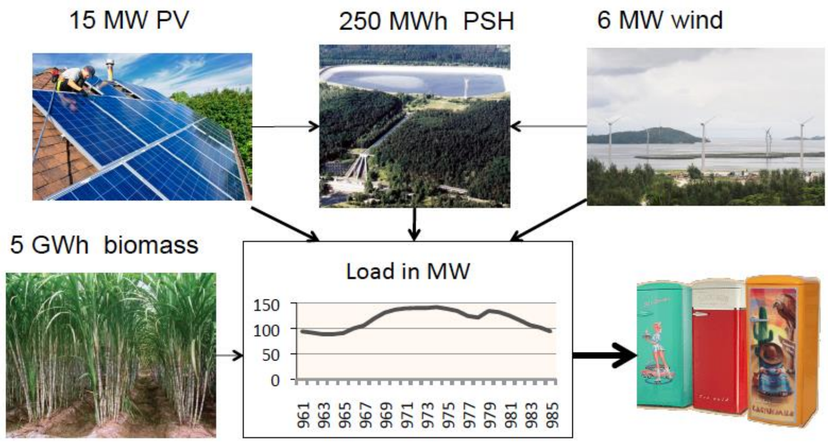
CENTER FOR SUSTAINABLE ENERGY SYSTEMS (CSES/ZNES)
System Integration Department

A 100% renewable Seychelles

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

Report 2: Praslin and La Digue



March 2017

Discussion Papers 9 (electronic)

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Flensburg, March 2017

Discussion Papers 9
ISSN: 2192-4589 (Electronic version)

0. Executive Summary

This report is based on some first simulation of the power systems of Praslin and La Digue based on the hourly demand data for 2015 reported by the PUC and internationally available wind and solar data (NASA 2016) reported for a coordinate close to Praslin and La Digue (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 90 million SCR/a in 2014 (PUC 2016, personal communication) for Praslin and La Digue 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 Praslin and La Digue

Based on an annual total electricity demand (including system losses) for Praslin and La Digue of 43 GWh and a scenario with 6 MW of installed wind power capacity, 15 MW of installed solar energy (PV) capacity, an assumed liquid biomass volume of 5 GWh/a equivalent to 1 000 t of biodiesel and a pump storage hydro plant with a storage volume of 250 MWh it can be shown that Praslin and La Digue 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 Praslin and La Digue.

A 100% renewable power supply will cost about 2.16 SCR/kWh, which is approximately 3% higher costs than Praslin's and La Digue's fuel costs for power production of 2.08 SCR/kWh in 2014. If the real transport cost of the fuel used for conventional power generation would be taken into account (at the moment this is not the case) the cost of a 100% renewable power supply would most likely be lower than the fuel costs of conventional production in 2014. These additional costs amount to about 3.3 million SCR per year. Nevertheless, compared to the average electricity rate for Praslin and La Digue charged to the customers of 3.66 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 Praslin's and La Digue's fuel imports for electricity production can be reduced by about 90 million SCR per year. At the same time renewable energy technology worth approximately 33 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 57 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 Praslin and La Digue can be increased by more than 15 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 57 million SRC/a will induce an additional tax income of 8.5 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 57.5 million SCR/a in fossil fuel imports and lead to net import savings of about 53.2 million SCR/a. Such development would boost Praslin's and La Digue's 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 Praslin and La Digue.

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. A short paper describing such a fund is supplied in the Annex to this paper.

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 Praslin and La Digue in order to establish a solid grid infrastructure as backbone of the future development of renewable power up to 100%
- Introduce automatic generation control (AGC) for the existing diesel generators to improve the response capacity to input fluctuations from increased shares of wind and solar power
- Use of the NAMA framework or similar mechanisms to secure up front financing for all preparatory measures
- 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 Praslin and La Digue from it
- Based on the wind atlas and GIS data on the islands produce a white are map for the possible sites of wind turbines as the basis for all future planning
- Extend the present analysis by more in depth studies of the costs of the different renewable energy options under the specific circumstances found in Praslin and La Digue 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
- Set up a facility for short term local wind speed and solar radiation forecasts to be integrated into the central system control facility to improve the foresight on short term fluctuations of wind and solar energy production
- Ensure that only high quality products are installed in order to have a well functioning and reliable power supply system
- Introduce quality control for solar and wind installations making comparing the actual production of the installations continuously to the performance promised by the company selling and installing the technology and make these data easily accessible by the general public
- Keep the existing power generation facilities as back-up as long as possible, as they complement the expansion of renewable power supply very well
- In case of new necessary new investments in diesel generators due to increase system load make sure that these are combined with flywheel devices to increase the ability for frequency regulation even when the engines are not running
- 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.
- Conduct a detailed analysis of the overproduction of the system at different development stages and the construction lead time of the pump storage plant to find the best timing for the phasing in of the pump storage plant
- Build up a specialised labour force for planning, construction operation and maintenance of the necessary technologies and their full scale system integration

- Develop a stipend system to allow bright young staff members to spend substantial time at the main facilities of the technology providers to build up a staff that has the capacity to run, maintain and expand the new facilities of the 100% renewable energy system
- 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. Praslin's and La Digue's present power supply

Unlike many other non-highly industrialised countries Praslin and La Digue 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 43.4 GWh/a including system losses (PUC 2016). With a maximum load in the range of 7.5 MW in 2015 (PUC 2016) the installed capacity of about 14.9 MW (PUC 2016) allows a considerable reserve margin for unscheduled downtimes due to equipment failure as well as downtimes for scheduled equipment maintenance. All 11 generation units are diesel generators with a wide age span (PUC 2016).

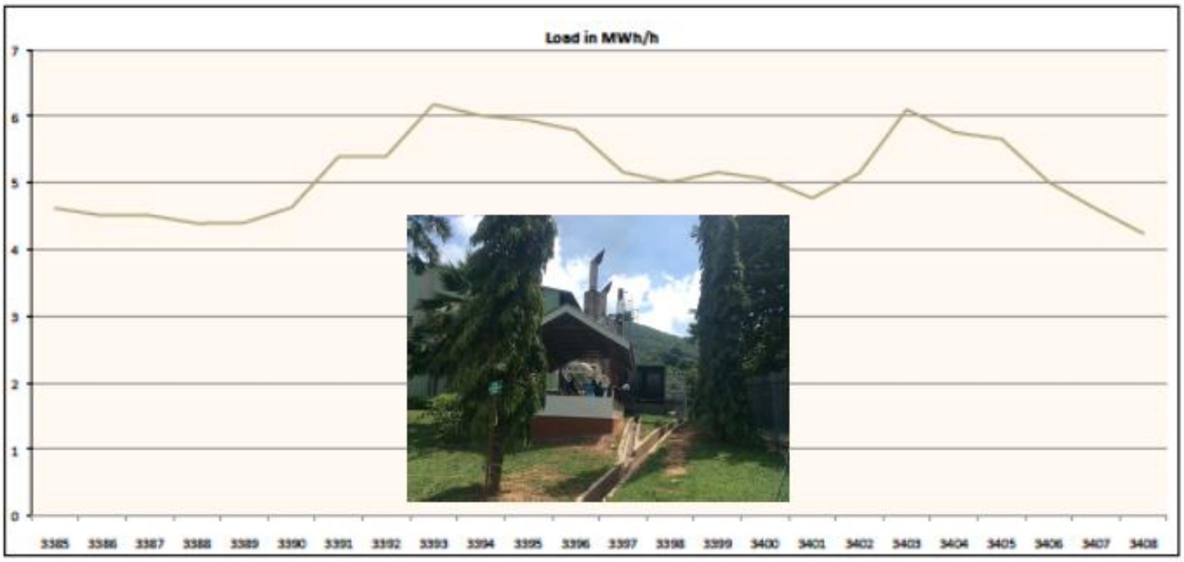
A major advantage of the power generation technologies presently used on Praslin and La Digue is the high degree of flexibility of all units. All units should need only a few minutes from start to full production. In contrast to this situation large base-load power plants, forming the backbone of many 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 that the large utility companies strongly objecting a faster build up of the renewable generation capacity.

Currently the flexibility of Praslin's and La Digue's power system is only needed to meet the change in the daily load (demand for electricity), which is 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, Praslin's and La Digue's power system is only exposed to fast or sudden load changes in the case of an equipment failure of large single units with a maximum size of 2.7 MW (see PUC 2016).

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 Praslin and La Digue load curve for a day in May (22nd) (Source: graph based on PUC 2016)



Unfortunately Praslin's and La Digue'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 Praslin and La Digue. 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, Praslin's and La Digue's power generation remains expensive and extremely vulnerable with regard to crude oil price changes.

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 the Seychelles use 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 fossil 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 Praslin and La Digue, 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 from the global MERRA 2 data set (NASA 2016) for the coordinate 4.5°S / 55.625°E have been used. As these NASA data sets calculated from satellite data have proven to overestimate real data they were multiplied with a factor of 0.8 to represent this bias.

Figure 2a shows the distribution of the wind energy output from an installed capacity of 6 MW based on the adjusted MERRA 2 data for the year 2010. This year was chosen, as records from Mahé airport available for 1978 to 2014 show that 2010 was a year with wind speeds very close to the long term average (101%). It is quite obvious from the graph that Praslin and La Digue display 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 2b 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 2a: Output from 6 MW installed wind capacity across a year based on the 2010 MERRA 2 wind data (80 m hub height, shear factor 0.2) (calculations based on SNMS 2016)

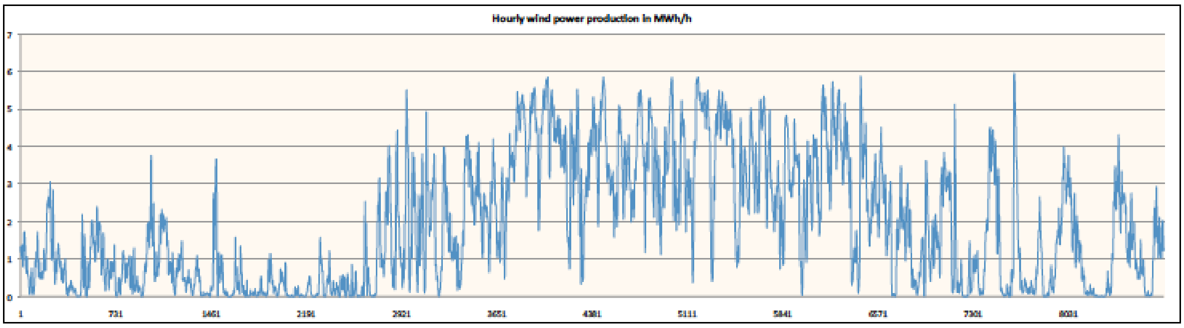
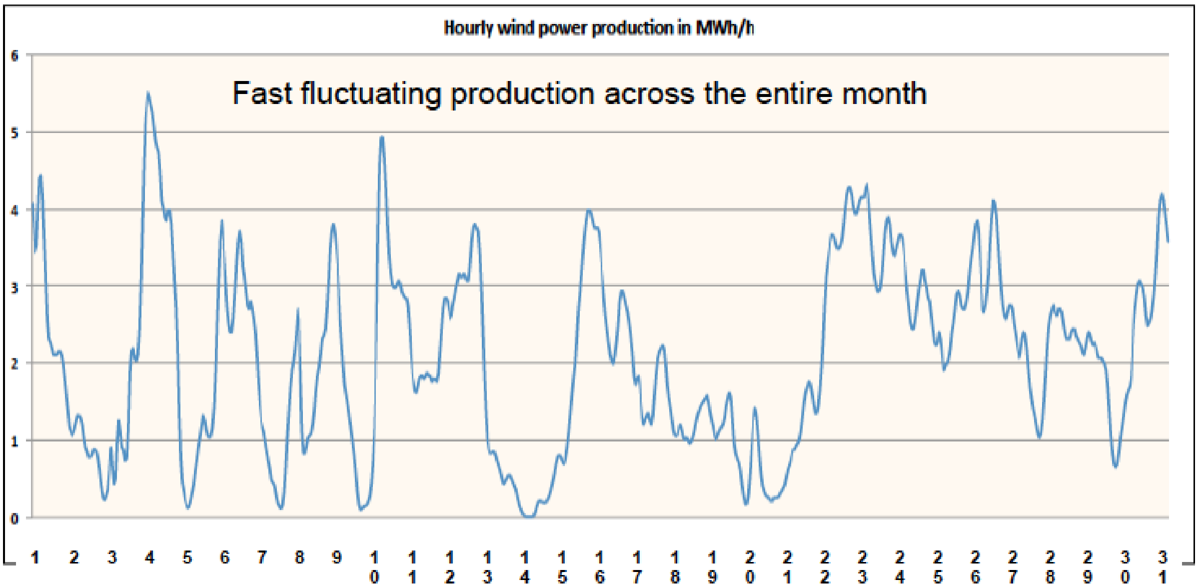


Figure 2b: Output from 6 MW installed wind capacity for the month of May based on the 2010 MERRA 2 wind data (80m hub height, shear factor 0.2) (calculations based on SNMS 2016)



The theoretical wind energy potential of Praslin and La Digue with a size of 47.7 km^2 is about 480 MW, if the entire area of the islands would be used. A first very rough estimate of the wind power capacity of Praslin and La Digue suggest a potential of well over 25 MW. Thus, the assumed 6 MW installation should not cause any problems for finding suitable sites for the necessary turbines (about 3 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.

Taking the downscaled hourly MEERRA 2 wind energy data 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 0.781 SCR/kWh or 0.05 €/kWh, which compares favourably to costal sites in northern Germany. The wind speeds taken lead to full load hour equivalents of about 2 750 h/a or a load factor of 0.31, 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 Praslin and La Digue internationally available MERRA 2 solar radiation data were 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 47.7 km^2, Praslin and La Digue have a theoretical potential of 610 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 15 MW would only require an area of roughly 0.12 km^2 or 0.25% of Praslin's and La Digue'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 3a 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 3a: Hourly output of solar energy for an entire year based upon an installed capacity of 15 MW on Praslin and La Digue (solar radiation data of 2010) (calculations based on NASA 2016)

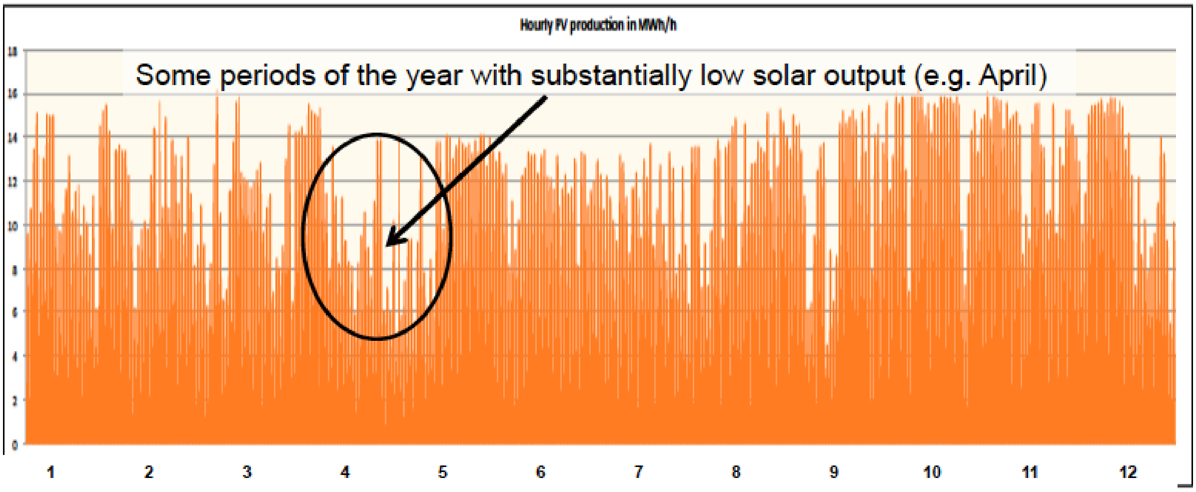
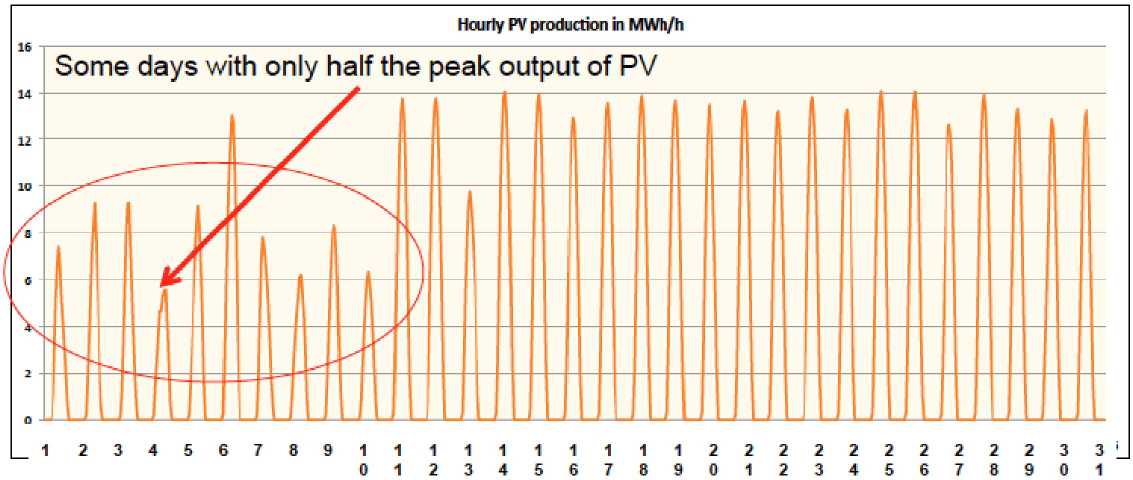


Figure 3b: Hourly output of solar energy for the month of May based upon an installed capacity of 15 MW on Praslin and La Digue (solar radiation data of 2010) (calculations based on NASA 2016)



Even though Praslin and La Digue are 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 3b) clearly shows. During some days the noon peak in output is reduced from about 14 MW on a bright day down to as little as 6 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 (15 MW) than wind energy (6 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 4 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 5 shows the load and the residual load for Praslin and La Digue employing wind and solar PV for May 22nd. We can see that the residual load can change by more than 3 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 (1.6 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 4: 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)

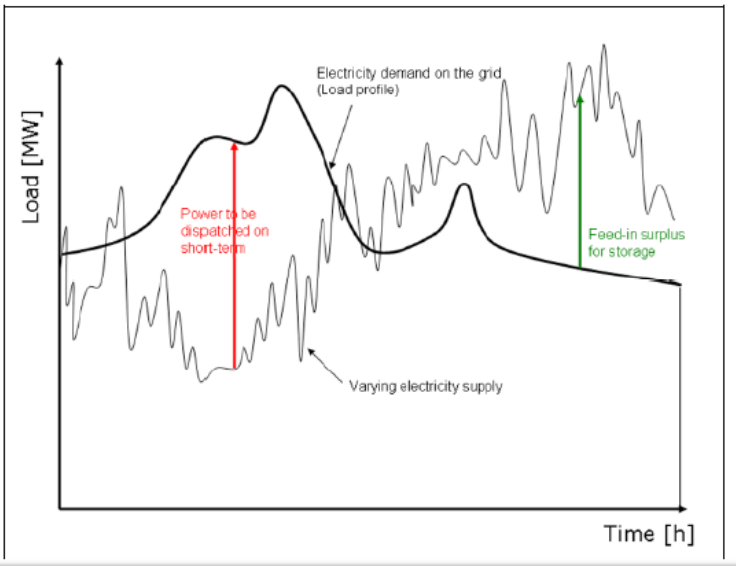


Figure 5: Load curve and residual load for Praslin and La Digue on May 22nd with 6 MW wind and 15 MW of PV installed (Source: own calculations)

Figure 5a: Load curve Praslin and La Digue May 22nd 2014 (source: graph based on PUC 2016)

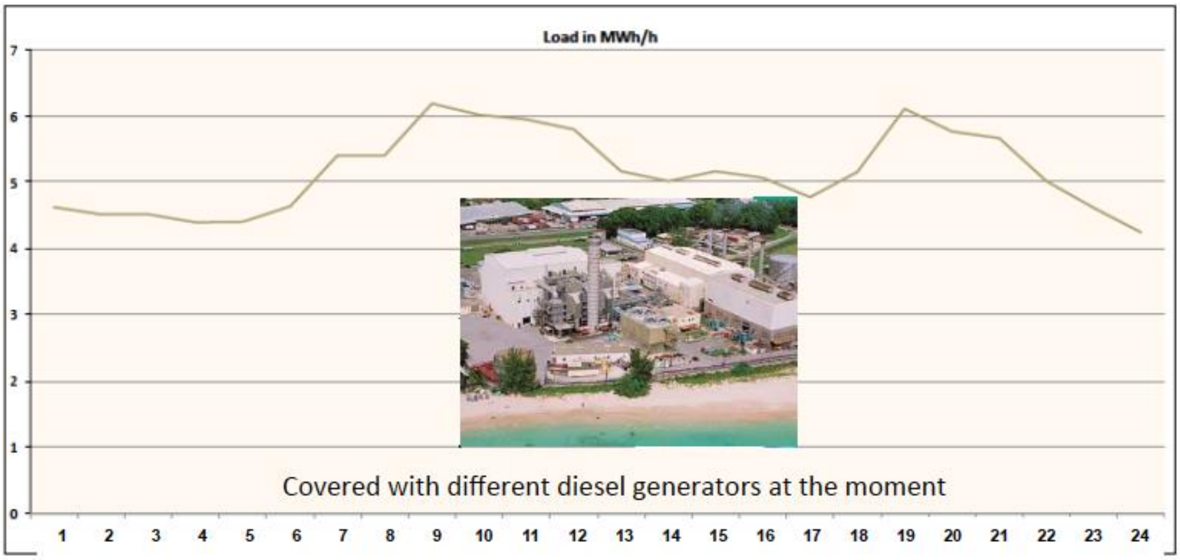


Figure 5b: Residual load curve Praslin and La Digue May 22nd 2014 with 100% RE power generation

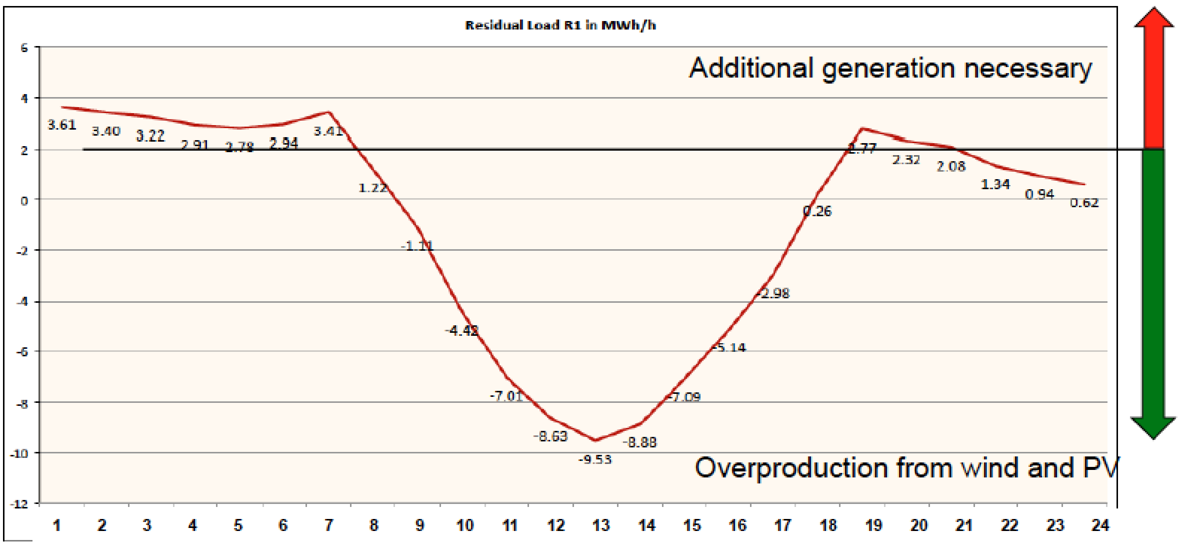
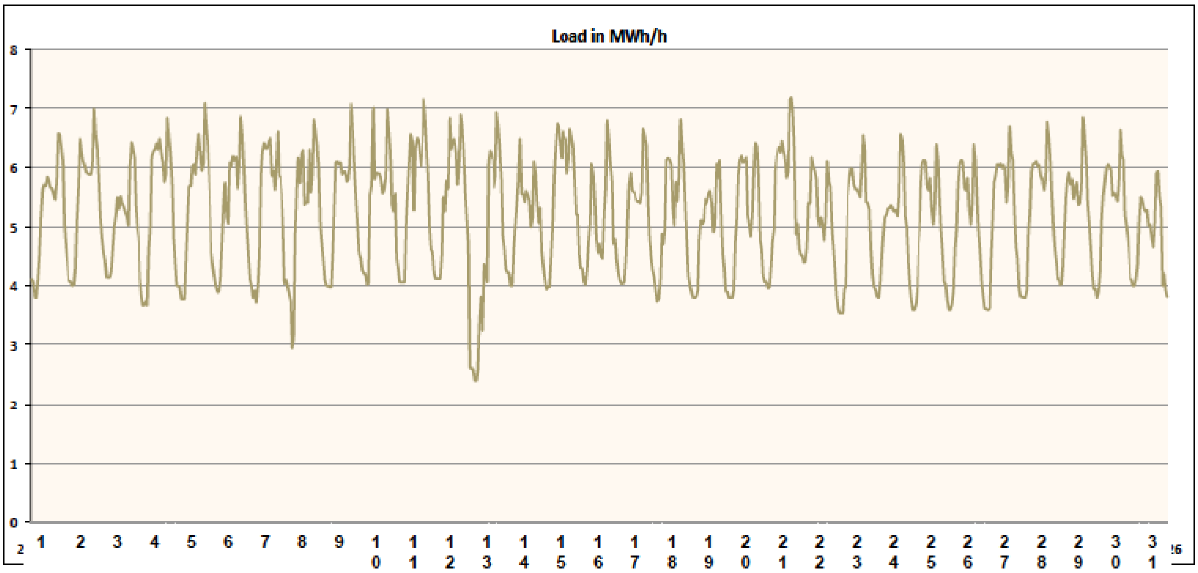


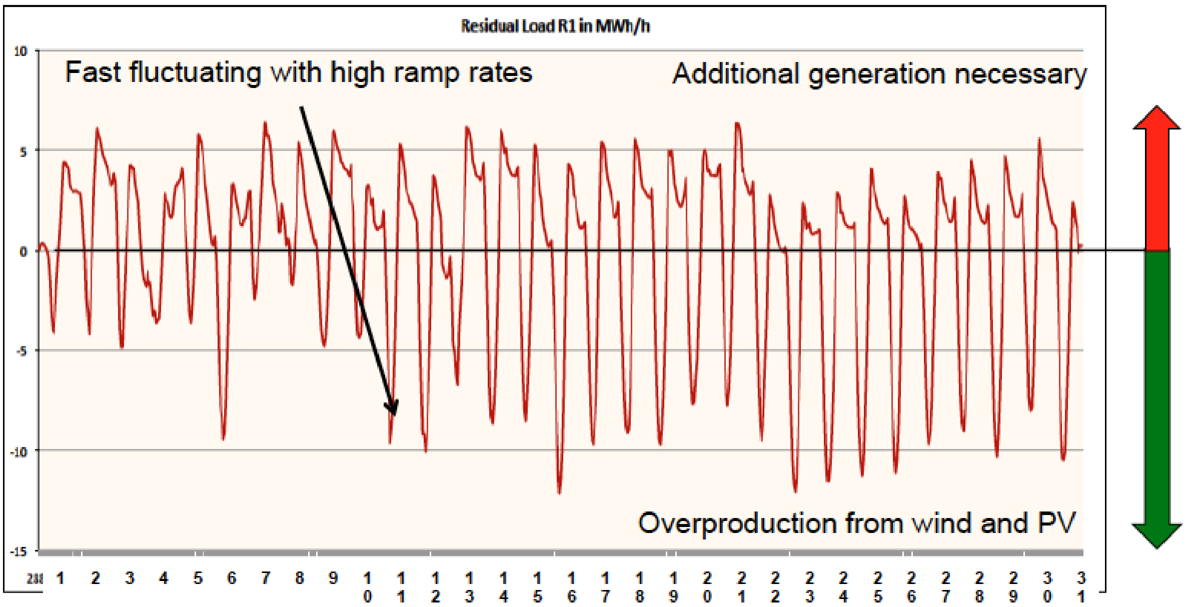
Figure 6a shows the daily and weekly pattern of the electrical load for the month of May, which needs to be met every hour of the month. Subtracting the wind and solar energy production of an installed capacity of 6 MW wind and 15 MW of solar energy leads to the fast fluctuating residual load shown in Figure 6b, which has to be covered by the controllable units of the system. The structure of the residual load suggests that Praslin and La Digue will need substantial storage to balance the residual load in the case of a 100% renewable energy supply.

Figure 6: Load curve for the month of May (7.a) and resulting residual load with 6 MW wind energy and 15 MW PV installed (7.b) covering an increased electricity demand and load

6.a Hourly load curve (Source: graph based on PUC 2016)



6.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 Praslin and La Digue and be converted into biodiesel. With the suggested configuration of the renewable power system an annual demand for about 1,000 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 Praslin and La Digue 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.

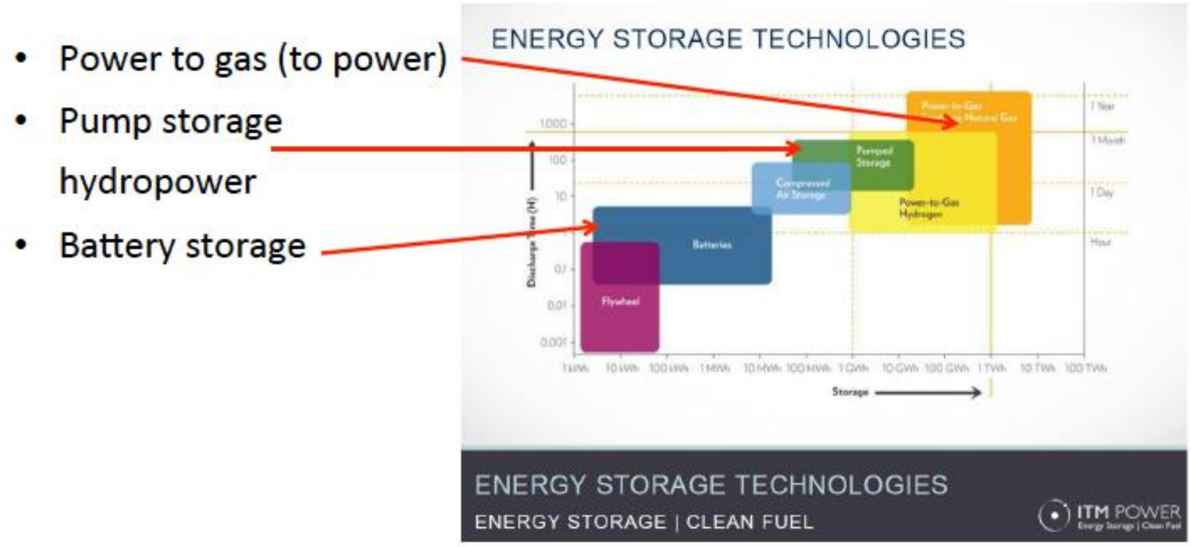
3.3 Storage

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 Praslin and La Digue the storage needs to have a generation capacity of about 7.43 MW, a pump capacity of about 15.6 MW to make the best use of the available overproduction and a storage volume of about 250 MWh. 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 7 shows, there are at least six different storage technologies that might be considered for use in Praslin's and La Digue'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 Praslin and La Digue starts at 0.05 GWh or 50,000 kWh. Thus, flywheel storage is far to small for this application.

Figure 7: 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 in the Seychelles 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). CAES is not an applicable storage option for Praslin and La Digue as these are practically solid granite islands, although it could supply storage in volumes of up to 250 MWh.

Thus, four storage technologies seem to remain for an application in the case of Praslin and La Digue, 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 250 MWh (250 000 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 8: Pros and cons of battery storage (Source: adapted from Hohmeyer 2015, Figure 9)

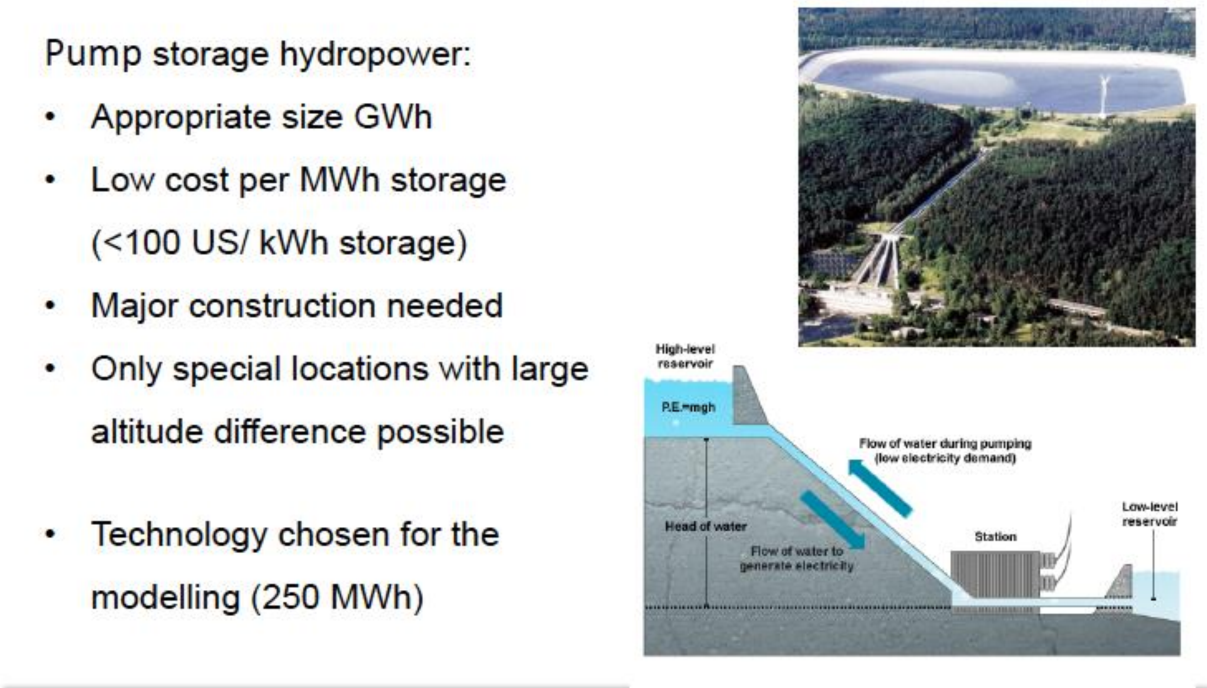
As battery storage can be bought 'off the shelf' in containers ready to be connected to a grid, it is very easy to install. It just takes the cabling and some foundations for the containers to set up this storage option. Figure 8 shows a picture of containerised battery storage and sums up the main pros 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$/kWh of storage volume. Thus, a storage volume of 250 GWh would cost about 125 million US$. At the same time batteries have a far shorter lifetime than pump hydro storage (discussed below), 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 9 shows a picture of the upper lake and the power plant of a pump storage hydro plant as well as 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 9: Pump storage hydro systems and their main advantages and disadvantages (Source: adapted from Hohmeyer 2015, Figure 10)



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 300 m the necessary storage volume of each lake to store 250 MWh (250,000 kWh) is about 317 500 m^3. At an average water depth of 20 meters each storage lake would measure approximately 126 by 126 meters. As Praslin has substantial suitable areas with an elevation around 300 m above sea level, the necessary storage volume can easily be estimated by multiplying each kWh of necessary energy storage by 1.25 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 7 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 Praslin and La Digue. 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.

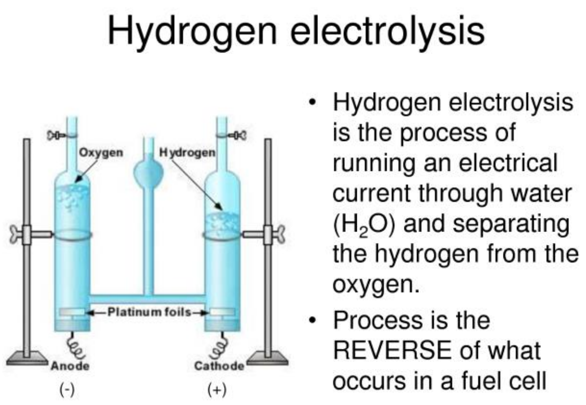
One of the historic reasons for including pump storage hydro systems in almost all major electricity supply systems is the ability to ramp a pump storage system from no operation to full load operation in about 90 seconds. Thus, such a system can change from full load operation for storage to full load 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 Praslin, this technology seems to offer the right size and technical properties for the storage needed for a 100% renewable electricity supply for Praslin and La Digue 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 10 shows the basic principle of the electrolysis process.

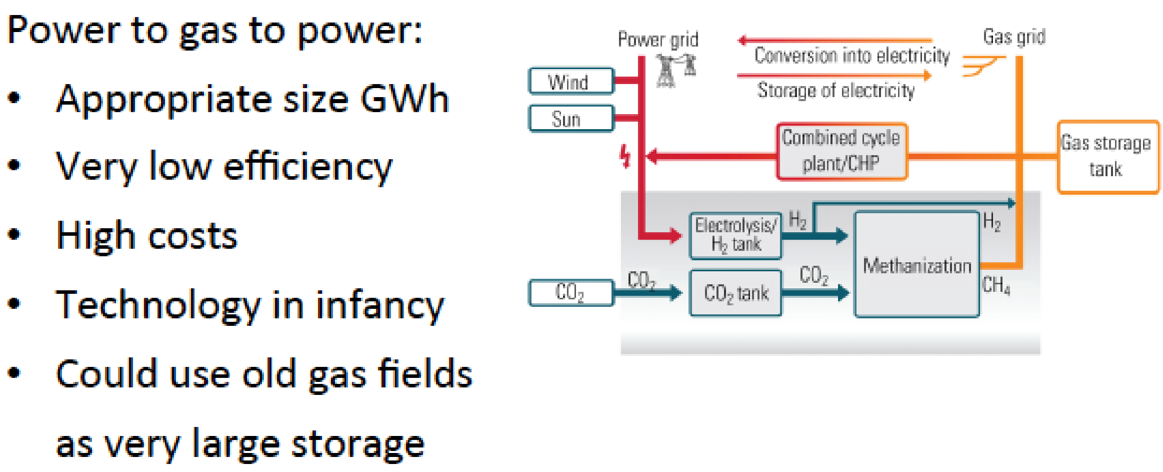
In the electrolysis process the two produced gases (oxygen and hydrogen) have to be separated, because a mixture of the two forms a highly explosive gas (detonating gas). The energy is stored in the form of the hydrogen produced. As soon as this is recombined with oxygen from the surrounding air, the 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 10: Electrolysis: splitting water with electricity (Source: imagekid.com 2015)



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 11 shows the principle of power-to-gas storage of electricity.

Figure 11: The principle of power-to-gas storage and its major advantages and disadvantages (Source: Hohmeyer 2015, Figure 12)



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 Praslin and La Digue 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 Praslin and La Digue 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 Praslin and La Digue

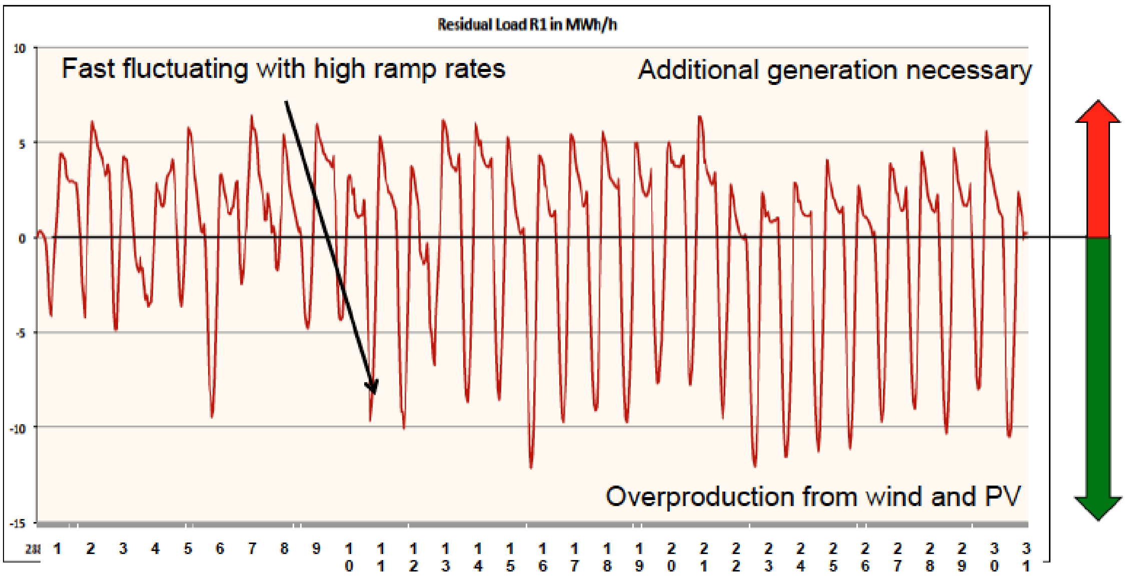
After the basic technology selection has been made we can analyse how Praslin's and La Digue's electricity demand can be met every hour of the year. For this purpose a simple simulation tool has been developed by the author and one of his colleagues (Sönke Bohm) at the University of Flensburg.

For the simulation an hourly load curve was derived from the available daily power production data for Praslin and La Digue supplied by the PUC for the year 2015 (PUC 2016). This hourly load curve is shown for the month of May in Figure 6a above. The data supplied by the PUC for Mahé, Praslin and La Digue 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 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 Praslin and La Digue and Praslin is the coordinate with the best representation for Praslin and La Digue.

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 12.

Figure 12: Calculated hourly residual load for Praslin and La Digue in May (load 2014, wind and solar data for 2010) (Source: own calculations)



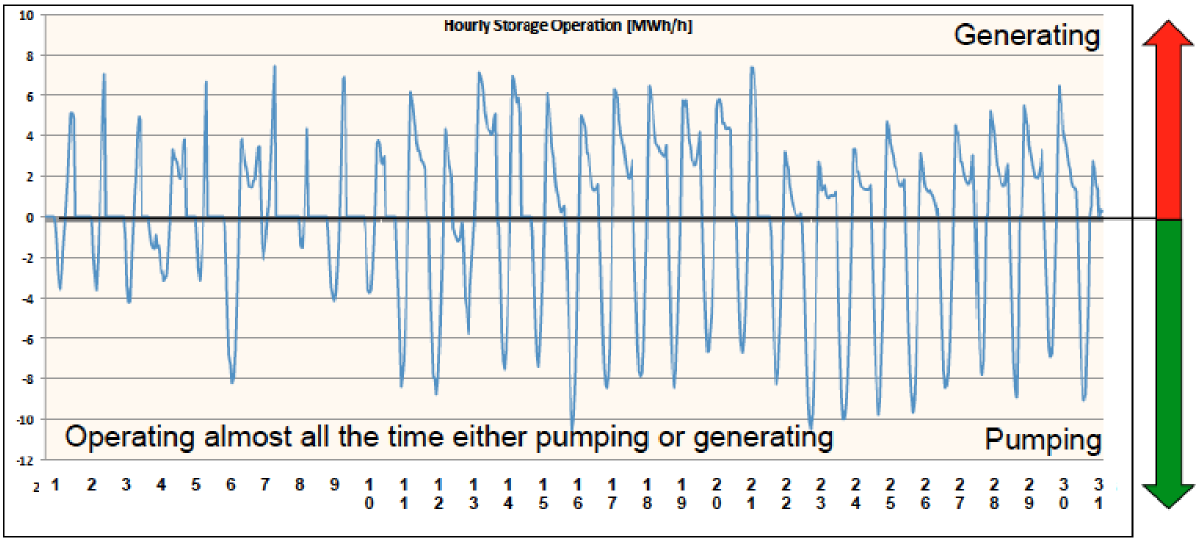
Whenever this residual load is positive we have demand not covered by the wind and solar power produced in this hour. This has to be met either by production from the storage or, if the storage is already emptied out, by electricity production from our liquid biomass in the form of biodiesel.

A detailed analysis of the data shows that the residual load is massively positive during the months February to April. 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 13 shows the resulting operation of the pump storage plant for the month of May. A storage volume of 250 GWh (250 000 kWh) was chosen, resulting in an electricity generation capacity of about 7.5 MW and a pumping capacity of 15.6 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 13: The simulated hourly operation of the pump storage plant during May (Source: own calculations)



The filling level of the storage displayed in Figure 14 touches the bottom during the time from May 1st to 22nd almost every day and the biodiesel back-up has to be used to fill in the gaps during the night time of the first 22 days of the month as shown in Figure 15. During the last days of the month the solar and wind conditions are sufficient to keep the storage from running dry. In the last days of the month the storage reaches its upper limit almost every day around noon time and Figure 16 shows the resulting 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 14: Filling level of the pump storage system in MWh during May (Source: own calculations)

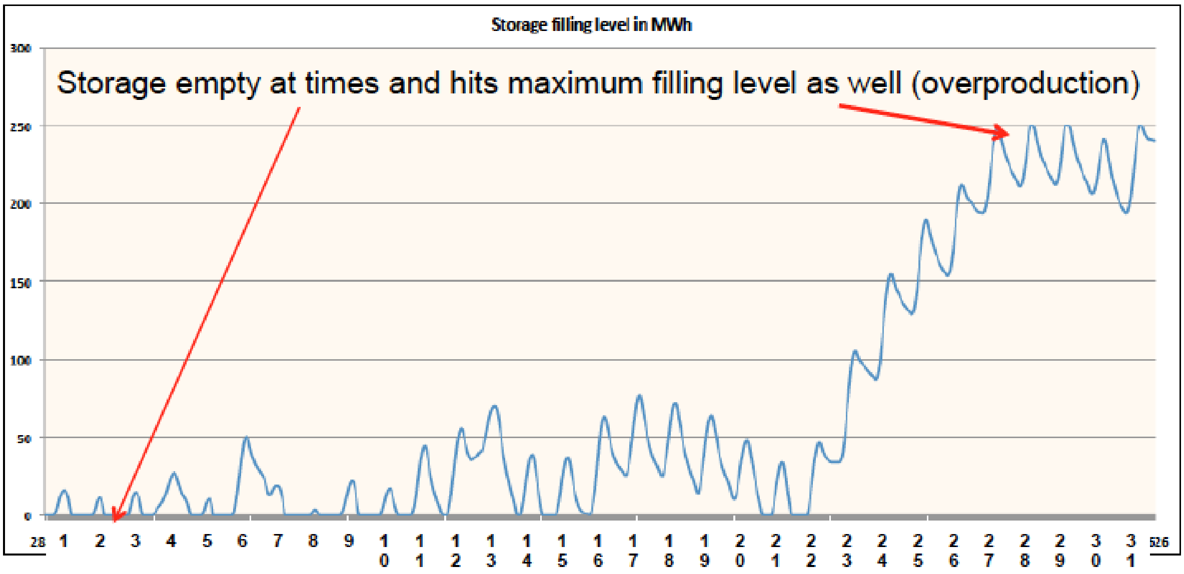


Figure 15: The use of biomass in March to meet the remaining the residual load after storage has been used (Source: own calculations)

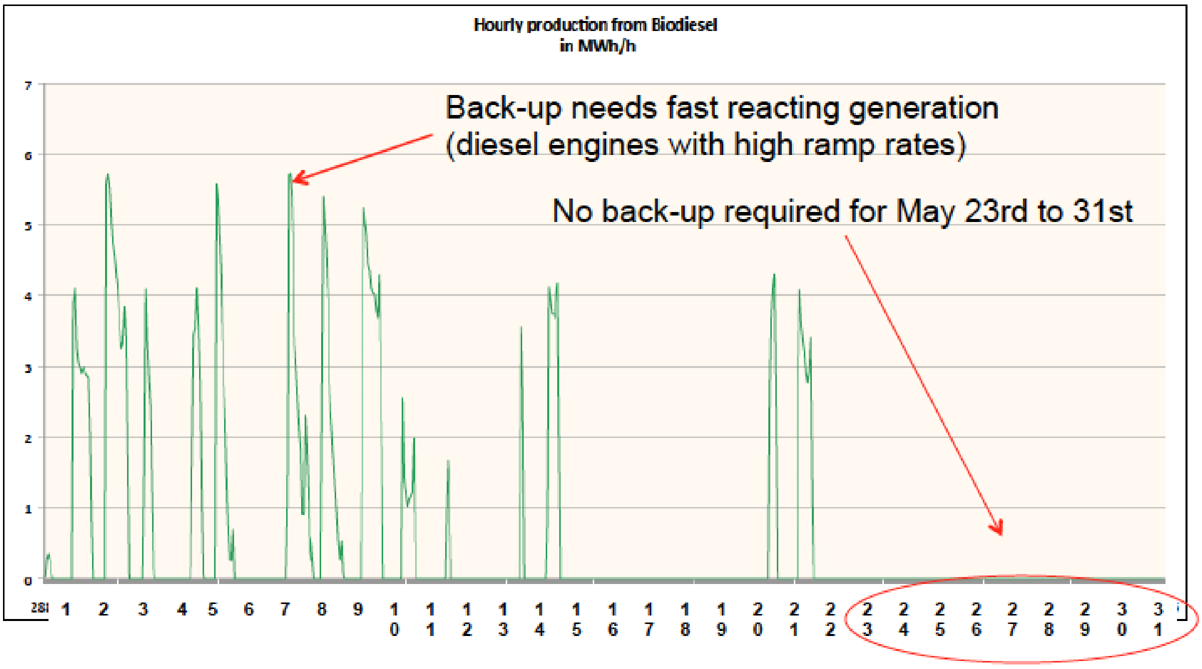
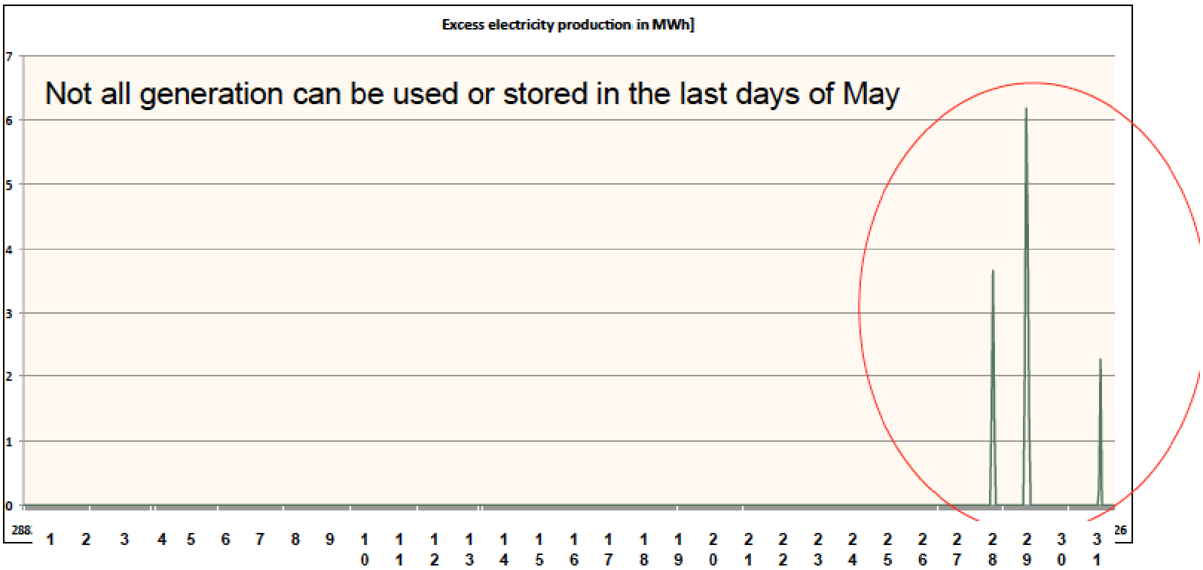
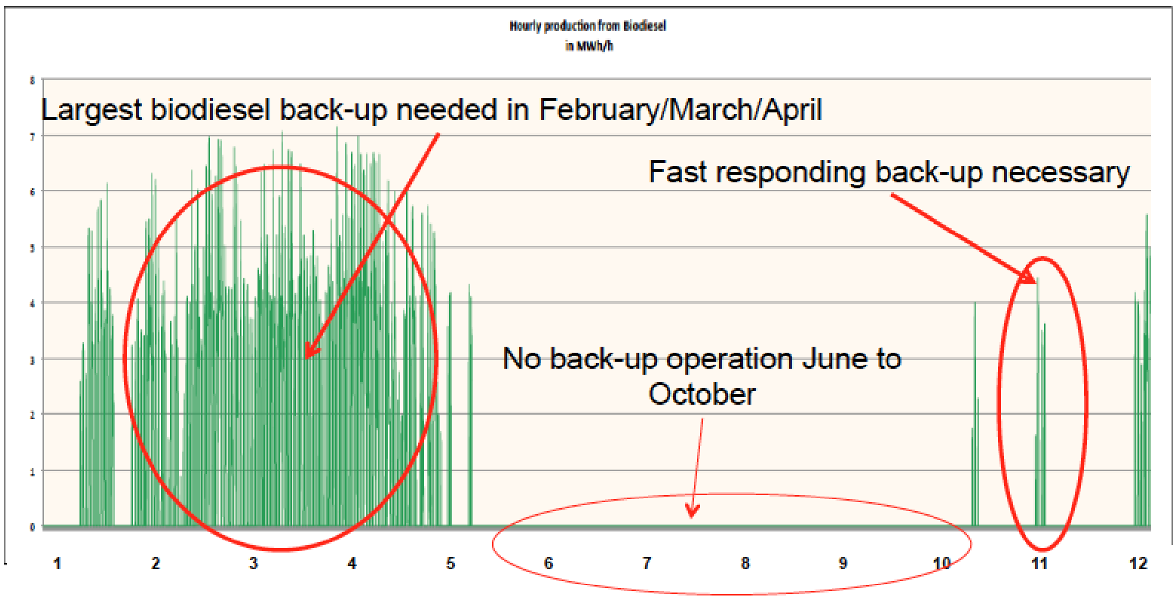


Figure 16: Overproduction of electricity from wind and solar energy in May in MWh/h (Source: own calculations)



The use of biomass is a very good indicator showing, when the system is at its limit. Figure 17 displays the necessary use of liquid biomass across the entire year. It shows that during the months 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 October, November and December.

Figure 17: The use of biomass during the entire year simulated (Source: own calculations)



5. A scenario for a 100% renewable power supply for Praslin and La Digue

Once the six major parts of Praslin's and La Digue'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), Praslin's and La Digue'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.

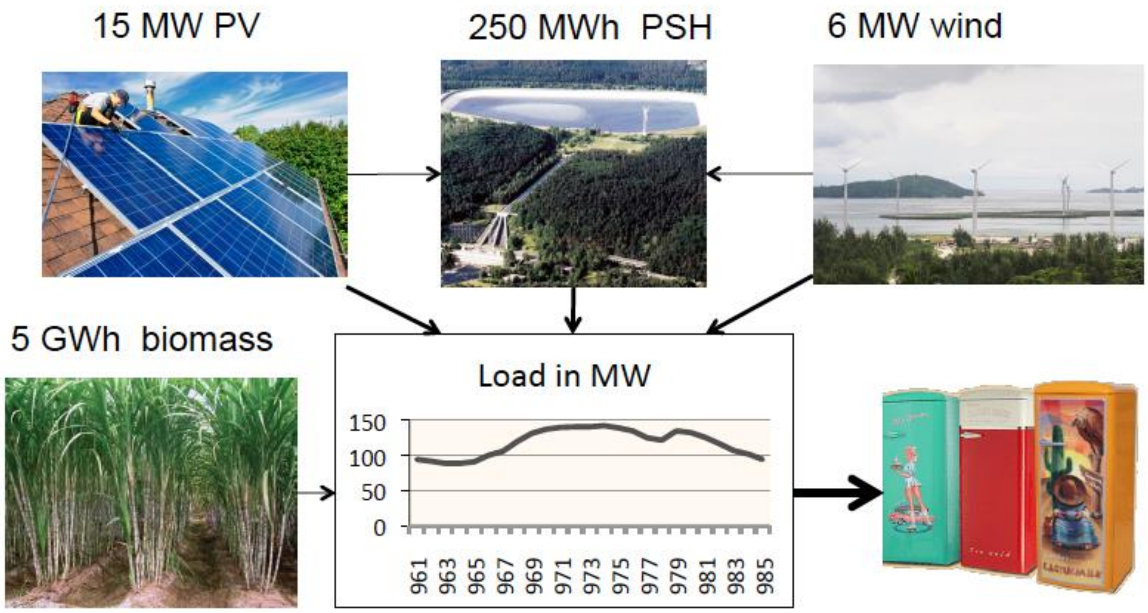
Table 2: Technical and economic assumptions made for the scenario presented in this report

Demand curve	- based on actual hourly operation data of PUC 2014	
Demand	- base year 2015	43.4 GWh/a
	- Peak demand	7.5 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	MERRA 2 (4.5°S / 55.625°E) *0.85
	- 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	300 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 5 GWh of liquid biomass (either imported or produced locally), the size of the storage was varied between0.1 GWh and 1 GWh. A variation of the wind and solar generation capacities under each of these combinations showed that a storage volume of 250 MWh leads to the lowest costs. In the most extreme cases only wind or only solar power were 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 (5 GWh of biomass and 250 MWh of storage capacity) at an installed solar capacity of 15 MW and an installed wind energy capacity of 6 MW. This system configuration is depicted in Figure 18. This configuration is based on the energy consumption and peak load of the year 2015.

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 7.5 MW of generation capacity and 15.6 MW of pump capacity in the minimum cost scenario.

Figure 18: 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 Praslin and La Digue entirely independent of future world market developments for crude oil products and at the same time reduce Praslin's and La Digue'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 2.16 SCR/kWh.

This figure can be compared to the **2014 fuel costs** of Seychelles PUC for the electricity generation in Praslin and La Digue, 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 0.08 SCR/kWh compared to the fuel costs of 2014. This is a cost increase of about 3% 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 19 summarises the costs of the 100% renewable electricity supply and shows the cost changes compared to the present electricity costs.

Figure 19: Costs of a 100% renewable power supply for Praslin and La Digue 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)

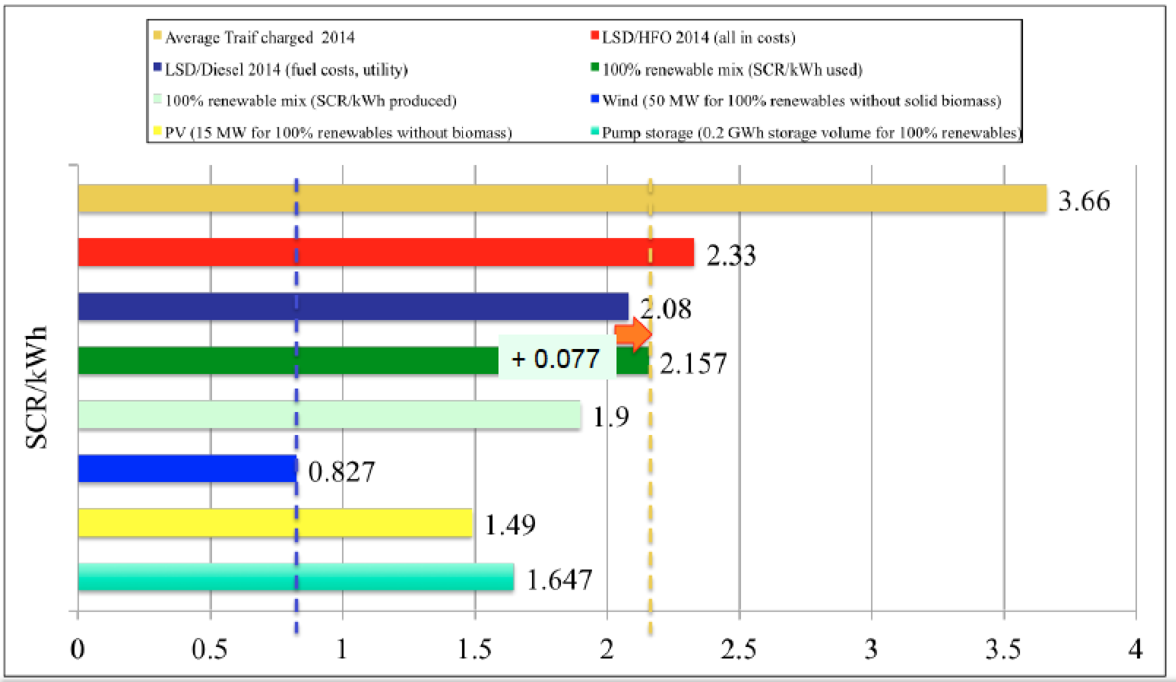


Table 3 summarises the economic results of the minimum cost scenario. It shows that the total electricity cost increase would have amounted to about 3.3 million SCR/a in 2014.

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

Costs and imports	
Praslin and La Digue PUC electricity generation costs 2014 (all in costs) SCR/kWh	**2.33**
Praslin and La Digue PUC Fuel cost 2014 only in SCR/kWh	**2.08**
Wind (6 MW for 100% renewables without biomass)	**0.781**
PV (15 MW for 100% renewables without biomass)	**1.49**
Biodiesel (5 GWh/a)	**3.0**
Pump storage (250 MWh storage volume)	**1.647**
100% renewable mix (SCR/kWh used)	**2.157**
Cost increase compared to 2014 (fuel cost minus renewable cost) in SCR/kWh	**+0.077**
Electricity cost increase in % (of 'all in costs')	**3.3%**
Electricity cost increase per year in SCR/a compared to 2014	**3 300 000**
Import reduction in SCR over 20 years (57 Mill. SCR/a)	**1 140 000 000**

6. Impacts on the economy and taxes

The proposed change of Praslin's and La Digue's electricity production to a 100% renewable electricity supply will have a substantial impact the Seychelles' economy. The electricity cost increase of about 3.3 million SCR/a is equal to a small decrease in national spending power of 0.017%, 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 90 million SCR/a (2014) (source PUC 2016) can be eliminated. At the same time **net imports**, taking into account necessary new imports of about 33 million SCR/a for technical equipment for the use of renewable energy, **can be reduced by about 57 million SCR/a, which is equal to a GDP increase by 0.29%**.

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 33 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 the Seychelles are 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 90 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 57 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 57 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 8.6 Million SCR/a. Assuming that the remaining income of (57 – 8.6 =) 48.4 will be spend in the Seychelles again and a VAT of 15% applies, this would lead to a second tax income of about 7.3 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 15 million SCR/a**.

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

Net import reductions?

• Diesel import reductions	-	90 Million SCR/a
• PV, wind, pump storage imports	+	33 Million SCR/a
• **Net import reduction per year**	**-**	**57 Million SCR/a**

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 57 million SCR/a and increase the governments tax income by more than 15 million SCR/a at the same time in the case of Praslin and La Digue.

In this situation the question arises, how the Seychelles in general and Praslin and La Digue as two of its main islands 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 fifteen years. To complete the task by 2035 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 Praslin and La Digue 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.

8. Switching to 100% renewables powered e-mobility

Once Praslin and La Digue 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 90 million SCR in 2014 the imports petrol for cars ('motorspirit') for Praslin amounted to 2 000 t/a (NBS 2015a, p22) or 2.68 million litres in 2014, if we assume that the number of cars on Praslin is about 10% of the joint fleet of Mahé and Praslin. Assuming an import price of about 15 SCR/l assumed for 2014 the fuel imports for the cars on Praslin are equivalent to about 57.5 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 Praslin and La Digue 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 Praslin and La Digue during the night time or in the company parking lot during the working day.

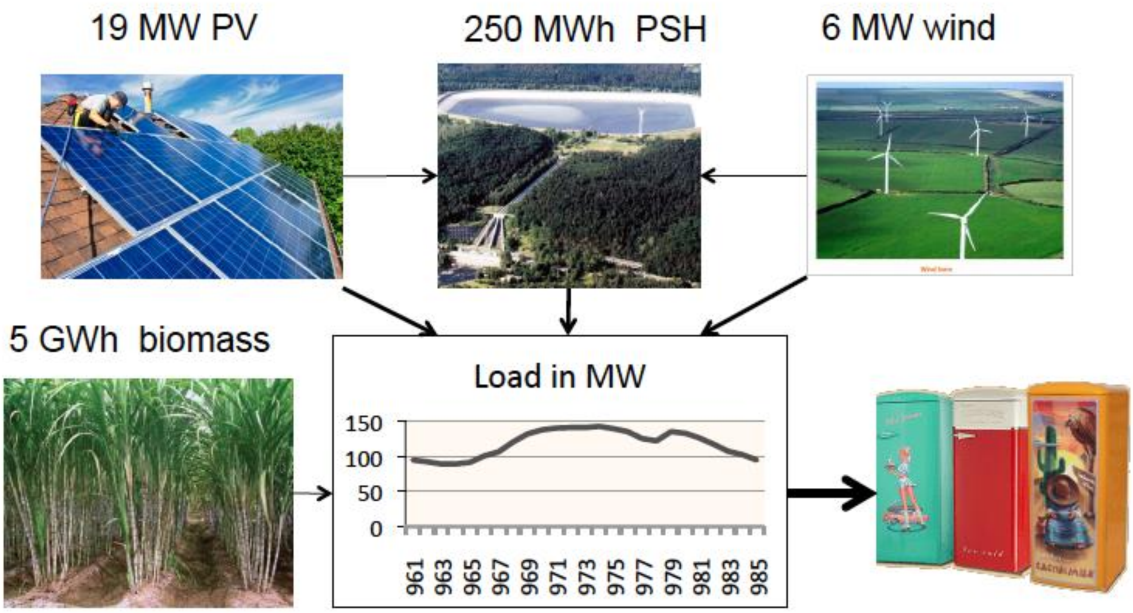
Although electrical cars are still more expensive than normal cars with combustion engines, it can be expected that this will change substantially during the next ten years, as electrical cars will most likely be cheaper in mass production than cars with combustion engines, gear boxes and mechanical 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 Praslin and La Digue 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.

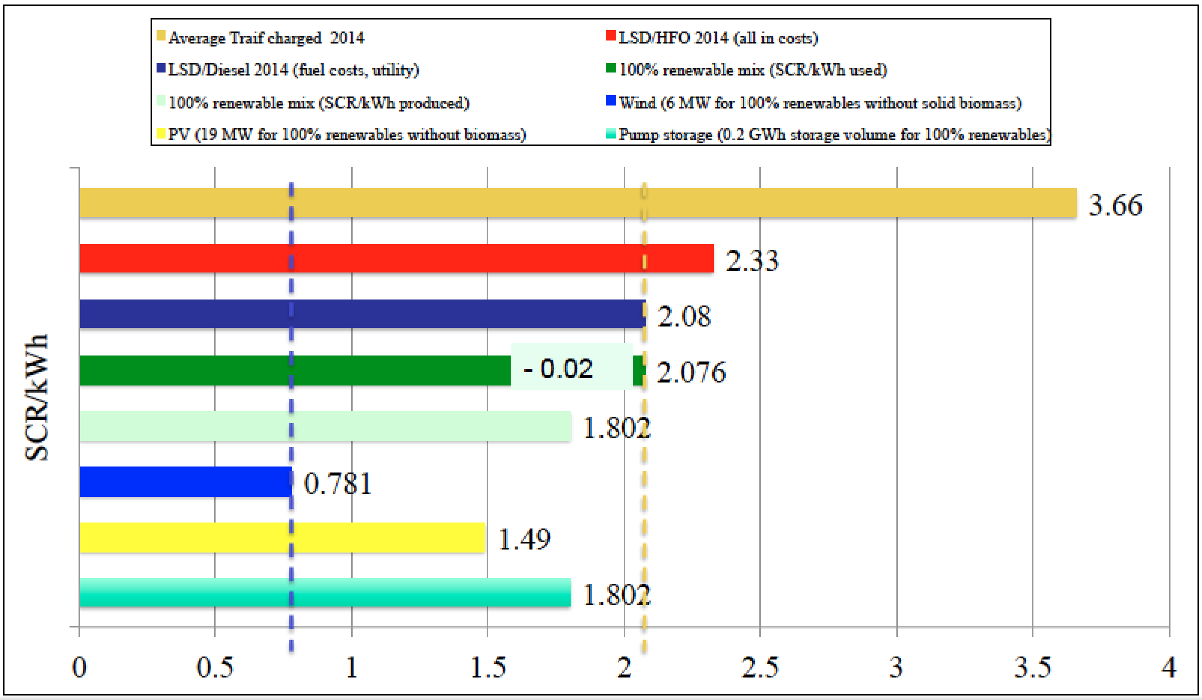
Figure 20: Basic configuration of Praslin's and La Digue's electricity system supplying the regular electricity demand plus the demand for electrical mobility 100% by renewable energy sources (Source: own calculations)



A very rough calculation extending the electricity demand by 8.1 GWh/a for the transportation sector can be covered by an increase of the solar PV generating capacity to 19 MW (+4 MW) while the wind power capacity can stay at 6 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

22 MWh/d. With the pump storage system remaining at 250 MWh storage volume and the liquid biomass at 5 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 2.076 SCR/kWh. Figure 20 shows the basic configuration of the electricity system to supply all the electricity demanded in the new e-mobility situation. Figure 21 shows the slightly changed cost situation and the cost reduction as compared to the present conventional electricity supply.

Figure 21: Costs of a 100% renewable power supply for Praslin and La Digue 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 57.5 million SCR/a in imports can be saved by switching to electrical mobility once Praslin and La Digue 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 4.3 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 53.2 million SCR/a and an additional positive impulse for 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)	**2.054**
Cost decrease (renewable cost minus fossil fuel cost) in SCR/kWh	**- 0.026**
Electricity cost decrease in % (of 'all in costs')	**- 1%**
Electricity cost decrease per year in SCR/a	**1 330 000**
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	**21 900 000**
Minimum Import reduction in SCR over 20 years (53.2 million SCR/a)	**1 064 000 000**

9. Conclusions and recommendations

From the first analysis conducted by the author it is clear that Praslin and La Digue 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 57 million SCR/a through the substitution of the crude oil products used for electricity production today.

If Praslin and La Digue would change to electrical mobility in its transport sector based on renewable electricity produced on Praslin and La Digue then the import reductions could most likely be raised by an other 53 million SCR/a.

As a result of the transition to a 100% renewable electricity supply Praslin and La Digue could reduce the drain of hard currency, boost the economy of Praslin and La Digue.

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 Praslin and La Digue.

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11. Annex 1: A guarantee funds for 100% renewable power

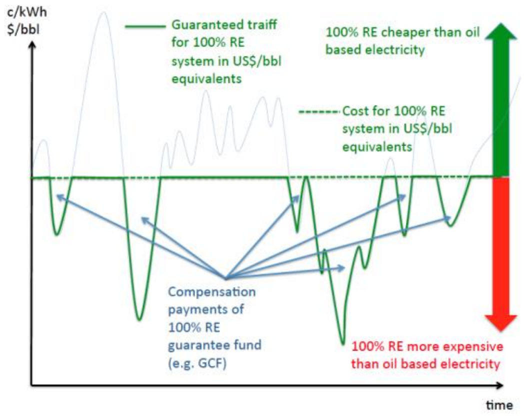
A renewable power price guarantee fund for SIDS and small developing countries underwriting strategies to achieve 100% renewable power supply by 2035 - A quantum leap in climate protection?

(Publication in preparation)

Keeping the anthropogenic global warming well below 2°C as recommended by COP 21 in the Paris Accord will require net zero global GHG emissions after 2050. This can only be achieved, if the world energy system will be completely decarbonized by 2050. The only sustainable option to achieve such an extremely ambitious target is the conversion of the global energy system to a 100% renewable energy supply. The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (2011) has shown that such conversion does not meet resource constraints.

A number of small island states are quite willing to move towards a 100% renewable energy supply, due to extremely high and fluctuating power costs resulting from their sole dependence on mineral oil products for their power production. Nevertheless, every policy targeting 100% renewable power supply soon, does meet with a high political risk. A 100% renewable power strategy will cap power cost at a certain level, in the case of Barbados this cost cap is equivalent to an oil price of around 60 US$, but in the instance of temporarily low oil prices it entails the political risk that a government pursuing such strategy will be accused by the opposition to have underwritten too high energy costs by opting for the climate friendly 100% renewable energy strategy. Thus, any government aware of this risk will not endorse a 100% renewable energy strategy, unless this political risk can be eliminated.

To eliminate this risk, which stops many governments of smaller and poorer states around the world from moving decisively towards a climate friendly 100% renewable energy supply, a guarantee fund is suggested, which finances the difference between the baseline conventional power price and the 100% renewable energy price whenever the oil price drops to a level, which results in a baseline price lower than the 100% renewable power price. The functioning of the fund is sketched in the graph to the right an explained in detail in the accompanying document.



It is suggested that COP 22 in Marrakesh adopts this proposal of a 100% renewable energy guarantee fund as one of the central mechanisms to combine global climate mitigation funding with the necessary fast track renewable energy development for the SIDS and other small developing countries around the world. It will enable more than 100 countries to immediately shift to a sustainable energy path achieving the COP 21 aim well ahead of time.

How does the guarantee fund function?

Presently small island states and many small developing countries depend either exclusively or predominantly on diesel or heavy fuel oil based power generation. This leads to the effect that these economies are extremely vulnerable towards the highly fluctuating and often very high costs of oil. Figure 1 shows the fluctuations of the world market oil price of the past years and the resulting fluctuations in the fuel costs of countries with oil based power production like Barbados, the Seychelles or Vanuatu. As the fuel costs constitute the vast share of the power costs (more than 80% in many cases) the electricity rates charged to consumers are fluctuating widely parallel to the oil price. What is more, in times of high oil prices this has led to a massive drain of hard currencies from these economies of up to 10% of the GDP for the imported mineral oil products.

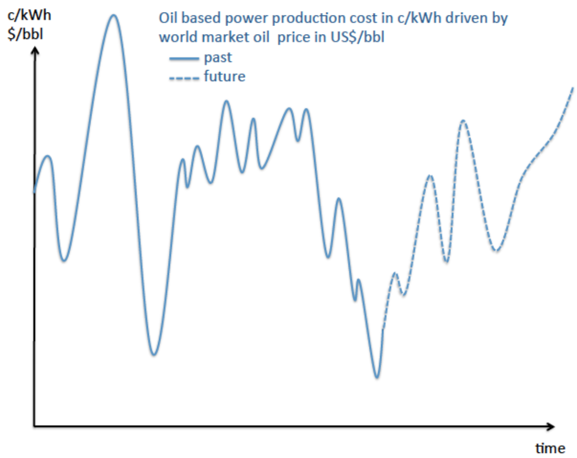


Figure 1: Development of the cost of oil based electricity in the last years

Converting the energy supply of a country to 100% renewable energy will lead to constant energy costs as in almost all cases (except in the case of biomass) the energy costs are only depending on the investment costs of the technologies and rather constant operation and maintenance costs as pictured in Figure 2 to the right. Thus, once the investment is made the production costs of energy are frozen. Nevertheless, there is a tendency of declining renewable energy production costs over time, as new investments are made at lower specific investment costs than in prior years. For the sake of simplicity the graph does not take this into account.

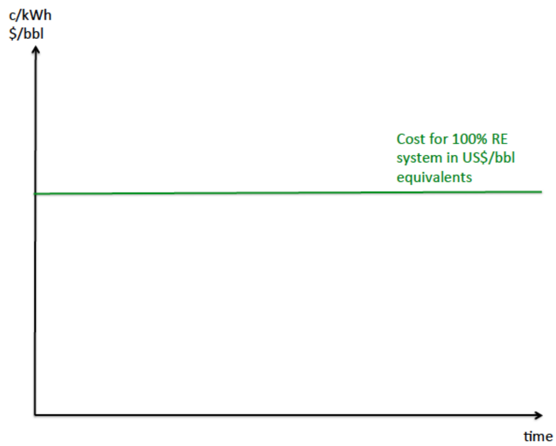


Figure 2: Cost of 100% renewables based electricity over time

Compared to the energy costs in a mineral oil based economy, the 100% renewable energy supply is able to cap the energy costs at a certain level as shown in Figure 3. But while it caps the costs from getting higher than a certain level (equivalent to a certain crude oil price), it also freezes the energy costs at this level, even when the oil based energy production would result in lower costs than the 100% renewable energy system. Although for reasons of climate change mitigation the only sustainable energy supply will be the 100% renewable system, there is the risk that policymakers, who are pursuing the environmentally sustainable energy strategy, will run into stiff resistance to such a strategy in times when the oil price is low and the conventional energy price would have been lower than the

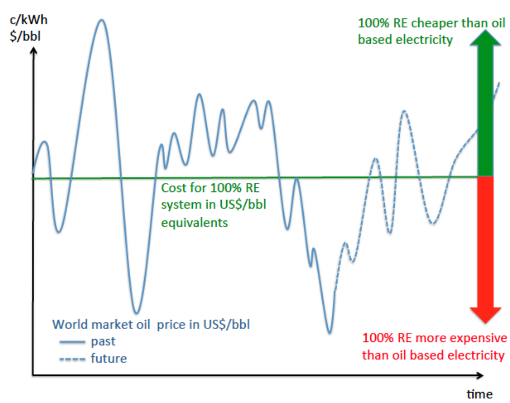


Figure 3: 100% renewable electricity as a cap compared to oil based electricity costs

frozen energy price based on the new 100% renewable energy system. The recognition of this political risk stops policy makers in many countries, which are quite willing to move towards a 100% renewable energy supply, even in times of high oil prices from moving decisively into the direction of climate protection and sustainable development.

It is suggested that this massive barrier to a large scale switch to the necessary climate friendly 100% renewable energy supply can be removed by the creation of an international climate fund guaranteeing that the energy prices in eligible countries decisively moving towards a 100% renewable energy supply (to be achieved by 2035) will never be higher than the conventional energy prices, which these countries would have faced without their transition to a 100% renewable energy supply as shown in Figure 4.

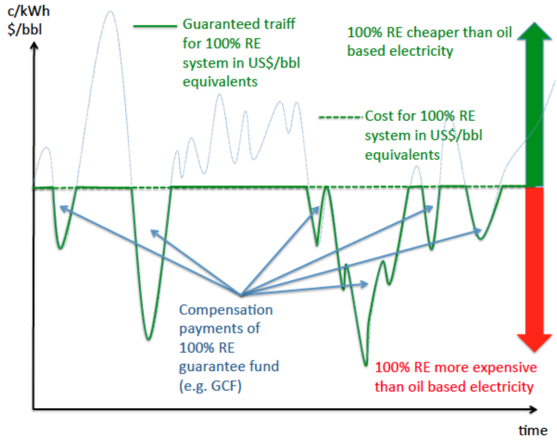


Figure 4: Compensation payments by the guarantee fund

Through the guarantee fund the political risk of moving into the right direction and adopting a sustainable energy supply strategy can be neutralized. Thus, many countries, which are still hesitant to go for a 100% renewable energy supply can move immediately towards a sustainable climate friendly system. The guarantee fund can jump start a broad movement of up to 100 countries around the world towards a 100% climate neutral energy supply system. Thus, the fund could catalyze the achievement of a major share of the targets of the Paris Accord. Combined with a similar development towards a 100% renewable energy supply in the industrialized countries of the North and the BRICS countries this could actually constitute a major building block of the future global climate protection strategy. As most of the countries eligible for the fund will strive for high economic growth rates until the middle of the century the mid and long term effect of the induced change in the energy technology development trajectories of these countries will be far bigger than the initial effect induced by the guarantee fund. What is more, massive volumes of stranded investment of these countries investing in fossil fuel based energy technologies without the guarantee fund can be avoided.

How can it be financed in principle?

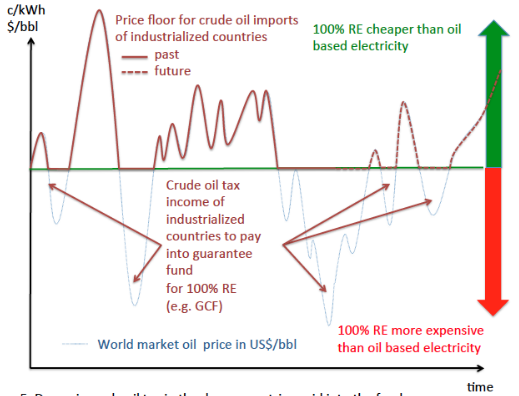


Figure 5: Dynamic crude oil tax in the donor countries paid into the fund

As pictured in Figure 4 the guarantee fund will only need to pay whenever the oil price is lower than the threshold price based on the 100% renewable energy supply of the eligible countries. The highest payments will be necessary in times when the oil price is exceptionally low. To create a financing mechanism which follows the same dynamics it is suggested that the industrialized countries responsible for financing the fund by their contributions introduce a dynamic import tax on mineral oil products as shown in Figure 5. Such a tax can create a national price floor for mineral oil products at a similar level as the renewable energy equivalent costs of the eligible countries receiving the guarantee payments from the fund. By this virtue the income from the import tax is the highest, when the world market oil price is exceptionally low and it will be zero, when the oil price is higher than the equivalent price of the 100% renewable energy systems of the eligible countries. Thus, the tax produces a dynamic income stream with exactly the same dynamics as the necessary guarantee payments to be made by the fund.

At the same time the minimum price for mineral oil products will lead to a situation in the donor countries where all energy efficiency measures and renewable energy based substitution efforts for mineral oil products can bank on a minimum cost of the substituted oil products. This will allow far better economics of energy efficiency and renewable energy technologies competing with mineral oil products in the donating countries.

How much will it cost?

Even if the suggested guarantee fund is accepted as a good idea for advancing climate protection in the global energy supply, the question remains, what the costs of such a fund will be and whether these costs can reasonably be covered by the donating countries?

If we assume that the donating countries follow the approach describe above setting a dynamic mineral oil import tax at the same level as the average mineral oil equivalent price cap of the eligible countries constituted by the average energy costs of their 100% renewable energy supply systems, the only question that remains is whether the volume of the oil taxed is equivalent to the volume of oil replaced in the eligible countries by renewable energy inducing the guarantee payments whenever the baseline oil based energy costs would be lower than the renewable energy based costs.

Obviously this volume depends on the definition of eligible countries on the one hand and the definition of donor countries on the other. A first back of the envelope calculation allows to compare the orders of magnitude on the basis of the 2014 oil consumption data of the world (BP 2015). It reveals that a maximum of 15% of the world oil consumption can be attributed to eligible countries, if the industrialized countries, Russia, China, India, Brazil, South Africa and the major oil producing countries are considered not to be eligible to the guarantee fund payments. These countries together had a share 84.8% of the world oil consumption. If only the industrialized countries would pay into the guarantee fund, they could raise the tax on 50.3% of the world oil consumption (if they would tax internal oil consumption likewise in accordance with WTO/GATT rules). Thus, setting the import tax to the same level as the payment threshold for the guarantee fund would result in more than three times the necessary volume for all the guarantee fund payments. Germany alone consumes more mineral oil as all small island states of the world. Thus, even a German guarantee fund financed by the dynamic import tax would have enough resources to guarantee a 100% renewable energy development in all 52 small island states.

The EU, with a share 13.5% of the world oil consumption, could most likely raise the necessary volume of taxes by the dynamic mineral oil import tax to fund the entire guarantee payments of the fund.

Taking these facts into account the costs of the fund do not seem to pose any major problem. Nevertheless, the political resistance of oil producing countries and the national car lobbies to finance the guarantee fund can be foreseen.

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Flensburg, March 2017

Discussion Papers 9

ISSN: 2192-4589 (electronic version)