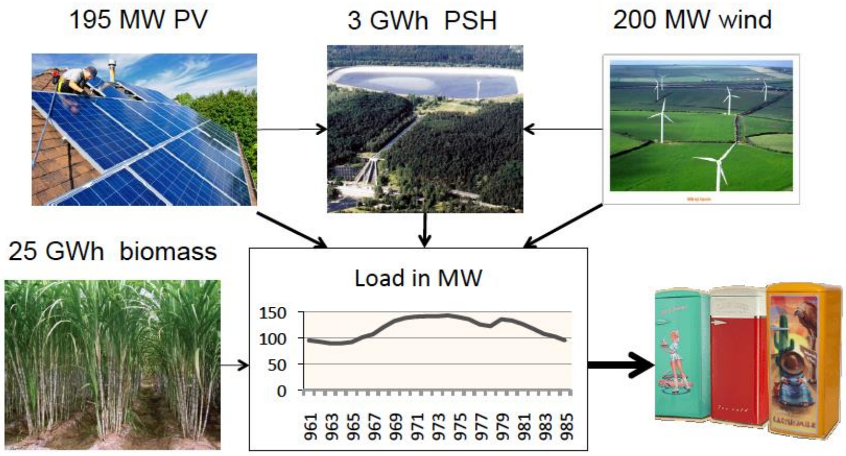
CENTER FOR SUSTAINABLE ENERGY SYSTEMS (CSES/ZNES)
System Integration Department

A 100% renewable Barbados and lower energy bills

A plan to change Barbados' power supply to 100% renewables and its possible benefits



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0. Executive Summary

This paper is based on the research done for the BREA Energy Lecture 'A 100% renewable Barbados and lower energy bills', held on November 10th 2014 at the Central Bank of Barbados in Bridgetown. As the interest in the subject by key players from the civil society and from government has proven to be quite substantial, and as the issue is of great importance for Barbados' 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 shortly based on more complete data for Barbados' specific situation. This will take into account local wind energy data, which was not available at the time of the BREA lecture.

0.1 The Problem

Although Barbados enjoys a very reliable high quality power supply it has experienced massive power price increases during recent years due to its sole reliance on crude oil products for electricity generation. Out of a total electricity production cost of 0.566 BBD/kWh (in 2013) fuel costs alone made up a share of 0.413 BBD/kWh (calculation based on: BLP 2014, p. 7 and 28). These high fuel costs have lead to extremely high electricity bills for private households and enterprises as well as to a massive drain of hard currency from Barbados' economy in the order of 377 million BBD/a in 2013 (BLP 2014, p. 28). Even if oil prices may drop from the high levels reached in 2013, the oil based power supply will remain a major economic burden on Barbados' economy and private households as well as a major risk to Barbados' future development.

At the same time it is obvious that Barbados, together with the other Caribbean countries, enjoys very favourable conditions for wind and solar energy production, two domestic energy resources, which are hardly used so far. Both being roughly twice as good as the conditions in Germany, the home country of the author, which had installed more than sixty thousand Megawatts of wind and solar energy systems by the end of 2013. With roughly twice the energy output from wind and solar energy systems compared to the German situation the cost of the produced electricity is cut in half, making for very attractive economic conditions for the production of renewable energy based electricity.

Confronted with this situation on his first visit to Barbados in November 2013 for teaching a course in Energy Economics at the University of the West Indies, the author started to analyse the situation of Barbados' power supply and its possible development 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.

0.2 Aim of the report

This report summarises the findings of the analysis that the author performed in preparation for his second stay on Barbados in order to make them available to policy makers and the general public of Barbados. It is anticipated to be a first input into the discussion on the future development of Barbados' power supply and the possible transition to an electricity supply on the basis of renewable energy sources, mainly wind and solar energy.

0.3 Results of the analysis

Based on a scenario with 200 MW of installed wind power capacity, 195 MW of installed solar energy (PV) capacity, an available biomass volume of 35 GWh/a and a pump storage hydro plant with a storage volume of 3 GWh it can be shown that Barbados can easily be supplied with electricity from renewable energy sources every hour of the year. Thus, a 100% renewable power supply could be technically feasible for Barbados.

Compared to present electricity costs, a completely renewable power supply can save ~30% of Barbados' electricity bill at present technology prices for renewable energy. These savings amount to about 175 million BBD per year, if only the saved fuel costs are taken into account.

At the same time Barbados' fuel imports for electricity production can be reduced by about 375 million BBD per year. As energy technology worth approximately 75 million BBD/a would need to be imported, as averaged over the twenty year lifetime of the equipment, the average net import reduction amounts to about 300 million BBD/a.

As the import reduction stops the drain of hard currency from the country and at the same time increases the spending power of Barbadian citizens, the change of the energy system creates a triple boost to the economy. Imports are reduced, spending for energy produced locally is increased and the energy bill is substantially lowered leaving more money to be spent in Barbados for other goods and services produced locally.

In addition the tax income of Barbados can be increased by at least 100 million BBD/a, as more money stays on the island and is kept in the economic cycle of production, earnings and spending.

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 years.

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 250 to 300 million BBD/a in fossil fuel imports and lead to net import savings of 200 to 250 million BBD/a. Such development would boost Barbados' 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 Barbados to draw on substantial international climate funds to finance the upfront costs for the preparation of the transition to 100% renewable power supply for Barbados.

0.4 Recommendations

It is strongly 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.

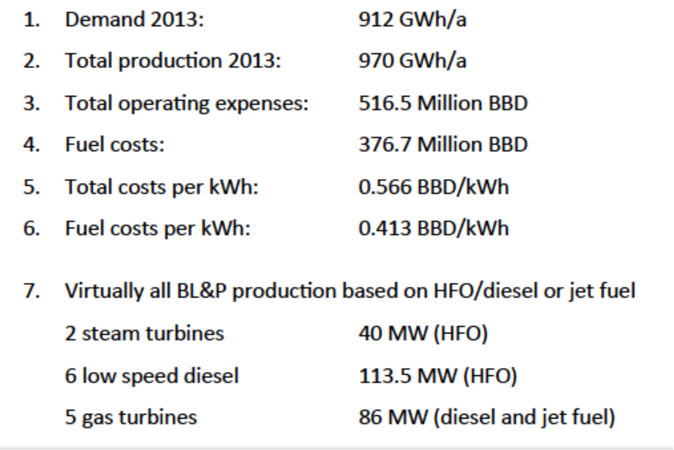
In order to allow such development, a number of (preparatory) steps/considerations need to be taken:

- Use of the NAMA framework to secure up front financing for all preparatory measures
- 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 natural preservation
- Conduct a detailed assessment of the hourly wind speeds on the island at heights between 10 and 150 m in the prime locations for onshore wind power (about five measuring masts)
- Extend the present analysis by more in depth studies of the costs of the different renewable energy options under the specific circumstances found in Barbados
- Perform a thorough site and underground assessment for the location of the pump storage plant(s)
- Conduct a more in depth analysis of possible 100% renewable power supply scenarios
- Set up a policy and regulatory framework 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 Barbados economy
- Use a pricing policy for wind and solar power that enables a broad local participation in the investment in order to generate additional income for as many Barbadian 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)
- 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
- 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.
- Secure experienced independent scientific and technical advise for the entire process in order to be independent of the information from the power and oil companies, which might have vested interests not always coinciding with the long term interest of Barbados.

1. Barbados' present power supply

Unlike many other non-highly industrialised countries Barbados enjoys the service of a very reliable electricity system, which services practically every citizen and has very few downtimes. The total annual electricity demand is in the range of 900 GWh/a (see Table 1). With a maximum load in the range of 170 MW the installed capacity is at about 240 MW allowing a considerable reserve margin for unscheduled downtimes due to equipment failure as well as downtimes for scheduled equipment maintenance. As shown in Table 1 the production units are all based on mineral oil products in the form of heavy fuel oil (HFO), diesel or kerosene (jet fuel).

Table 1: Barbados' electricity production and demand, total cost of power generation, the share of fuel costs in 2013 and composition of production units (source BLP 2014)



1.	Demand 2013:	912 GWh/a
2.	Total production 2013:	970 GWh/a
3.	Total operating expenses:	516.5 Million BBD
4.	Fuel costs:	376.7 Million BBD
5.	Total costs per kWh:	0.566 BBD/kWh
6.	Fuel costs per kWh:	0.413 BBD/kWh
7.	Virtually all BL&P production based on HFO/diesel or jet fuel	
	2 steam turbines	40 MW (HFO)
	6 low speed diesel	113.5 MW (HFO)
	5 gas turbines	86 MW (diesel and jet fuel)

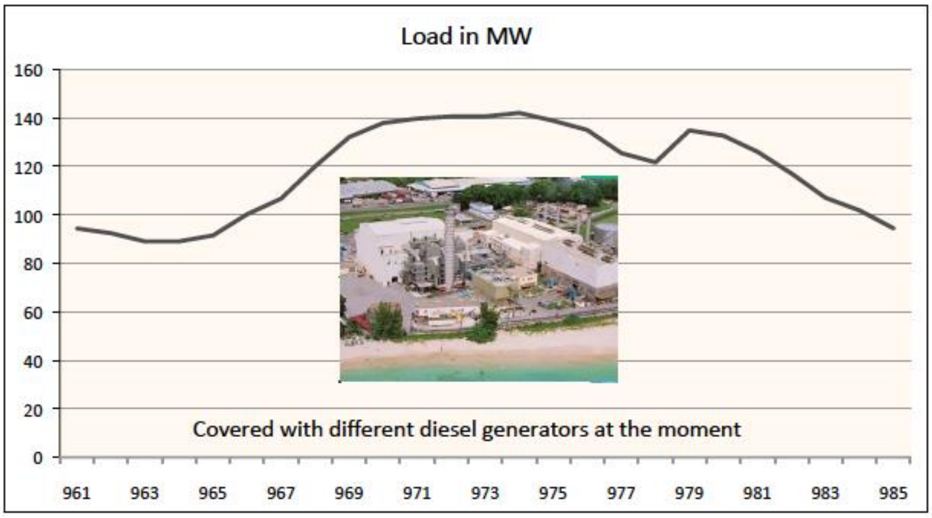
The major advantage of the power generation technologies used on Barbados is the high degree of flexibility of most units. With the exception of the two steam turbines all other units should need only a few minutes from start to full production. Large base-load power plants, forming the backbone of many national power systems, 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.

Currently the flexibility of Barbados' 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, the Barbados power system is only exposed to fast or sudden load changes in the case of equipment failure.

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 Barbados load curve for a day in February (synthetic load curve based on data from BLP as output from the model simulations performed for the analysis) (Source: Hohmeyer 2014, slide 5)



Unfortunately Barbados'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 Barbados. This has lead to the situation that the fuel costs per kilowatt-hour (kWh) made up almost 75% of the total power generation costs in 2013. Although crude oil prices are declining at the moment, Barbados power generation remains extremely expensive and vulnerable with regard to crude oil price changes.

The volume of the present fuel import for electricity production has withdrawn approximately 5% of the national income (gross domestic product) per year creating a major burden on the economy. What is more, together with the imports of transport fuels about 10% of the national income has to be used every year to pay Barbados' fuel bill with hard currency. This poses a major threat to the economic development and stability of Barbados. Thus, the present electricity system, although supplying power very reliably, cannot be sustained in the long run without jeopardising Barbados' future economic development.

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

To the visiting energy expert Barbados displays a stunning picture. On the one side it uses a very 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 extremely good wind and solar resources. Thus, it is very likely that a major part of the expensive present electricity production can be replaced by the less expensive use of domestic renewable energy resources.

To analyse the possible contribution of renewable energy sources to Barbados' 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 Barbados, 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 for the presentation forming the basis of this paper the author had to use internationally available hourly wind speed data. From international databases a set of hourly wind speeds was available for the island of Dominica (about 300 km west of Barbados), which was used as a first proxy. Later comparisons with the wind speed data for Barbados' Grantley Adams International Airport showed that the use of this data set led to a substantial underestimation of the actual wind speeds found on Barbados resulting in slightly higher wind energy costs than Barbados data would suggest.

The size of Barbados is roughly 430 km^2. If we assume that with present technology it is possible to place about 10 MW of wind turbines on 1 km^2 of land, the size of the island is equal to a theoretical potential of roughly 4,300 MW onshore wind energy capacity. By subtracting all other competing uses from the total land area and by including minimum distances to the nearest dwelling, this potential is most likely reduced to a technical potential of 5 to 10% of the total land area of Barbados - depending on the assumed minimum distance to dwellings. This technical potential would then need to be translated into an economic potential of wind energy, which in the case of Barbados would most likely be limited by the demand, as the costs of wind energy appear to be very competitive. The economic potential would then be limited by factors such as the acceptance of wind energy deployment by citizens living close to the turbines or wind parks – leading to the potential that can actually be realised.

As it was not possible to break down the theoretical potential any further, the above analysis had to serve as a rough guide to the orders of magnitude of wind energy capacity that might possibly be deployed on Barbados. An assessment of the technical wind energy potential will require a detailed analysis of the exact land use patterns on Barbados.

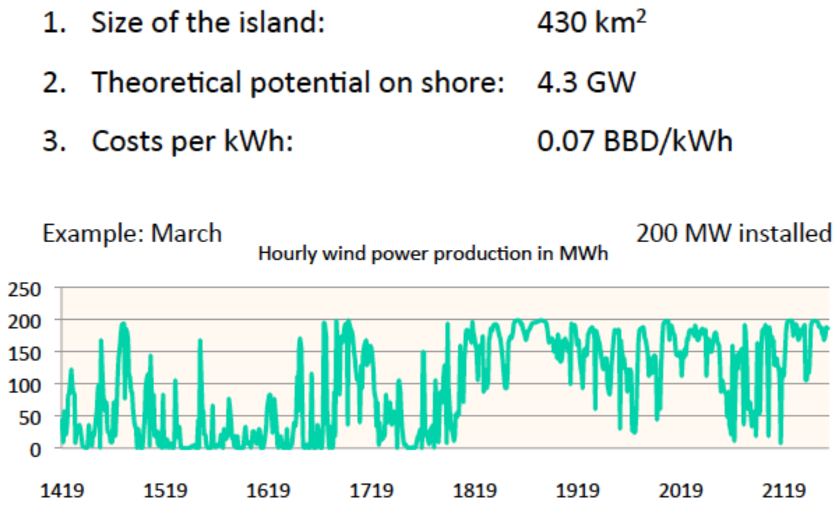
Taking the given hourly wind energy data for Dominica and scaling these to a hub height of 100 m for modern 2.5 to 3 MW standard wind turbines and assuming investment costs of 1,330 US$/kW installed (1,050 €/kW), 5% of the investment costs as annual operation and maintenance costs, a life time of 20 years for the wind turbines and an interest rate of 6%/a results in specific wind electricity costs of 0.07 BBD/kWh.

Later calculations using the 2011 data for Barbados' Grantley Adams International Airport resulted in costs of 0.063 BBD/kWh. This calculation used a shear factor of 0.28, assumed for scaling the wind speeds from the measured height of 10m to a hub height of 100m. The shear factor is a measure of the roughness of the surface around the measuring site. A very rough surface, like buildings or forests, causes a high shear factor or a large difference between the wind speeds close to the ground and at a height of 100m. The assumed shear factor of 0.28 is typical for areas with barriers of up to 15m in height. A shear factor of 0.16 would be typical for open spaces. Using a shear factor of 0.16 translates into lower wind speeds at 100m and an increase in wind energy costs from 0.063 to 0.093 BBD/kWh.

As pointed out before, the simulations for the presentation were based on wind energy data leading to costs of 0.07 BBD/kWh. The wind speeds taken from Dominica lead to full load hour equivalents of about 5,200 h/a or a load factor of 0.59, which compares very favourably 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. Lowering the hub height to 65 m and using the wind data from Dominica would lead to a reduction in output to about 4,300 full load hours per year or a load factor of 0.49 leading to specific wind power costs of 0.085 BBD/kWh instead of 0.07 BBD/kWh at 100 m hub height.

Figure 2 shows the theoretical wind energy potential and the calculated wind energy costs for Barbados based on the wind speed data taken from Dominica. It depicts the output from an installed capacity of 200 MW of wind energy produced by the hourly distribution of wind speeds in the month of March. The wind energy output is fluctuating considerably. During the first half of March wind speeds are untypically low, resulting in rather low energy production, while the second half of the month experiences high wind energy production due to typical wind speeds for that month. Nevertheless, even during this period there are hours with hardly any wind energy production.

Figure 2: Theoretical wind energy potential and wind energy costs calculated for Barbados and the fluctuating wind energy production in March based on wind data for Dominica (Source: Hohmeyer 2014, slide 7)



1. Size of the island: 430 km^2
2. Theoretical potential on shore: 4.3 GW
3. Costs per kWh: 0.07 BBD/kWh

Example: March

200 MW installed

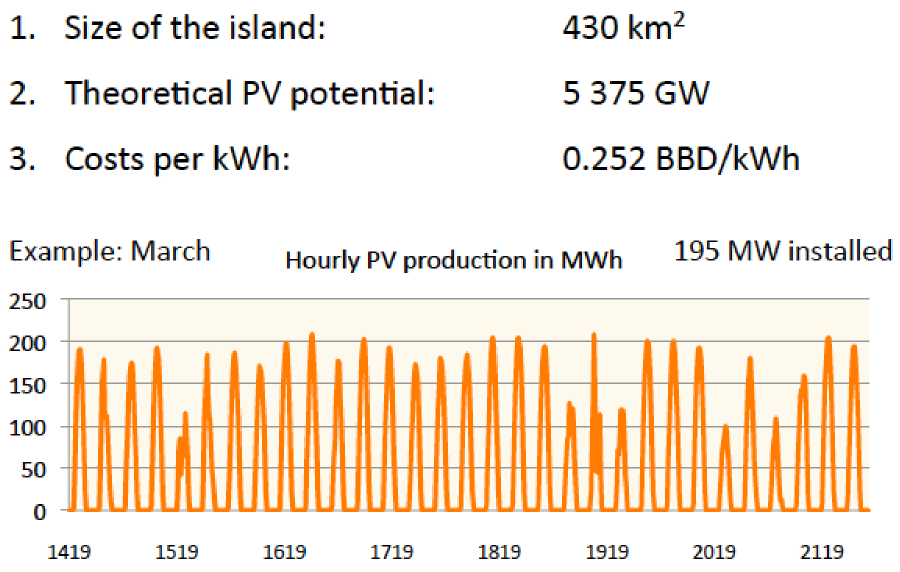
0.5 Solar energy

For the calculation of solar energy production on Barbados internationally available solar radiation data was used. An annual irradiation of 2,025 kWh/m^2 was assumed. All calculations were performed for photovoltaic solar systems (PV).

With a size of 430 km^2, Barbados has a theoretical potential of 5,375 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 not allow any agricultural use of the land 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 200 MW would only require an area of roughly 1.6 km^2.

The system efficiency was assumed to be 12.75% and the system costs to be 1,900 US$ or 3,800 BBD/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 0.252 BBD/kWh. Figure 3 shows the typical fluctuation in the production of solar electricity for March, as well as the theoretical solar energy potential and the calculated solar energy costs. It can clearly be seen that solar energy only provides maximum electrical output for just a very few hours around noon every day. During the other hours it provides just some or no electricity.

Figure 3: Theoretical solar energy potential and solar energy costs calculated for Barbados and the fluctuating solar energy (PV) production in March (Source: Hohmeyer 2014, slide 8)



1. Size of the island: 430 km^2
2. Theoretical PV potential: 5 375 GW
3. Costs per kWh: 0.252 BBD/kWh

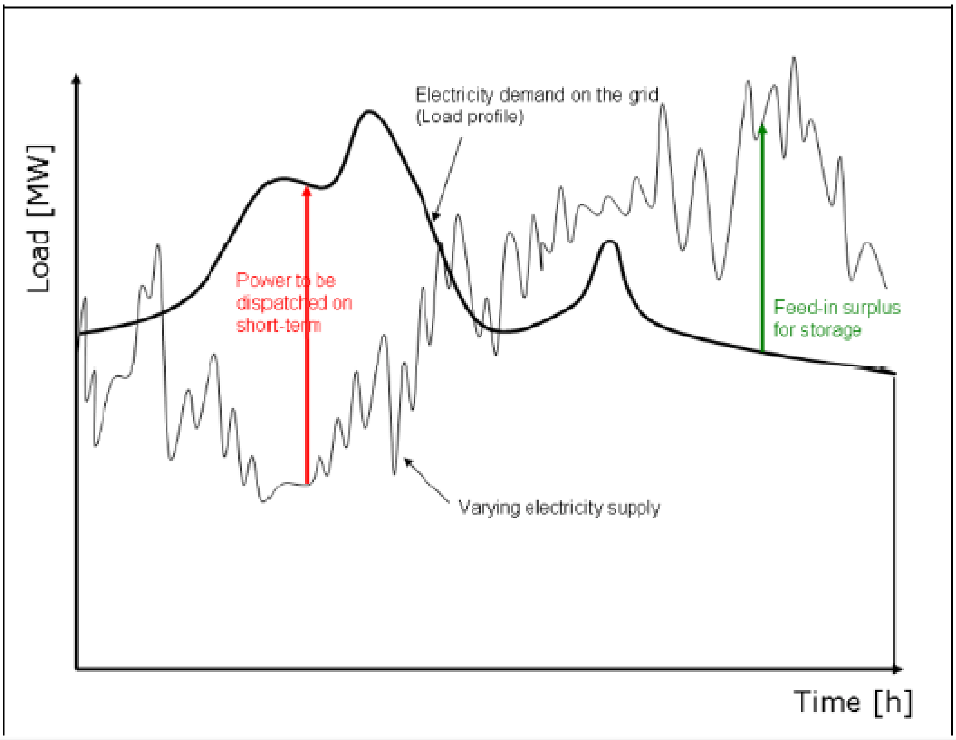
As wind and solar energy are the two major renewable energy resources available to Barbados it is quite clear from the energy production patterns shown for the month of March that they will not be able to satisfy the electricity demand in every hour of the year without the help of other sources or substantial storage capacities.

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.

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 2014, slide 9)



As an example, Figure 5 shows the load and the residual load for a Barbados employing wind and solar PV for February 9th. We can see that the residual load can change by more than 100 MW (50% of the maximum system load) within an hour up or down. This is more than the change in the load during the entire day. 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 seems to be 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: Load curve and residual load for Barbados on February 9th with 200 MW wind and 195 MW of PV installed (Source: Hohmeyer 2014, slides 5 and 10)

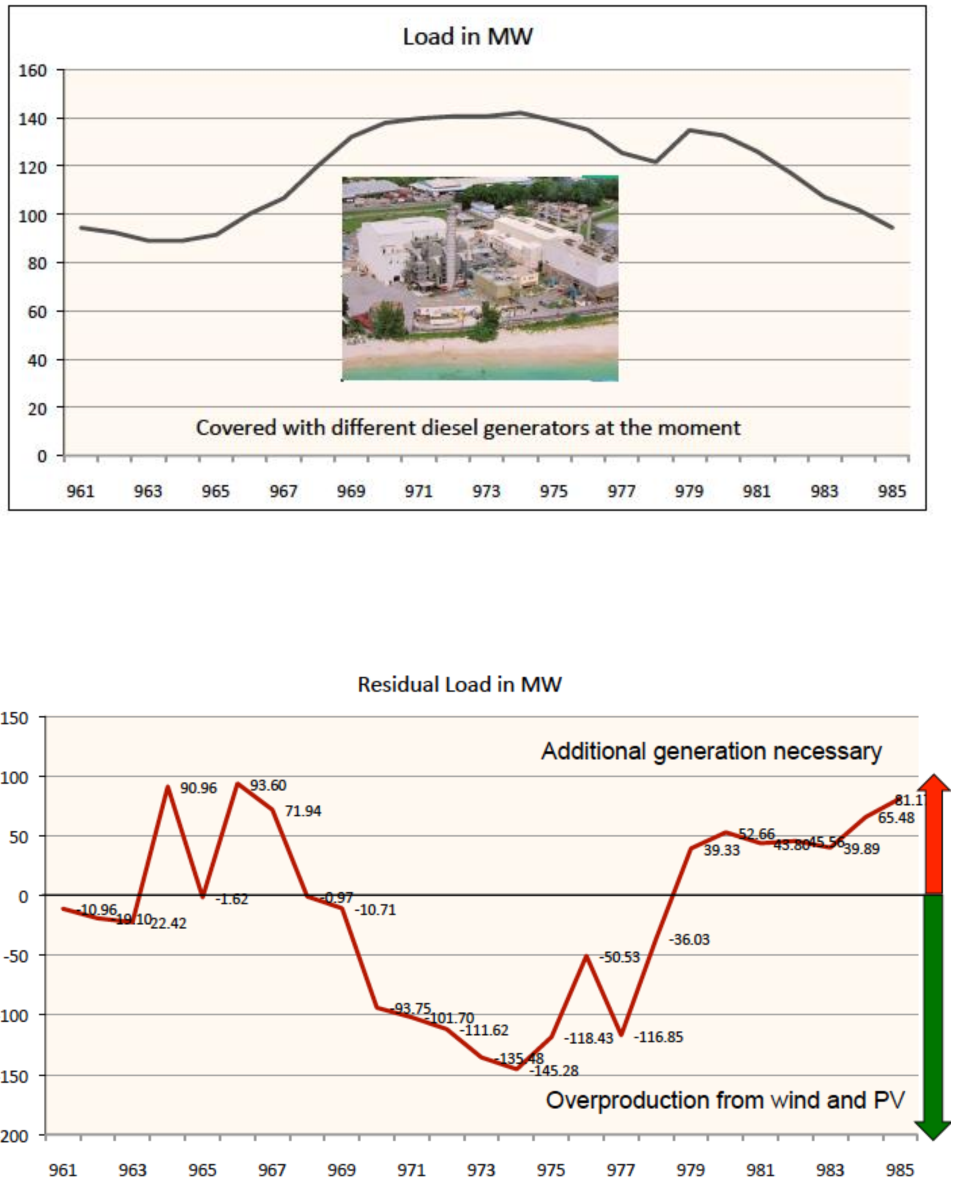
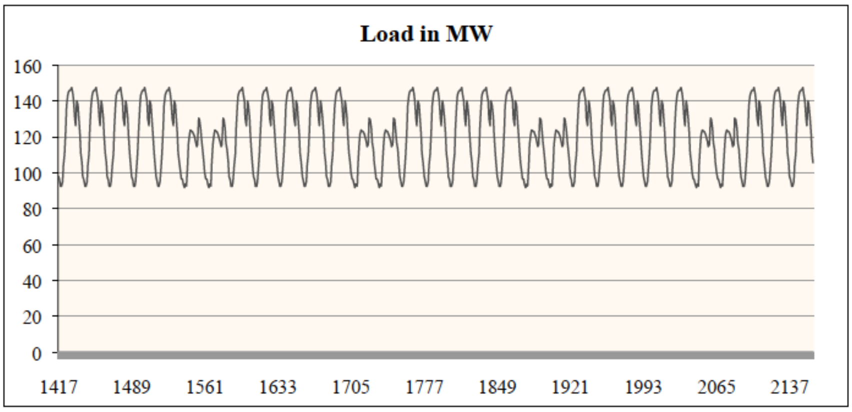


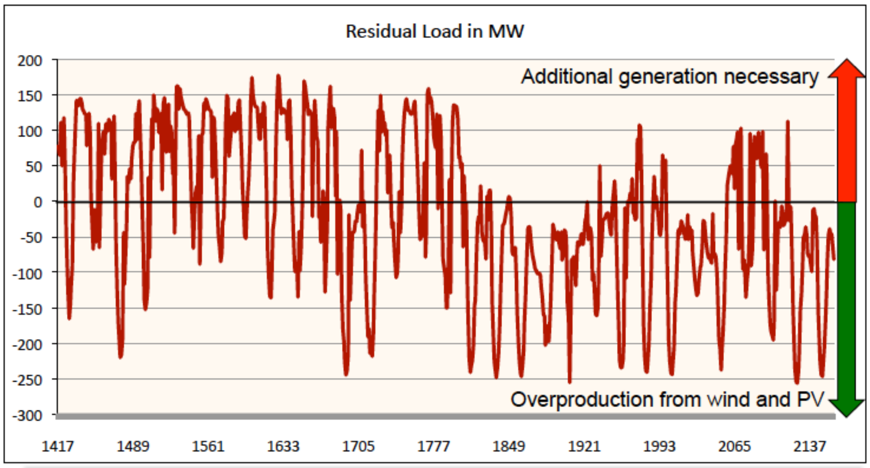
Figure 6a shows the daily and weekly pattern of the electrical load for the month of March, which needs to be met every hour of the month. Subtracting the wind and solar energy production of an installed capacity of 200 MW wind and 195 MW of solar energy leads to the fast fluctuating residual load shown in Figure 6b, which has to be covered by the controllable units of the system. In the first half of the month we have too little production from wind and solar energy to meet the full demand, while in the second half we produce more electricity than needed. The structure of the residual load suggests that Barbados 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 6: Load curve for the month of March (6.a) and resulting residual load with 200 MW wind energy and 195 MW PV installed (6.b) covering an increased electricity demand and load

6.a Simulated hourly load curve (Source: Hohmeyer 2014, slide 15)



6.b Hourly residual load curve (Source: Hohmeyer 2014, slide 18)

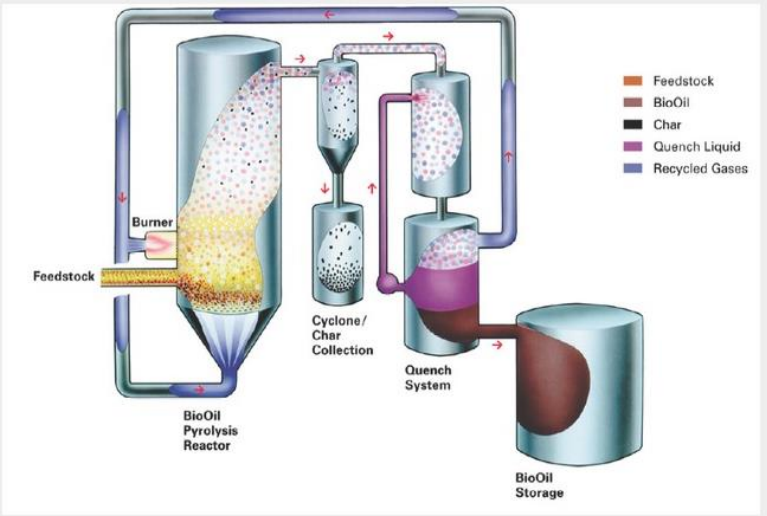


3.2 Biomass

The easiest use of biomass on Barbados seems to be the use of the bagasse from sugar cane production. 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 convert the produced bagasse into a liquid biofuel through the route of pyrolysis.

In the pyrolysis process (in this case most likely flash-pyrolysis) the bagasse is converted at about 475°C in the absence of oxygen into a gas, which condenses to a liquid pyrolysis oil, when cooled down immediately. This oil has about half the energy content of mineral oil based heating fuel oil. The pyrolysis oil contains about 70 to 75% of the energy of the bagasse used for its production. The by-products charcoal and wood gas are used to heat the process. Therefore, only ash will remain as a residue of the process. Before the pyrolysis oil can be used in large diesel engines, it needs to be cleaned and conditioned in order not to damage the machines.

Figure 7: Conversion of bagasse to bio oil (source: Carbon Trust 2015)



Assuming a sugar cane production of 258,600 t/a (see Cilto-Bowrin et al. 2013, p. 106), as in 2012, a bagasse volume of about 33,600 t/a results (if we assume a production of 0.13 t of bagasse per ton of sugar cane). If the pyrolysis oil produced from bagasse contains about 70% of the initial energy of the bagasse and if we assume an energy content of 12 MJ/t of bagasse, the available volume of bagasse can be turned into pyrolysis oil with an energy content of about 284 TJ. If this is used in a diesel engine with an assumed efficiency of 40%, this energy content translates into an electricity production of about 31 GWh/a.

If the sugar produced on Barbados would not be sold but converted to ethanol, each ton of sugar could be converted into about 135 l of ethanol. Based on the 24,500 t of sugar produced in 2012 ethanol with an energy content of about 70 PJ can be produced. If this is used in combustion engines at an efficiency of 40% it can be converted into a little less than 8 GWh/a of electricity. Although this energetic use of the sugar can deliver some electricity, the potential is relatively small as compared to the energy, which can be produced from the bagasse. At the same time the bagasse is a residue of the process, while the sugar is the main product of the present production.

Compared to Barbados total electricity consumption of about 912 GWh/a the biomass potential of about 40 GWh/a from bagasse and sugar seems to be rather small. Nevertheless, this biomass can be converted into storable liquid biofuels, which can augment the necessary power production during the hours when it is dark, the wind is very low and the storage reservoir has already been emptied out. Thus, the use of the available biomass can help to reduce the necessary storage volume. How much storage can be saved by the easily available biomass can be derived once the decision on the storage system to be used has been made.

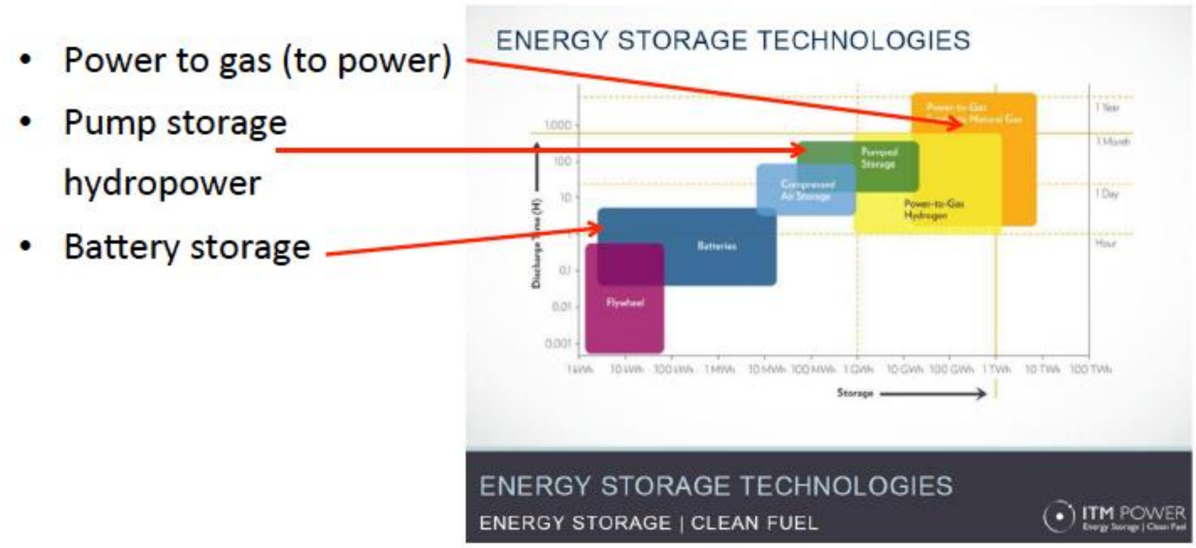
3.3 Storage

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 or weeks, depending on the load characteristics of the country being served and the specific cost of storage. For the power supply of Barbados the storage needs to have a generation capacity of 150 to 200 MW and a storage volume of 1 to 10 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 and the demand from a single household. 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 Barbados' 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 necessary capacity starts at 1 GWh or 1,000,000 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 2014, slide 14)



- Power to gas (to power)
- Pump storage hydropower
- Battery storage

ENERGY STORAGE TECHNOLOGIES

ENERGY STORAGE TECHNOLOGIES
ENERGY STORAGE | CLEAN FUEL
ITM POWER
Energy Storage | Clean Fuel

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 Barbados. If this holds true, CAES is not an applicable storage option for Barbados, 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 Barbados, 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 10,000 MWh (10,000,000 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: Hohmeyer 2014, slide 13)

Battery storage:

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

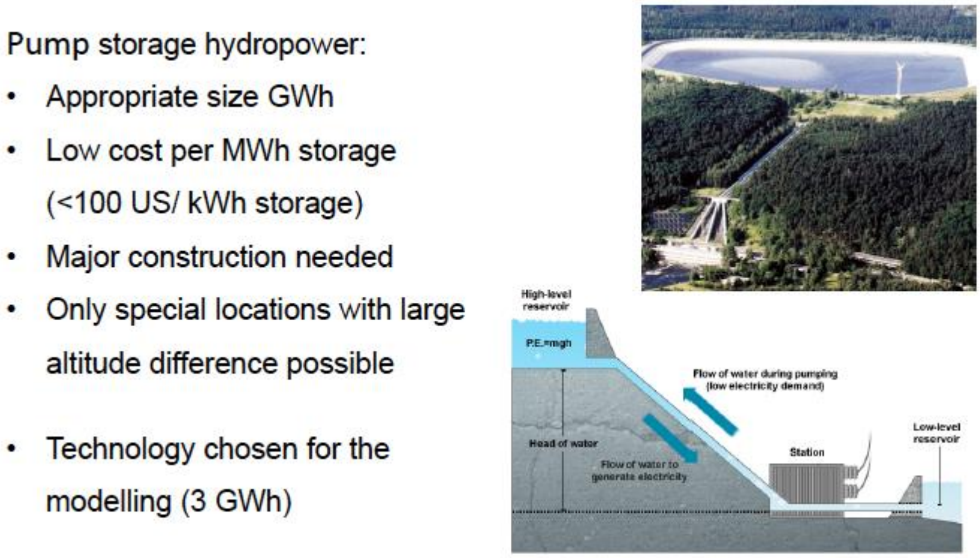
As battery storage can be bought 'off the shelf' in containers ready to be connected to a grid, it is very easy to install. It just takes the cabling and some foundations for the containers to set up this storage option. Figure 9 shows a picture of containerised battery storage and sums up the main pros 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 range of 500 to 600 US$/kWh of storage volume. Thus, a storage volume of 1 GWh would cost about 500 to 600 million US$. 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: Hohmeyer 2014, slide 14)



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 (3 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 300 m the necessary storage volume of each lake to store 1 GWh (1,000,000 kWh) is about 1,250,000 m^3. As Barbados has substantial 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 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 covers the most likely size range of the necessary storage for Barbados. 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.

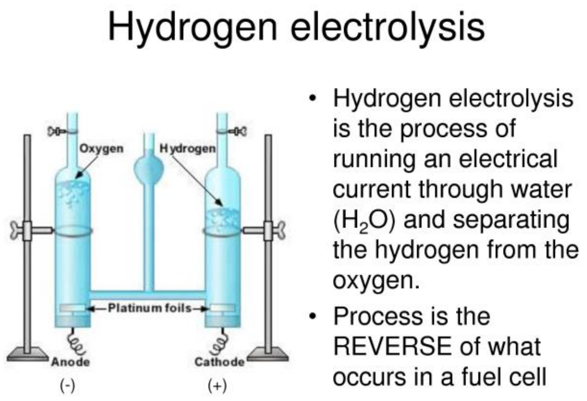
One of the historic reasons for including pump storage hydro systems in almost all major electricity supply systems is the ability to ramp such a system from no operation to full load operation in about 90 seconds. Thus, such a system can change from full load operation for storage to full load operation for electricity production within three minutes. 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 GW, 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 Barbados, this technology seems to offer the right size and technical properties for the storage needed for a 100% renewable electricity supply for Barbados 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 to be stored is stored in the form of the hydrogen produced. As soon 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 so-called 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)

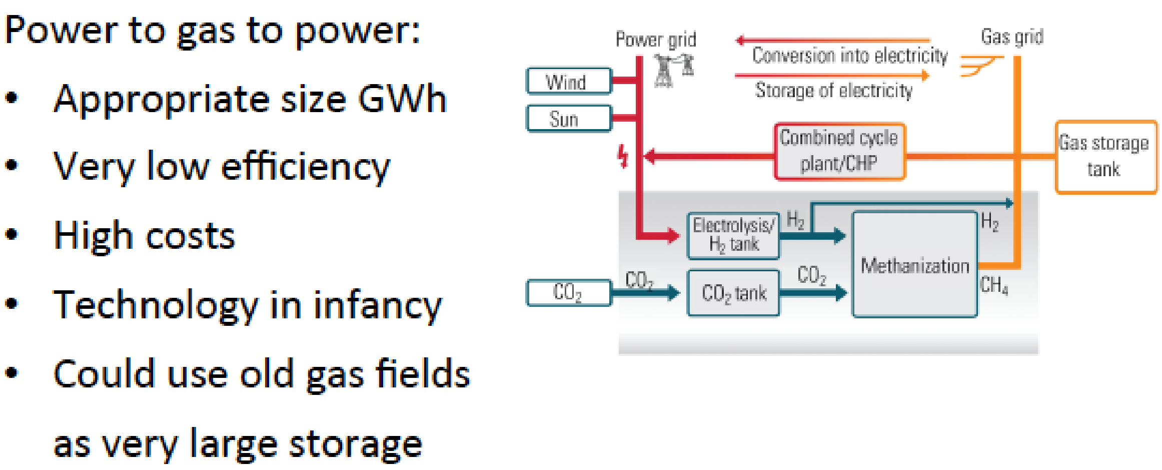


Hydrogen electrolysis

- 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 methanisation 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 2014, slide 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, from these types of storage

2.5 to 5 kWh of electricity needs to be produced and fed into such 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 Barbados and old gas fields could be used for methane storage 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.

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 Barbados 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 Barbados

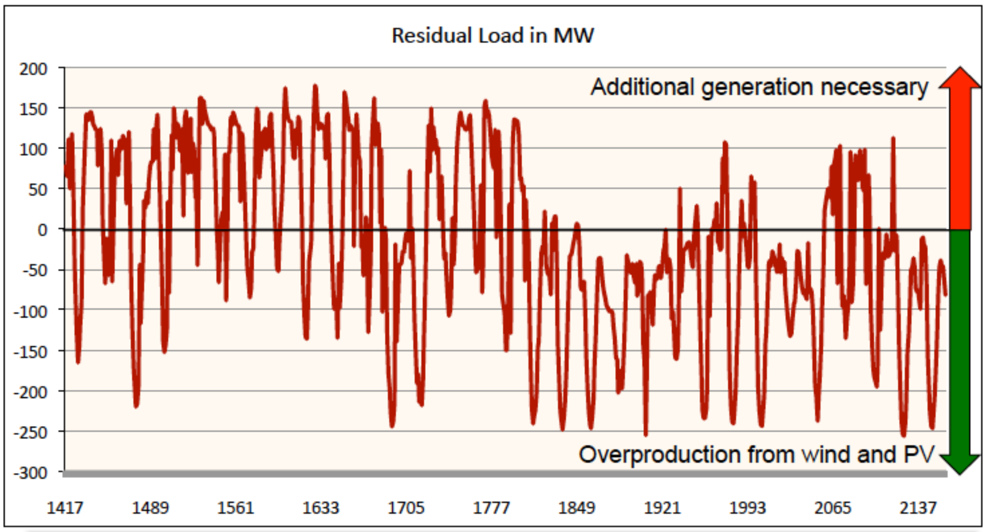
After the basic technology selection has been made we can analyse how Barbados' electricity demand can be met every hour of the year. For this purpose a simple simulation tool has been developed by the author and one of his colleagues (Sönke Bohm) at the University of Flensburg.

For the simulation an hourly load curve was estimated from the available data for Barbados, which comprised an hourly load curve for one day and the monthly electricity sales of Barbados Light and Power for the year 2010. This estimated load curve is shown for the month of March in Figure 6a above.

The next input into the simulation was the hourly solar radiation and the hourly wind speeds for an entire year, which were taken from international databases. As the author did not have Barbados wind data available at the time and place of the analysis (in October 2014 calculations were performed in Germany), hourly data for the island of Dominica was used, which was readily available. A later comparison with hourly data from Barbados' Grantley Adams International Airport showed that the use of the Dominica data lead to underestimating the wind resource on Barbados and a somewhat different seasonal pattern of wind speeds.

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 month of March in Figure 2 above, while the hourly solar energy production for the month of March is shown in Figure 3 above. The installed wind and solar power can easily be put into the system, 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 Barbados in the month of March (Source: Hohmeyer 2014, slide 10)

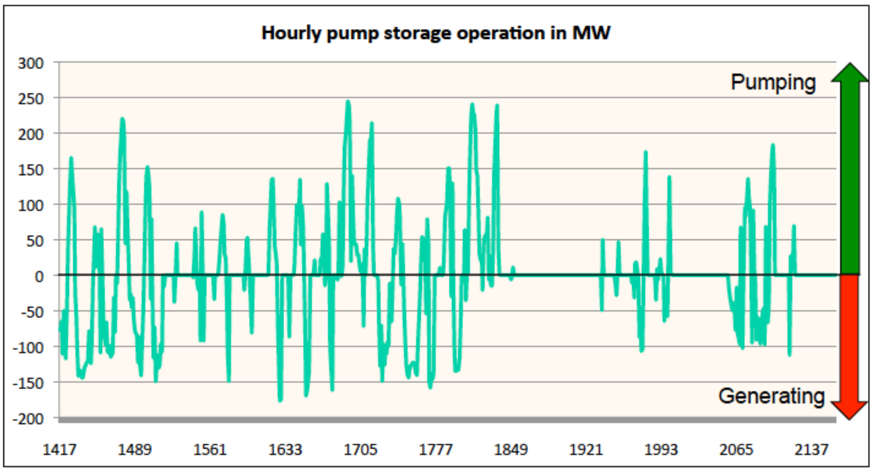


Whenever this residual load is positive we have demand not covered by the wind and solar power produced in this hour. This has to be met either by production from the storage or, if the storage is already emptied out, by electricity production from our liquid biomass, the purified pyrolysis oil produced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

We can see from Figure 13 that the residual load is positive during the first four hundred hours of March (hour 1,417 to roughly hour 1,800). Thus, we will need to produce a lot of electricity from storage or from biomass. During the second half of the month we find 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.

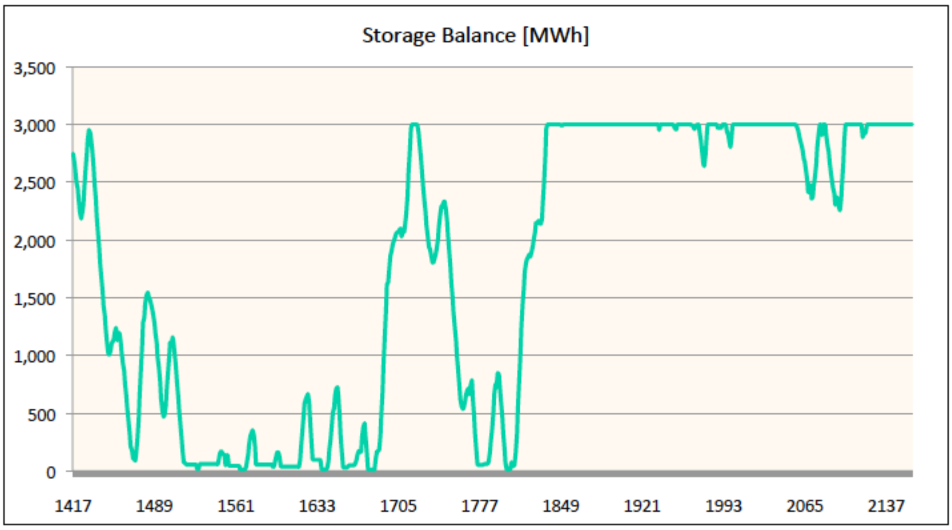
Figure 14 shows the resulting operation of the pump storage plant, which was chosen to have a storage volume of 3 GWh (3,000,000 kWh), an electricity generation capacity of about 180 MW and a pumping capacity of 250 MW.

Figure 14: The simulated hourly operation of the pump storage plant during March (Source: Hohmeyer 2014, slide 19)



During the first half of the month the pump storage plant changes quite frequently from electricity generation to pumping for storage and back, while after hour 1,850 there is a period of about 80 hours of almost no activity. Then it changes back to generating and storage activities for another 80 hours and sits idle for about 50 hours again, before it resumes generation. The explanation of this very special pattern of operation is given in Figure 15 displaying the actual filling level of the upper storage lake in Megawatt hours (MWh). The storage is emptied out during the first one hundred hours of the month and is filled just a little, whenever excess electricity (negative residual load) is available. But shortly afterwards it is emptied out again. Thus, until the middle of the month the storage is operating at its lower limit. In the middle of the month we see a short period when the storage is filled within a few hours, but it is emptied out for necessary production soon afterwards. After a short period of an almost empty storage it is filled completely again, but this time it remains full for quite some time until it is drawn upon for some production. During this idle period, wind and solar energy are producing enough electricity to meet the demand for a period of about 80 hours, after which we find some minor generation and almost instantaneous filling again until the end of the month.

Figure 15: Filling level of the pump storage system in MWh during March (Source: Hohmeyer 2014, slide 20)



During the hours when wind and solar energy are obviously producing more electricity than the demand and the possible need for storage, the production has to be turned down a bit not to over power the system. The energy is lost, but no harm is done. Figure 16 shows the energy that can neither be used nor stored.

During the hours when the storage is emptied out, there is obviously some residual load, which can neither be met by wind and solar energy nor by production from storage. This is the time for the use of biomass to fill in the gaps.

Figure 16: Overproduction of electricity from wind and solar energy in MWh/h (Source: Hohmeyer 2014, slide 22)

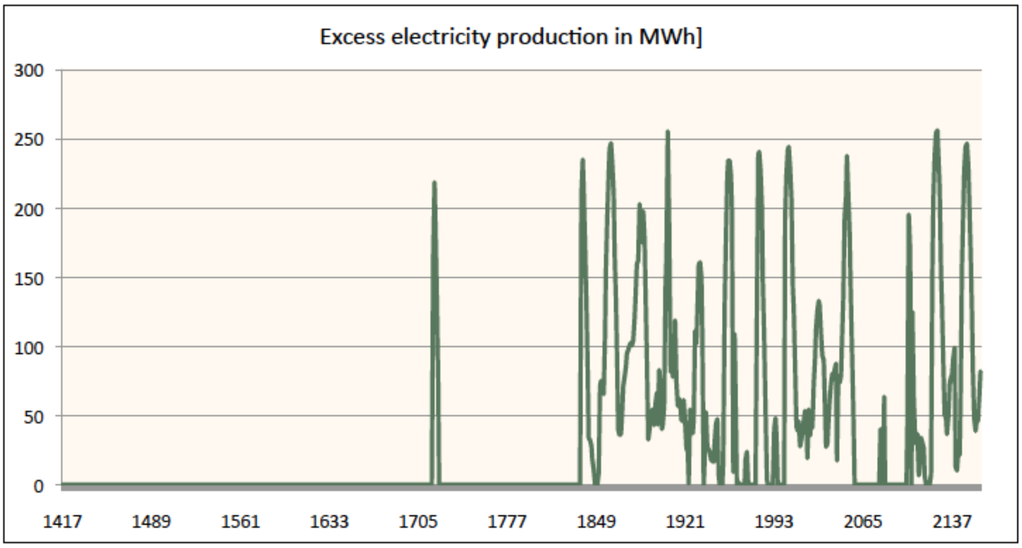


Figure 17 shows the electricity production from biomass during March to match the remaining residual load. We find very short spikes of production, which only last a few hours or even just one hour, but which reach very high levels of necessary production capacity. There is a one hour biomass production spike for example in hour 1,471 where the production reaches 90 MW. Directly before and after the generation spike there is no need for electricity produced from biomass. At the maximum electricity generation from biomass reaches about 130 MW, while it is only used for a few hours even in the period between hour 1,530 and 1,680. After hour 1,680 there are only two short additional episodes of biomass use between hour 1,776 and 1,781 and 1,797 and 1,802. For the remaining 350 hours of the month biomass is not needed any more.

Figure 17: The use of biomass in March to meet the remaining the residual load after storage has been used (Source: Hohmeyer 2014, slide 21)

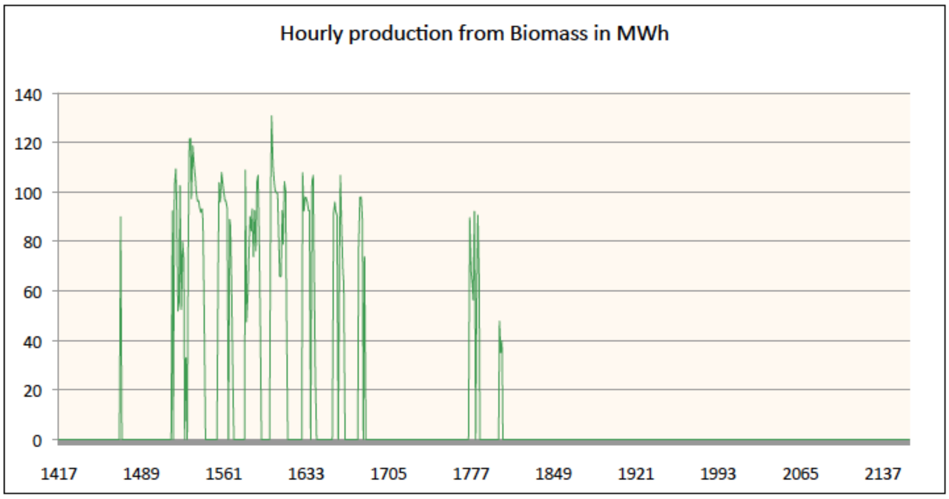
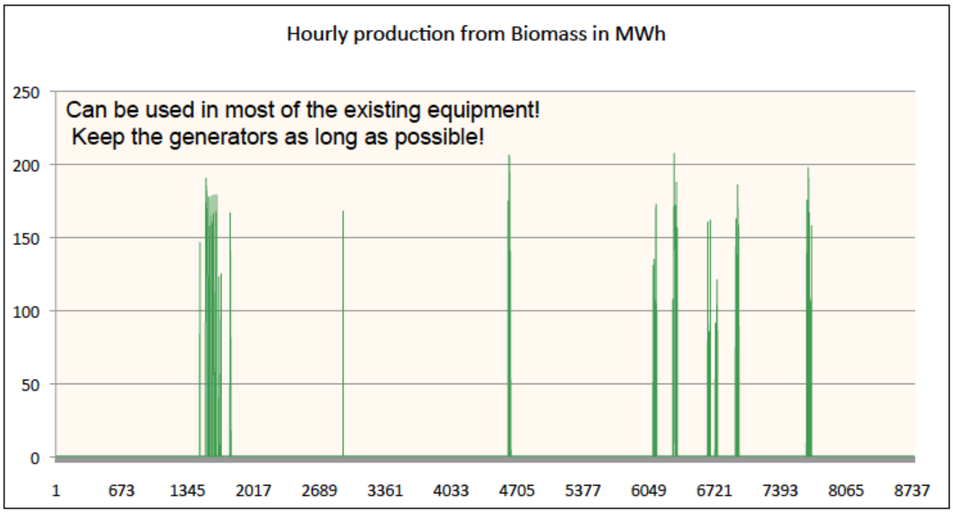


Figure 18 shows by the use of biomass around the year that March had been an exceptionally bad month, but that there are short periods around the year during which biomass is needed once and again to fill the remaining gap in meeting the hourly electricity demand.

Figure 18: The use of biomass during the entire year simulated (Source: Hohmeyer 2014, slide 23)



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

Once the six major parts of Barbados' 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), Barbados' future power supply can be analysed under different scenario assumptions.

The starting point of a scenario is the volume of biomass available, and then 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.

For the scenario introduced in the presentation held at the Central Bank of Barbados on November 10th 2014 a number of technical and economic assumptions had to be made, which are summarised in Table 2.

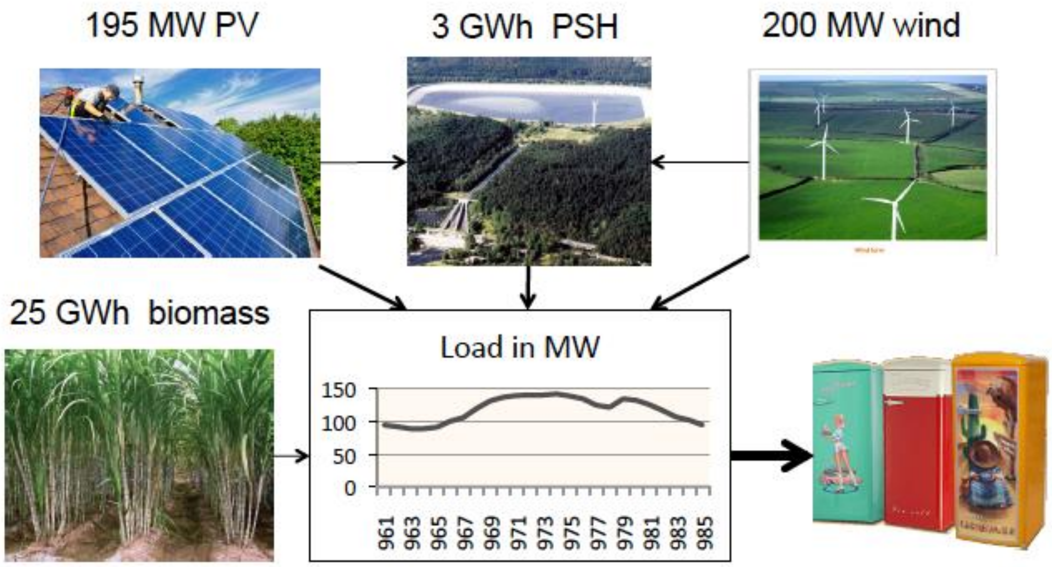
Table 2: Technical and economic assumptions made for the scenario presented on November 10th at the Central Bank of Barbados

Demand curve	- estimated based on a single day's hourly load curve, a weekend to weekday ratio and monthly sales data of BLP	
Demand	- base year 2010	1,065 GWh/a
	- Peak demand	150 MW
Exchange rates	- Euro to BBD	2.534
	- Euro to US$	1.267
	- US$ to BBD	2.0
All systems	- interest rate for financing	6%/a
Wind energy	- turbine size	2.5 MW
	- hub height	100 m
	- shear factor	0.28
	- investment costs	1,050 Euro/kW
	- operation and maintenance costs	5%/a of investment costs
	- hourly wind data	Dominica 2010
	- measurement height of wind data	10 m
Solar energy (PV)	- solar radiation per year	2,025 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	Barbados
Pump storage	- investment costs	100 US$/kWh of storage
	- operation and maintenance costs	4,000 Euro/MW pump capacity
	- altitude difference	300 m
	- turn around efficiency	0.75
Bio fuel	- fuel costs per metric ton	520 Euro/t
	- electricity cost from bio fuels	200 Euro/MWh

Starting from an assumed biomass availability of 25 GWh of liquid biomass, the size of the storage was varied between 1 GWh and 20 GWh. A variation of the wind and solar generation capacities under each of these combinations showed that a storage volume of 3 GWh leads to the lowest costs or the highest savings in power generation costs as compared to the present situation. 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 3 GWh of storage capacity) at an installed solar capacity of 195 MW and an installed wind energy capacity of 200 MW. This system configuration is depicted in Figure 19. This configuration is based on the assumption of roughly 25% higher energy consumption and increased peak demand as compared to the year 2010.

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 180 MW of generation capacity and 250 MW of pump capacity in the minimum cost scenario.

Figure 19: System configuration of the minimum cost scenario chosen for the presentation of November 10th, 2014 at the Central Bank of Barbados (Source: Hohmeyer 2014, slide 6)



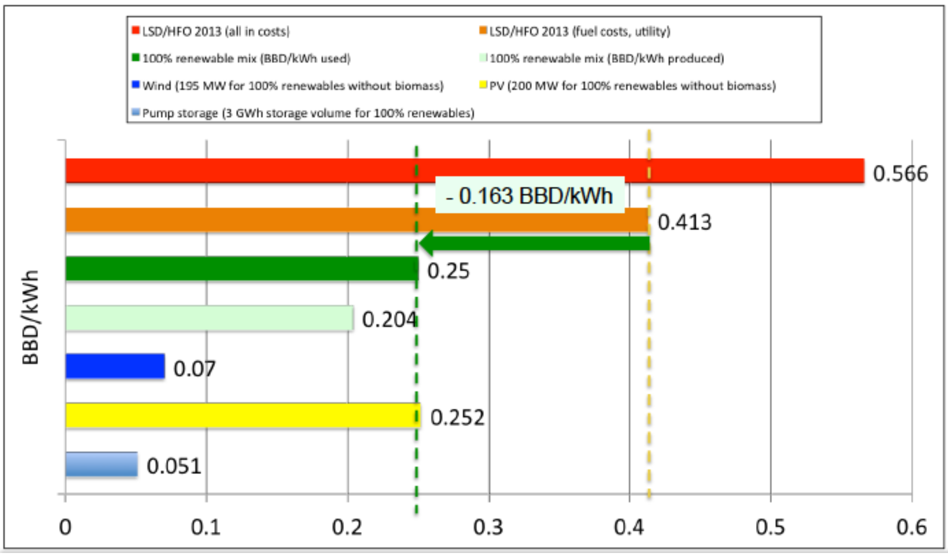
It can be concluded from the simulations that a 100% renewable power supply is technically feasible on the basis of wind and solar energy, if sufficient storage is built and some liquid biomass can be made available. Such energy supply would make Barbados entirely independent of future world market developments for crude oil products and at the same time reduce Barbados' 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, of biomass and the full costs of storage. All costs include the investment costs as well as the operation and maintenance costs based on the assumptions summarised in Table 2 above. These costs do not include the costs for the operation of the electrical grid and general overheads of Barbados Light and Power.

The total costs of electricity production in the minimum cost scenario were calculated to be 0.25 BBD/kWh.

This figure can be compared to the 2013 fuel costs of Barbados Light and Power (BLP) for electricity generation, which have been at 0.413 BBD/kWh. As these do not include investment costs or operation and maintenance costs (besides fuel costs) for the present power generation facilities of BLP, these fuel costs can be taken as the minimum cost savings achievable by renewable electricity generation at the crude oil prices of 2013. This assumption allows us to keep the existing generation equipment to be used with the liquid biofuel, as these investment costs are already covered by the

Figure 20: Costs of a 100% renewable power supply for Barbados compared to present generation costs (2013) based on present prices for renewable energy technologies (minimum cost scenario) (Source: Hohmeyer 2014, slide 24)



present overheads of BLP. Thus, the cost savings, which can be achieved by renewable energy generation are 0.163 BBD/kWh compared to the fuel costs of 2013. This is a cost reduction of 39.5% as compared to the fuel costs or a cost reduction of 28.8% as compared to the total electricity cost of 2013, which amounted to 0.566 BBD/kWh. Figure 20 summarises the costs of the 100% renewable electricity supply and shows the cost savings compared to the present electricity costs.

Table 3 summarises the economic results of the minimum cost scenario. It shows that the total electricity cost reductions would have amounted to about 175 million BBD/a in 2013. The savings to the average household consumer would have been 550 BBD/a, while an average commercial customer would have saved about 6,400 BBD/a.

Table 3: The economic results of the minimum cost scenario(Source: Hohmeyer 2014, slide 25)

Technology	**BBD/kWh**
Barbados L&P electricity generation costs 2013 (all in costs) BBD/kWh	0.566
Barbad**os L&P Fuel cost 2013 only in BBD/kWh**	**0.413**
Wind (200 MW for 100% renewables without biomass)	0.070
PV (195 MW for 100% renewables without biomass)	0.252
Biomass (25 GWh/a)	0.507
Pump storage (3 GWh storage volume)	0.051
100% renewable mix (BBD/kWh used)	**0.250**
Minimum cost reduction (fuel cost minus renewable cost) in BBD/kWh	**-0.163**
Minimum electricity cost reduction in % (of 'all in costs')	**28.8%**
Minimum electricity cost reduction per year in BBD/a	**174 700 000**
Minimum Import reduction in BBD over 20 years	**6 000 000 000**

6. Impacts on the economy and taxes

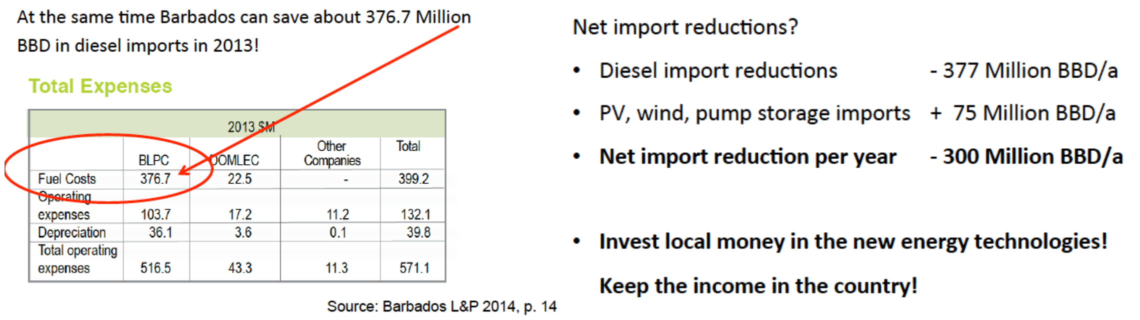
The proposed change of Barbados' electricity production to a 100% renewable electricity supply will have a substantial impact on Barbados' economy. The electricity cost reduction of about 175 million BBD/a is equal to an increase in national spending power of 2%, if we assume a national GDP of about 8,500 BBD/a in 2013 (IMF 4,284 million US$/a or CIA 4,262 million US$/a data for 2013).

In a 100% renewable energy future the entire fuel imports for electricity generation of 376.7 million BBD/a (as of 2013) can be eliminated (Barbados L&P 2014, p. 14). At the same time net imports, taking into account necessary new imports of about 75 million BBD/a for technical equipment for the use of renewable energy, can be reduced by about 300 million BBD/a, which is equal to a GDP increase by 3.5%. What is more, this import reduction saves Barbados from having to spend hard currency in the order of 150 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 Barbados, about 75 million BBD/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 on Barbados; 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. Figure 21 shows the import balance of the transition to the new energy system.

Figure 21: Impacts of the transition to 100% renewable electricity on imports (Source: Hohmeyer 2014, slide 28)



At the same time Barbados can save about 376.7 Million BBD in diesel imports in 2013!

Total Expenses

2013 $M				
	BLPC	DOMLEC	Other Companies	Total
Fuel Costs	376.7	22.5	-	399.2
Operating expenses	103.7	17.2	11.2	132.1
Depreciation	36.1	3.6	0.1	39.8
Total operating expenses	516.5	43.3	11.3	571.1

Source: Barbados L&P 2014, p. 14

Net import reductions?

- Diesel import reductions	- 377 Million BBD/a
- PV, wind, pump storage imports	+ 75 Million BBD/a
- **Net import reduction per year**	**- 300 Million BBD/a**

- **Invest local money in the new energy technologies!**

  Keep the income in the country!

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

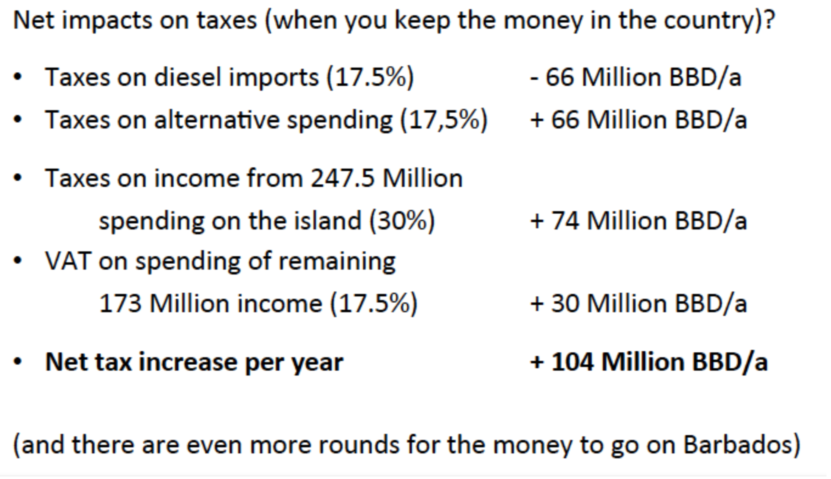
If Barbados is successful in moving to a 100% renewable electricity supply as one of the first countries in the region, it has a great chance to create the highly skilled labour force needed to facilitate the transition processes in the other Caribbean countries. This could lead to a substantial boost in employment for Barbados 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 the government, as the reduction of the fuel imports by 376.6 million BBD/a will lead to a loss in import taxes. Fortunately, the money spent on fuels today will not disappear with a 100% renewable Barbados. As the people will still have the same income in the first place, they are still able to spend the money, which was spent on crude oil based electricity. They will spend one part, about 200 million BBD/a on renewable energy based electricity to buy the same volume of electricity (912 GWh/a) and they will spend the rest of the money, about 175 million BBD/a or 550 BBD per household and year on other consumption, which they had reduced during the years, when the electricity bill started to increase due to highly increased crude oil prices. As about 75 million BBD will be needed on average per year to import the renewable energy systems, these could be taxed like the imports on crude oil products. At the moment these technologies are import tax exempt. In this case the energy bill is lowered by the volume of the taxes. This money is then spent on other purposes, which in turn are subject to taxation.

If we assume that imports and sales on Barbados are all taxed at the prevailing value added tax rate (VAT) of 17.5% then the tax income on the 376.6 million BBD/a (65.9 million BBD/a) will be the same if the money is spent the 'old' way on fuel imports or the 'new' way on electricity produced from renewable energy sources and on the additional consumption possible with the money not needed for payments for the electricity consumed.

In the case of diesel and kerosene imports for electricity production, the money leaves Barbados and the tax income will be limited to the 66 million BBD/a. In the case of renewable electricity generation, only 75 million BBD/a will leave the country. The remaining 300 million will stay in the country. Out of this money VAT of 52.5 million BBD/a will have been paid (part of the 66 million BBD/a). Thus, there is an income generated by the sale of electricity and other goods of 247.5 million BBD/a. If an average income tax rate of 30% is assumed, this will lead to an additional tax income of 74 million BBD/a, leaving about 173 million BBD/a to be spent. Once this money is spent on Barbados, it will lead to additional VAT income in the order of 30 million BBD/a.

Table 3: Net effect of a switch to a 100% renewable electricity production (Source: Hohmeyer 2014, slide 30)



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

• Taxes on diesel imports (17.5%)	- 66 Million BBD/a
• Taxes on alternative spending (17,5%)	+ 66 Million BBD/a
• Taxes on income from 247.5 Million spending on the island (30%)	+ 74 Million BBD/a
• VAT on spending of remaining 173 Million income (17.5%)	+ 30 Million BBD/a
• **Net tax increase per year**	**+ 104 Million BBD/a**

(and there are even more rounds for the money to go on Barbados)

Thus, just keeping the major part of the money spent on electricity generation in Barbados will already lead to more than a doubling of the tax income in the next round of spending and taxation.

This process will continue for all the money kept in Barbados. Thus in the end the tax income will most likely triple as compared to electricity production based on imported fuels. The results of the calculation are shown in Table 3.

7. Suggestions for a possible transition

The result of the preliminary analysis clearly shows that a 100% renewable electricity supply is possible for Barbados and that it can massively save on electricity production costs, reduce imports, stop the drain of hard currency in the order of 300 million BBD/a and increase the governments tax income at the same time. The only losers of this change will be the oil exporting countries, which have drained tremendous funds from the Barbados economy during the last decades.

In this situation the question arises, how Barbados can achieve a transition to a 100% renewable electricity supply to reap the full benefits of such an 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 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 (100m) 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
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 it 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
9. Set annual targets for the capacities of wind and solar energy to be installed
10. 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
11. Keep the existing diesel generators as back-up for as long as possible

12. Analyse the quality requirements for biofuels to be burned in the existing generators without technical problems
13. Do a very thorough site assessment for the pump storage facility (or facilities)
14. 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)
15. Modularise the storage in a number of units of about 50 MW generation and pumping capacity
16. 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
17. Find international sponsors for the implementation of the NAMA strategy (e.g. the UK-German NAMA Facility)
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 Barbados.

8. Switching to 100% renewables powered e-mobility

Once Barbados 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 heavy fuel oil, diesel and kerosene for electricity production amounted to 376.6 million BBD in 2013 the entire imports of crude oil products amounted to 925.8 million BBD in the same year (Barbados economy fact sheet 2014, Table 4). It seems fair to assume that by far the largest share of the additional imports of roughly 550 million BBD/a in 2013 were used for transportation in the form of petrol or diesel. These imports can be saved by switching to electrical mobility based on renewable electricity produced on Barbados.

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 Barbados 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 Barbados during the night time or in the company parking lot during the working day.

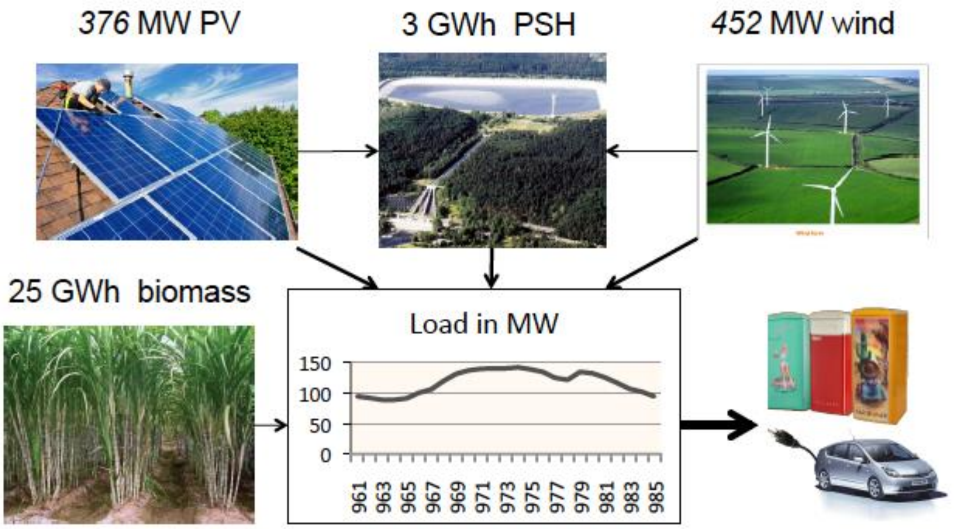
Although electrical cars are still more expensive than normal cars with combustion engines, it can be expected that this will change substantially during the next ten years, as electrical cars will most likely be cheaper in mass production than cars with combustion engines, gear boxes and mechanical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

fuel costs (as of November 2014)	3.12 BBD/l
petrol consumption per 100 km	6 l
cost per 100 km conventional car	**18.7 BBD**
green electricity costs per kWh	0.43 BBD
electricity consumption per 100 km	25 kWh
cost per 100 km electrical car	**10.75 BBD**

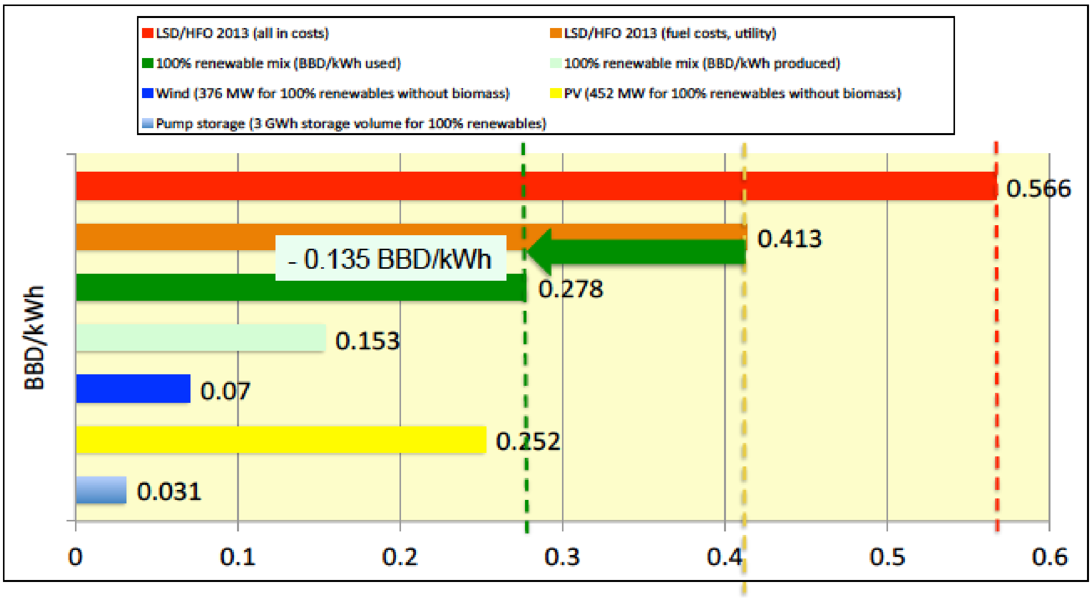
At a cost of 10.75 BBD per 100 km the electricity for driving is substantially below the 18.7 BBD per 100 km for a fuel-efficient conventional car, there seems to be room for similar tax rates as on gasoline or diesel and for cost savings to the average customer. Thus, a replacement of conventional cars 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 22: Basic configuration of Barbados' electricity system supplying the regular electricity demand plus the demand for electrical mobility 100% by renewable energy sources (Source: Hohmeyer 2014, slide 33)



A very rough calculation extending the electricity demand by 660 GWh/a for the transportation sector can be covered by an increase of the solar PV generating capacity to 376 MW and the wind power capacity to 452 MW. With the pump storage system remaining at 3 GWh storage volume and the liquid biomass at 25 GWh/a, such system would lead to slightly higher electricity costs than in the case without electrical cars. The total electricity production costs would be 0.278 BBD/a. Figure 22 shows the basic configuration of the electricity system to supply all the electricity demanded in the new e-mobility situation. Figure 23 shows the slightly changed cost situation and the cost reduction as compared to the present conventional electricity supply.

Figure 23: Costs of a 100% renewable power supply for Barbados including electrical mobility compared to present generation costs (2013) based on present prices for renewable energy technologies (Source: Hohmeyer 2014, slide 34)



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 250 to 300 million BBD/a in imports can be saved by switching to electrical mobility once Barbados is supplied 100% by renewable electricity.

As the expansion of the electricity production will need on average about 50 million BBD/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 200 to 250 million BBD/a and an additional boost to Barbados’ economy.

9. Conclusions and recommendations

From the first analysis conducted by the author it is clear that Barbados can switch to a 100% renewable electricity supply and reduce its electricity costs by as much as 30% as compared to the costs of 2013 based on present equipment prices.

The switch to a 100% renewable electricity supply can lead to a net reduction of imports by as much as 300 million BBD/a through the substitution of the crude oil products used for electricity production today.

If Barbados would change to electrical mobility in its transport sector based on renewable electricity produced on Barbados then the import reductions could most likely be doubled.

As a result of the transition to a 100% renewable electricity supply Barbados 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 Barbados.

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