to move one step further in reducing the drain of hard currency from the country for imports of mineral oil products.

While the imports of fuel oil and diesel for electricity production amounted to 650 million SCR in 2014 the imports petrol for cars ('motorspirit') amounted to 20 000 t/a (NBS 2015a, p22) or 26.8 million litres in 2014. Assuming an import price of about 15 SCR/l assumed for 2014 this is equivalent to about 400 million SCR/a.

Due to the size of the island, electrical mobility does not suffer from its major disadvantage, the need to recharge the batteries of an average electrical car after 150 km. While in large countries in extreme cases cars may be driven over one thousand kilometres in a day, the distance travelled by a car in a day on Mahé will most likely be considerably less than one hundred kilometres. Thus, the time necessary for recharging the batteries, four hours with normal charging and 30 minutes in fast charge mode, can easily be accommodated for travelling on Mahé during the night time or in the company parking lot during the working day.

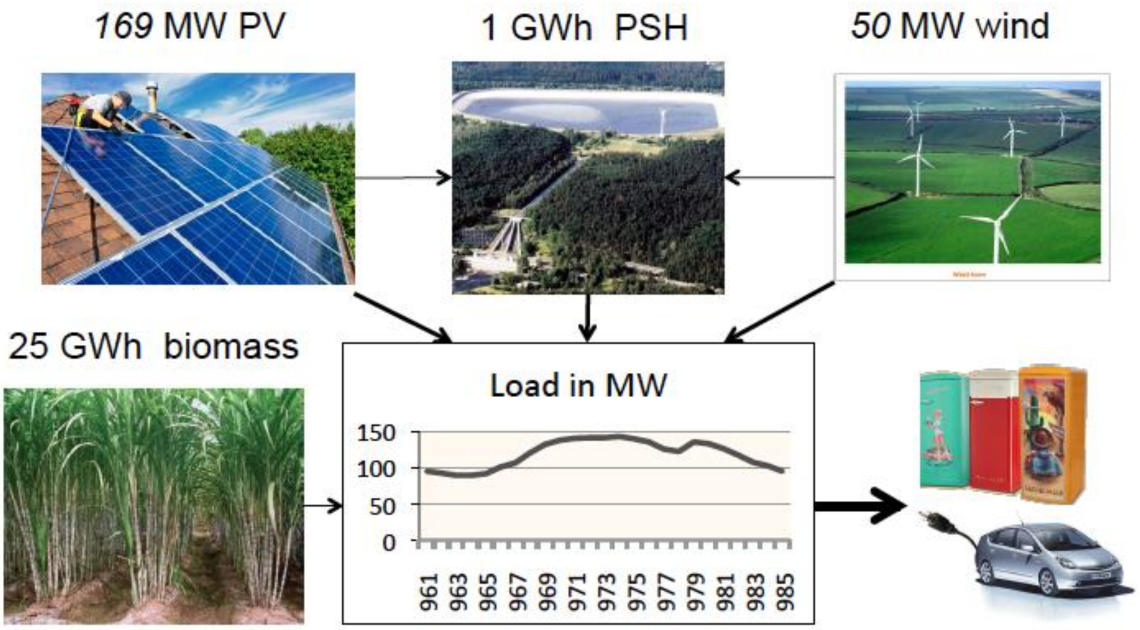
Although electrical cars are still more expensive than normal cars with combustion engines, it can be expected that this will change substantially during the next ten years, as electrical cars will most likely be cheaper in mass production than cars with combustion engines, gear boxes and mechanical transmission of the power to the wheels. What is more, electrical cars are far more efficient than combustion engine cars, as the electricity can be transformed into mechanical propulsion power at very low losses.

A rough comparison of the fuel costs of a combustion engine car for driving 100 km and an electrical car running on renewable power produced on Mahé gives the following result:

Assumed fuel costs (2014)	21.5 SCR/l
petrol consumption per 100 km	7.5 l
cost per 100 km conventional car	**160 SCR/100 km**
green electricity costs per kWh	2.5 SCR/kWh
electricity consumption per 100 km	40 kWh
cost per 100 km electrical car	**100 SCR/100 km**

At a cost of 100 SCR per 100 km the electricity for driving is substantially below the 160 SCR per 100 km for a conventional car, there seems to be room for similar tax rates as on gasoline or diesel and for cost savings to the average customer. Thus, a replacement of conventional cars by electrical cars as well as light trucks or busses by electrical vehicles could be economical and further contribute substantially to the reduction of imports and the drain of hard currency.

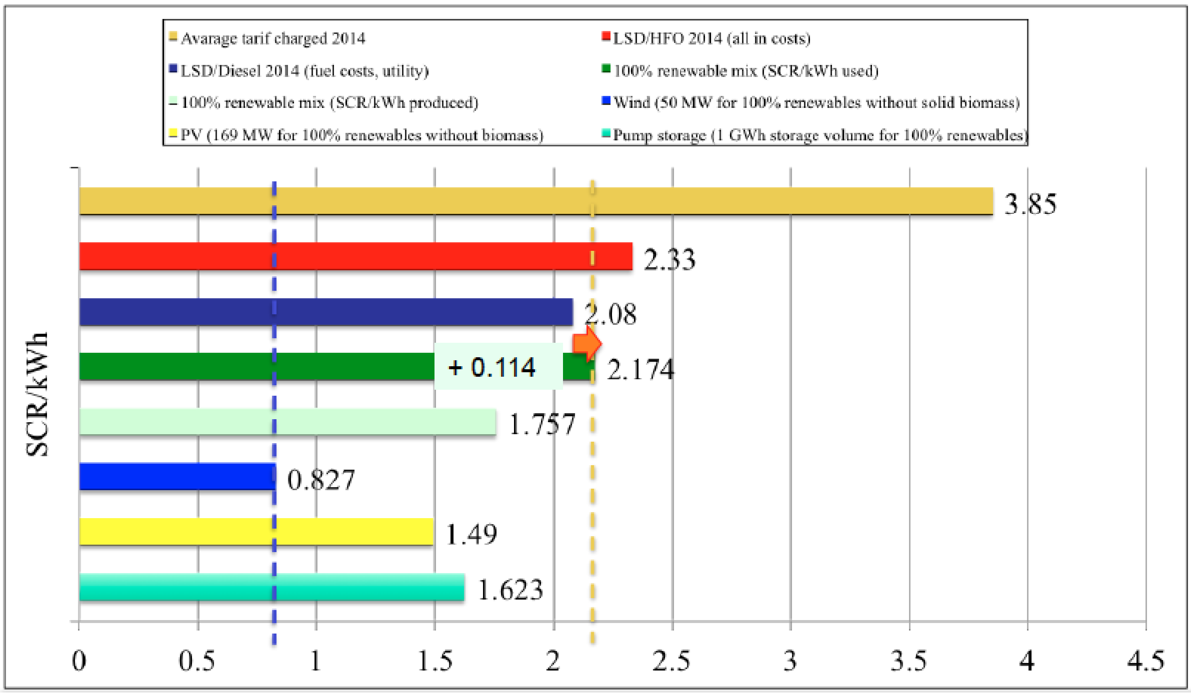
Figure 21: Basic configuration of Mahé's electricity system supplying the regular electricity demand plus the demand for electrical mobility 100% by renewable energy sources (Source: own calculations)



A very rough calculation extending the electricity demand by 81 GWh/a for the transportation sector can be covered by an increase of the solar PV generating capacity to 169 MW (+44 MW) while the wind power capacity can stay at 50 MW. This assumes an loading scheme adapted to the availability of solar power, using the six peak hours of solar radiation during the day for the necessary charging of about 220 MWh/d. With the pump storage system remaining at 1 GWh storage volume and the liquid biomass at 25 GWh/a, such system would lead to slightly lower electricity costs than in the case without electrical cars. The 100% RE based electricity production costs would be 2.174

SCR/kWh. Figure 21 shows the basic configuration of the electricity system to supply all the electricity demanded in the new e-mobility situation. Figure 22 shows the slightly changed cost situation and the cost reduction as compared to the present conventional electricity supply.

Figure 22: Costs of a 100% renewable power supply for Mahé including electrical mobility compared to present generation costs (2014) based on present prices for renewable energy technologies (Source: own calculations)



Although some exact figures on the gasoline and diesel consumption and imports for transportation are lacking, it may be concluded on the basis of this very preliminary analysis that another 400 million SCR/a in imports can be saved by switching to electrical mobility once Mahé is supplied 100% by renewable electricity. Table 5 summarizes the preliminary findings on the effects of shifting to electrical mobility under a 100% renewable power production.

As the expansion of the electricity production will need about 50 million SCR/a of equipment imports over an equipment lifetime of 20 years, this reduction in diesel and gasoline imports will lead to a net import reduction of about 350 million SCR/a and an additional boost to the Seychelles' economy.

Table 5: The economic results of the additional inclusion of e-mobility based on 100% renewable energy sources (Source: own calculations)

Costs and imports	
Mahé PUC electricity generation costs 2014 (all in costs) SCR/kWh	2.33
Mahé PUC Fuel cost 2014 only in SCR/kWh	2.08
100% renewable mix (SCR/kWh used)	2.174
Cost increase (renewable cost minus fossil fuel cost) in SCR/kWh	0.094
Electricity cost increase in % (of 'all in costs')	4%
Electricity cost increase per year in SCR/a	30 000 000
Fuel cost in SCR/100 km (renewable electricity at 2.5 SCR/kWh retail)	100
Conventional fuel costs (petrol) in SCR/100 km (at 7.5 l/100 km)	161
Fuel cost savings in SCR/100 km	61
Fuel cost savings in %	38%
Fuel cost reductions per year in SCR	219 000 000
Minimum Import reduction in SCR over 20 years	7 000 000 000

9. Conclusions and recommendations

From the first analysis conducted by the author it is clear that Mahé can switch to a 100% renewable electricity supply at hardly higher costs than the fuel cost for its conventional electricity production of 2014.

The switch to a 100% renewable electricity supply can lead to a net reduction of imports by as much as 570 million SCR/a through the substitution of the crude oil products used for electricity production today.

If Mahé would change to electrical mobility in its transport sector based on renewable electricity produced on Mahé then the import reductions could most likely be raised by an other 350 million SCR/a.

As a result of the transition to a 100% renewable electricity supply Mahé could massively reduce the drain of hard currency, boost its economy and boost its tax income substantially.

It seems to be highly recommendable to move to a 100% renewable electricity supply as soon as possible to realise the possible benefits for the economy and the citizens of Mahé.

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