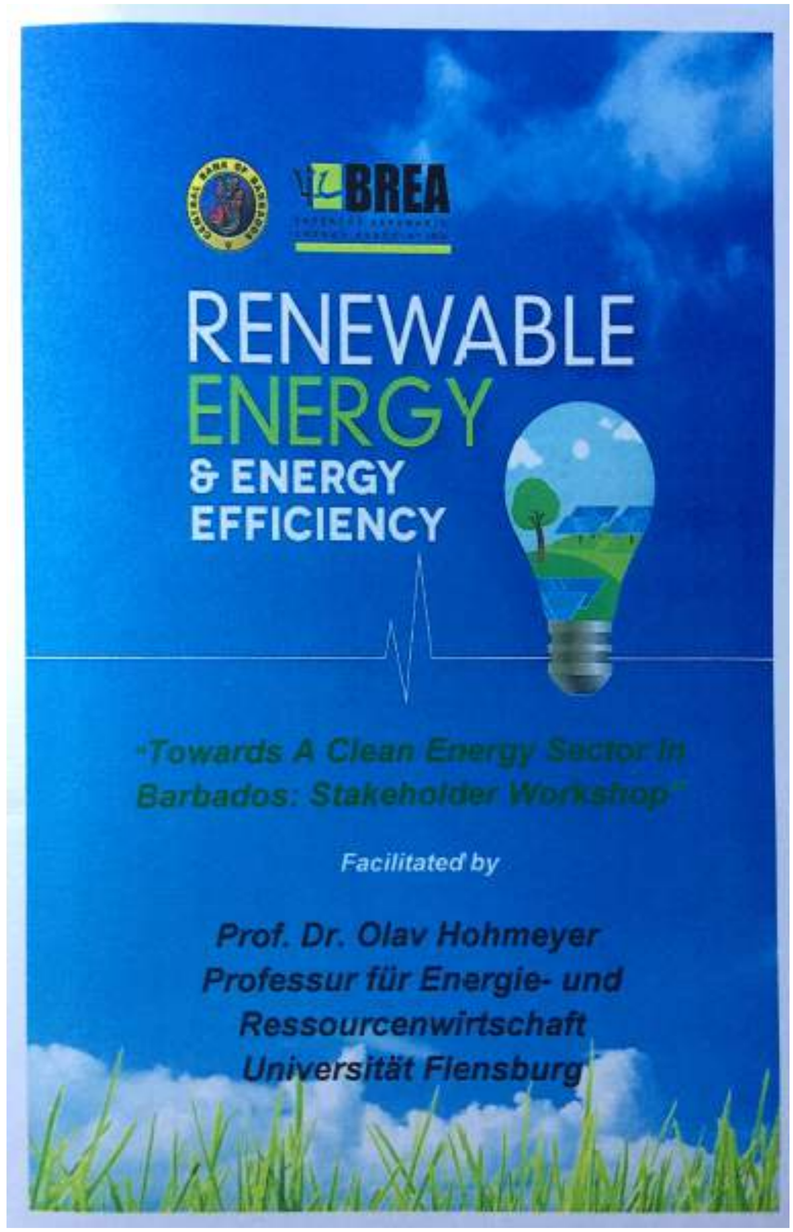
CENTER FOR SUSTAINABLE ENERGY SYSTEMS (CSES/ZNES)
System Integration Department



Central Bank of Barbados

Bridgetown, Barbados
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Table of Contents

1 Summary of the Results of the workshop 3
1.1 General results of the workshop 3
1.2 Results of the scenario simulations 4
1.3 Results on the necessary policy framework 7
2 Short description of the model and assumptions used 8
2.1 The logics of the simulation model 8
2.2 The assumptions made 10
2.3 Additional explanations on a possible feed-in-tariff and its structure and the future structure of Barbados' power costs 13
2.4 Structure of a feed-in-tariff 13
2.5 Future power cost structure for Barbados 15
3 Appendices 19
3.1 Presentation by Professor Hohmeyer 19
3.2 Presentation by Dr. Rogers 36
3.3 Paper on the original 100% scenario by Professor Hohmeyer 44

1 Summary of the Results of the workshop

Based on the initial calculations for a 100% renewable power supply for Barbados, introduced by Professor Olav Hohmeyer in November 2014, this workshop was designed to lay the foundations for a well informed discussion between the major stakeholders and decision makers on possible future energy scenarios with up to 100% renewable power supply for Barbados. The overall aim was to start a discussion process for building a consensus between the major stakeholders on the most desirable composition of a low cost, low risk sustainable energy future for Barbados.

1.1 General results of the workshop

The participants agreed that:

- A shift to a predominantly renewable power supply can help to reduce the heavy economic burden of fuel imports for power production and the future risk of highly fluctuation power costs
- The greatest economic benefit of a shift to renewable energy can be achieved, if the investment is done by domestic investors and the resulting income is kept in Barbados
- Domestic ownership may well be combined with international low interest loans for the initial financing of the imports of renewable energy equipment, as some experiences with solar investments show
- Wind energy will be the cheapest source of renewable energy for Barbados (0.07 – 0.15 BBD/kWh), even in years with very low average wind speeds
- Barbados has a wind power potential of about 400 MW in seven larger areas with good wind speeds, which are predominantly located in the northern and eastern parishes of the island
- Visual simulation showed that larger wind turbines (up to 3 MW in size) are clearly preferred over smaller (1 MW size) turbines due to the largely reduced clutter of the landscape of Barbados by the smaller number of necessary turbines
- The calculated wind potential can only be realized, if the present regulations for the siting of wind turbines are changed in as much as the distance regulations should not be based on the distance to the borders of a property but on the distance to dwellings and other objects, which need to be protected from the impact of possible wind turbine failures or noise impacts
- The transition towards a high share of renewable energy sources will need a high level of public acceptance, as renewable energy installations will likely need to impact the average Barbados citizen
- Barbados will need to consider citizen or community ownership models for wind energy in order to realize its cheapest renewable energy source.

1.2 Results of the scenario simulations

A substantial number of different scenario simulations were calculated based on variations suggested by the workshop participants.

The simulations started from a initial scenario of a 100% renewable power supply system based on:

- 230 MW of wind
- 200 MW solar PV
- 3,000 MWh of pump storage hydropower and
- 5,000 t/a (25 GWh/a) of biodiesel as backup
- The hourly wind speeds of 2012
- A shear factor at the measuring site of the wind speeds of 0.2
- 66 m hub height for wind turbines
- German PV investment of 2014
- German wind investment cost of 2014, which results in total average energy costs of 0.25 BBD/kWh (scenario Barbados Wind 2012xM1.xlxs).

Results of numerous scenario variations showed:

- A reduction in storage volume to 1,000 MWh can slightly reduce power costs to 0.223 BBD/kWh, increasing the use of biodiesel to 50 GWh/a (this system specification has been taken as new reference for all further calculations) (scenario Barbados Wind 2012x4 M1.xlxs)
- Further reductions of storage *increase* power costs (scenarios Barbados Wind 2012x1-5 M1.xlxs)
- A shift from wind to solar energy (150 MW wind, 330 MW PV, 50 GWh of biodiesel) would increase power costs from 0.223 to 0.267 BBD/kWh (scenario Barbados Wind 2012x6 M1.xlxs)
- The introduction of solid biomass combustion, as planned by the Barbados government, to make use of bagasse and River Tamarind with an electrical capacity of 23.5 MW will increase power cost to 0.314 BBD/kWh (scenario Barbados Wind 2012x7 M1.xlxs)
- A smaller solid biomass plant with 10 MW capacity would increase cost to 0.261 BBD/kWh (assuming the same specific investment costs per MW installed capacity (scenario Barbados Wind 2012x8 M1.xlxs)
- The use of biogas to level the wind and solar energy production will require very large storage volumes. Even if very cheap storage in depleted gas fields is assumed, the gasification of 23.5 MW of biomass and the gas storage will bring the energy cost up to 5.157 BBD/kWh (scenario Barbados Wind 2012x9 M1.xlxs)
- Using the hourly wind speeds of the year 2011 (the weakest wind year in the last 10 years), increases the power costs to 0.279 BBD/kWh and the residual biodiesel demand to 82 GWh/a or 16.400 t/a (scenario Barbados Wind 2011x1 M1.xlxs)
- A further change in the assumed surface roughness of the measuring site of the hourly wind speeds (0.2) to an extremely open surface with a shear factor of 0.08 would lead to vastly reduced wind speeds at hub height of the installed turbines increasing average power costs to 0.341 BBD/kWh based on wind year 2011 (scenario Barbados Wind 2011x2 M1.xlxs)

- A change in the assumed costs for solar PV systems from 1,500 €/kWp (3,801 BBD/kWp) to a present Barbados price for small roof top systems of about 6,000 BBD/kWp (2,368 €/kWp) suggested by the workshop participants increases the power costs from 0.223 BBD/kWh in the base case with smaller storage (1,000 MWh) to 0.2801 BBD/kWh (scenario Barbados Wind 2012x13 M1.xlxs)
- A cost change to 4,500 BBD/kWp for average solar PV installations (50% roof top and 50% utility scale) leads to a reduced increase in power cost to 0.2411 BBD/kWh (scenario Barbados Wind 2012x13a2 M1.xlxs)
- A cost increase for wind turbines to presently discussed Barbados cost of 1,630 €/kW (4,130 BBD/kW) suggested by the workshop participants, increase the average cost of electricity from 0.223 BBD/kWh in the base case to 0.267 BBD/kWh (scenario Barbados Wind 2012x14a M1.xlxs)
- An additional reduction of the shear factor from 0.2 to 0.08 further increases average electricity costs to 0.3045 BBD/kWh due to higher wind energy costs (scenario Barbados Wind 2012x14 M1.xlxs)
- The combination of high wind energy costs, low shear factor (0.08) and the measured wind speeds of 2011 lead to average electricity cost of 0.358 BBD/kWh (scenario Barbados Wind 2011x14 M1.xlxs)
- A realistic scenario based on the wind and solar investment costs suggested by the workshop participants (4,500 BBD/kW PV and 4,130 BBD/kW wind), a realistic shear factor of 0.2, a smaller pump storage volume of 1,000 MWh and wind year 2012 results in average power costs of 0.285 BBD/kWh as compared to 0.223 BBD/kWh in the minimal cost scenario (scenario Barbados Wind 2012x15 M1.xlxs)
- The same scenario assumptions combined with the wind speeds of the weak wind year 2011 result in average power costs of 0.319 BBD/kWh.

The scenario results show that assuming a realistic shear factor of 0.2 and present Barbados investment costs for wind and PV the average costs for a 100% renewable power scenario will be close to 0.30 BBD/kWh with variations between 0.285 and 0.319 BBD/kWh for a strong wind year like 2012 or a weak wind year like 2011 respectively.

Although the calculations showed that due to higher investment costs in Barbados, the costs for a 100% renewable power supply for Barbados would most likely be 0.30 and not 0.25 BBD/kWh, this still constitutes a very substantial cost reduction potential as compared to Barbados' power costs of 2013.

The results of all scenarios calculated at the workshop are summarized in Table 1 below. The results are augmented by some additional scenarios to give a more complete picture of the impacts of varying the parameters discussed. In scenario 2012x14, 2012x14a, 2012x15, 2011x14 and 2011x15 the cost for wind and PV have been simultaneously raised to the suggested Barbados investment costs to give a more realistic overall result. Furthermore, the scenarios for wind year 2011, which were only carried out with the large storage volume of 3,000 MWh at the workshop, have been carried out with the smaller volume of 1,000 MWh preferred by the participants in the detailed calculations for wind year 2012.

Table 1. Results of 26 scenarios calculated for Barbados

Scenario	*Power cost in BBD/kWh*	Wind year	*Biodiesel in GWh/a*	*Biodiesel capacity in MW*	Wind capacity in MW	PV capacity in MW	Solid Biomass capacity in MW	Biogas capacity in MW	Storage volume in MWh	PV investment cost in BBD/kw	Wind invest. cost in BBD/kW	Shear factor
	Scenarios based on wind year 2012											
	Variations of storage size											
2012x	***0.2501***		*24.7*	*143.8*		205			**3 000**			
2012xa	*0.2480*		*25.6*	*143.8*								
2012x1	*0.2796*		*14.3*	*138.7*					**5 000**			
2012x2	*0.2406*	2012	*29.6*	*143.8*	230	**200**	0	0	**2 500**	3 801	2 661	0.2
2012x3	*0.2334*		*34.2*	*143.8*					**2 000**			
2012x4	***0.2230***		*51.9*	*143.8*					**1 000**			
2012x5	*0.2458*		*146.7*	*146.2*					**0**			
	Increased solar share											
2012x6	*0.2667*	2012	*51.1*	*141.1*	**150**	**340**	0	0	1 000	3 801	2 661	0.2
	Use of solid biomass and biogas with seasonal gas storage in old gas fields											
2012x7	*0.3142*		*24.6*	*116.8*			**23.5**	0				
2012x8	*0.2612*	2012	*38.6*	*133.8*	230	200	**10.0**		1 000	3 801	2 661	0.2
2012x9	*5.1573*		*0*	*0*			0	**23.5**				
	Impact of a very low shear factor											
2012x10	*0.2606*	2012	*128.2*	*147.7*	230	200	0	0	1 000	3 801	2 661	**0.08**
	Variations of solar PV cost											
2012x11	*0.2893*		*128.2*	*147.7*						**4 903**		
2012x13a	*0.2787*		*128.2*	*147.7*						**4 500**		0.08
2012x13	*0.3179*	2012	*128.2*	*147.7*	230	200	0	0	1 000	**6 000**	2 661	
2012x13_2	*0.2801*		*51.9*	*143.8*								**0.2**
2012x13a2	*0.2411*		*51.9*	*143.8*						**4 500**		
	High wind investment cost with different shear factors											
2012x14	*0.3045*	2012	*128.2*	*147.7*	230	200	0	0	1 000	3 801	**4 130**	**0.08**
2012x14a	*0.2668*		*51.9*	*143.8*								**0.2**
	Barbados wind and PV cost with small storage and normal shear factor											
2012x15	***0.2848***	2012	***51.9***	***143.8***	230	200	0	0	1 000	**4 500**	**4 130**	0.2
	Scenarios based on wind year 2011											
	International investment costs with different storage volumes											
2011x M1	*0.2795*	2011	*82.0*	*146.8*	230	200	0	0	**3 000**	3 801	2 661	0.2
2011xa M1	*0.2579*		*116.3*	*146.8*					**1 000**			
	International investment costs with low shear factor and different storage volumes											
2011x M1_1b	*0.3409*		*215.9*	*147.1*	230	200	0	0	**3 000**	3 801	2 661	0.08
2011x M1_1a	*0.3135*		*237.6*	*147.7*					**1 000**			
	Barbados investment cost with low storage volume and different shear factors											
2011x14	*0.3575*	2011	*237.6*	*147.7*	230	200	0	0	1 000	**4 500**	**4 130**	**0.08**
2011x15	***0.3186***		***118.9***	***146.8***								**0.2**

1.3 Results on the necessary policy framework

Considering the scenario results derived at the workshop, the participants discussed that a reliable policy framework will be absolutely essential for a successful transition to a high level of renewable power.

The main results of this discussion can be summarized in the following points:

- The long term reliability of the policy framework is absolutely essential for all investments in renewable energy technologies
- A reliable discounted cash flow from the investment will secure very high bankability of the investments and low interest rates
- High bankability will allow a maximum share of domestic citizen ownership, cheap international loans and a maximum benefit for Barbados' economy
- A fair feed-in-tariff seems to be the most appropriate policy framework for the necessary investments, if established as a highly reliable system
- Feed-in-tariffs, once granted for a realized investment should therefore never be changed after the original tariff has been granted
- The details of a well functioning feed-in-tariff system can be derived from the German experiences made over almost twenty-five years
- Feed-in-tariffs should be differentiated according to a number of criteria (like renewable energy source, installation size or characteristics of a wind turbine site) to make for a level playing field
- A functioning feed-in-tariff system will require the right for every producer of renewable power to be connected to the grid and to sell electricity to the grid
- The uptake of renewable power by the grid will need to have priority over conventional power production
- The grid operator (BL&P) will need to be obliged to connect all renewable power producers to the grid
- In case the local grid is not strong enough for the uptake of all renewable power produced in the area, BL&P needs to be obliged to improve the grid to the necessary level as fast as possible
- If the government should decide to put additional taxes on the renewable energy investments, after fixed feed-in-tariffs have been granted, the tariff needs to be automatically adjusted to include these additional financial burdens on the investor
- The policy framework needs to include a strategic plan, with quantity targets for every year of the transition period to the final year set for reaching the 100% target
- Clear annual quantity targets can be used to prevent overshooting investment in to too much renewable energy capacity
- In order to keep the existing power generating equipment, which is mostly written off, as long term back up, a capacity payment needs to be guaranteed for BL&P in order to maintain the equipment in very good repair
- The present system costs of Barbados' power supply beyond the fuel costs, which were at 0.156 BBD/kWh in 2013, while fuel costs amounted to about 0.413 BBD/kWh, can be

seen as a good proxy for the long run system costs beyond the costs for the production and storage of renewable electricity
- If BL&P will receive approximately this sum for its future system operation, it could still make the same profits, even if generation investments were made by other investors from Barbados. This payment would already include a fair capacity payment for keeping all existing power generation equipment in good repair
- BL&P will be just one investor in renewable energy systems among all other players, with the same conditions applied to each investor
- Until a feed-in-tariff system is in place, fair standardized PPAs (power purchase agreements) can be used as an intermediate policy
- Although it is highly unlikely that solid waste gasification or solid waste combustion will be competitive in the future renewable energy system, a waste incineration facility may be necessary for waste management reasons
- Any waste to energy facility will need to be assessed on the basis of its merits for solving the waste problem on Barbados and its energy generation cost
- It may well be that a positive price on the incineration of waste needs to be charged to the producers of the waste to reduce the energy cost to a competitive level
- For economic reasons a possible waste incineration facility should be kept to the capacity necessary for handling Barbados' domestic waste
- The technology used for waste-to-energy conversion should be as cheap and robust as possible to keep the costs for solving Barbados' waste problem to the minimum.

2 Short description of the model and assumptions used

2.1 The logics of the simulation model

In the following section the logics of the model used for the simulations is briefly explained. The model calculates for every hour of a given year the electricity demand, the wind energy produced, the solar energy produced, the production from solid fuel combustion like solid biomass or waste, the hourly storage of excess power production, the production of power from storage, if the inflexible power production is not sufficient to meet demand and the power production from flexible back up like conventional diesel generators or diesel generators using liquid biofuels instead. The capacities for the generation technologies are given as scenario parameters specified by the users, as well as the storage volume for pump-storage hydro. The capacity for the backup system (biodiesel) is calculated by the model as are the capacity of the pumps and generators of the pump hydro storage system and the storage volumes for biogas and generator gas from waste gasification.

The logic used for the hourly calculation is the following:

- The power demand for the hour is taken from the load curve
- The wind power produced is calculated based on measured wind speed data and typical turbine characteristics
- The PV power generation is calculated based on the measured solar radiation and the characteristics of typical PV installations
- Power production from solid biomass is calculated with a profile complementing the average solar production of a day (biomass high at night and low during the day)
- Power production from solid waste combustion is calculated with a constant output in order to avoid maintenance problems with intermittent operation
- The hourly production from wind, PV, solid biomass and waste combustion are subtracted from the hourly demand
- The remaining difference is kept as residual load 1 (R1)
- If R1 is positive, additional production is necessary to meet demand
    - If additional power production is needed, this is taken from storage, as long as storage holds enough energy
    - If storage does not hold enough energy, the remaining load (R2) needs to be produced from other sources
        - If there is enough biogas stored, the remaining load, R2, will be covered by the use of biogas
            - If there is not enough biogas stored, the remaining load, R3, will be covered from stored generator gas produced from waste gasification
                - If there is not enough generator gas remaining to cover R3, the remaining load, R4, is covered by the use of biodiesel in the conventional generators. It is assumed that there will always be enough biodiesel or diesel stored in the existing storage tanks to cover the remaining load
- If R1 is negative, this volume of energy can be stored, if enough storage is available
    - If there is not enough storage volume remaining, the excess production is spilled or down regulated
- The model keeps track of the changes in all storage volumes (pump storage hydro, biogas and generator gas)
- The model can be run with a subset of the technologies mentioned
- The model can also include geothermal power production or run-of-river hydropower, if needed.
- The model includes the necessary economic data and calculations to derive levelized cost of electricity (e.g. investment costs, operation and maintenance costs, interest rates, operational life times of equipment).

The results of the model are summarized in the input/output sheet in a rather compact format as example in Table 2 below shows. These results are shown directly below the main input parameter settings, which are changed for the scenario runs. This part of the input/output sheet is shown in Table 3 below.

Table 2: Output section of the model showing the key results of a scenario run (scenario 2012x)

Summary of results	Barbados Wind 2012xM1.xlsx	
Cost per kWh used	**0.2501**	**BBD/kWh**
Max pump capacity	277.3	MW
Max turbine capacity pump storage	194.9	MW
Electricity stored	-143 623	MWh
Electricity produced from storage	122 571	MWh
Power generation capacity for Biogas Power	0.0	MW
Power generation capacity for Waste to Energy	0.0	MW
Biogas storage volume required	0.0	MWh gas
Syngas storage volume required	0.0	MWh gas
Biogas storage volume required at ambient pressure	0.0	m^3
Syngas storage volume required at ambient pressure	0.0	m^3
Necessary Biodiesel capacity	143.8	MW
Total biodiesel demand	24 747	MWh
Total biodiesel demand in t ((0,2l/kWhel)	4 949	t Diesel
Total overproduction power	486 624	MWh
Total overproduction gas	0	MWh gas

Table 3. Central parameter settings for specifying a scenario (scenario 2012x)

CAPACITIES (AGGREGATED)	Wind year	2012
Wind Power	230	MW
PV	205	MW
Solid Biomass Capacity installed	0.0	MW
Geothermal Capacity installed	0	MW
Waste to Energy Combustion	0	MW
Run of River Hydropower	0	MW
Biogas to Power Capacity installed	0.0	MW el
Waste to Energy Gasification installed	0.0	MW el
Start Volume Storage	0	MWh
Max Storage	3 000	MWh
Storage efficiency (one way)	0.866	

2.2 The assumptions made

For the operation of the model, a number of economic and technical assumptions need to be made. Table 4 below shows the standard settings for the economic and financial parameters, while Table 5 shows the technical parameter settings.

Table 4. Economic and financial parameter settings (scenario 2012x)

FINANCIAL PARAMETERS		
Lifetime Wind Turbine	20	a
Lifetime PV Plant	20	a
Lifetime Solid Biomass Plant	25	a
Lifetime Geothermal Power Plant	25	a
Lifetime Solid Waste to Energy Plant	25	a
Lifetime Run of River Hydropower	50	a
Lifetime Biogas to Power Capacity	20	a
Lifetime Waste to Energy Gasification	15	a
Biodiesel generator	25	a
Lifetime Pump Storage Hydro Plant	50	a
Lifetime Gas storage (gas field)	50	a
Investment cost Wind Power	1 050.00	€/kW
Investment cost solar PV	1 500.00	€/kWp
Investment cost Solid Biomass Plant	8 418.84	€/kW
Investment cost Geothermal Plant	5 000.00	€/kW
Investment cost Solid Waste to Energy Plant	4 000.00	€/kW
Investment cost Run of River Hydropower	5 000.00	€/kW
Investment cost Biogas to Power	2 500.00	€/kW
Investment cost Waste to Energy Gasification	10 523.55	€/kW
Investment Biodiesel generator	2 500.00	€/kWh
Investment cost Pump Storage Hydro Plant	120 000.00	€/MWh
Investment cost Gas storage (old gas field)	100	€/MWh gas
Operation and Maintenance cost (O&M) Wind Power	5	%/a of invest
O&M (PV)	5	%/a of invest
O&M Solid Biomass Power Plant	10	%/a of invest
O&M Geothermal Power Plant	5	%/a of invest
O&M Solid Waste to Energy Plant	5	%/a of invest
O&M Run of River Hydropower	3	%/a of invest
O&M Biogas to Power	5	%/a of invest
O&M Waste to Energy Gasification	10	%/a of invest
O&M Biodiesel Generator	5	%/a of invest
O&M Pump Storage Hydro Plant	4 000.00	€/MW Pump
O&M Gas storage	1	%/a of invest
Fuel Costs Solid Biomass	25	€/MWh (input)
Fuel Costs Waste	1	€/MWh (input)
Substrate cost Biomass	25	€/MWh (input)
Interest rate	6	%
Cost of Biodiesel in €/t	520.00	€/t
Cost of Biodiesel €/MWh	200.00	€/MWh

Exchange rates to US Dollar and to Euro	
Conversion factor Euro/US Dollar 2014	1.267
Conversion factor Euro/Barbados Dollar 2014	2.534

Table 5. Technical parameter settings (scenario 2012x)

LOAD		
2010 demand	1 065 964	GWh/a
Demand increase (rel. to 2010)	0.00	%
Wind power technical parameters		
Hub height of wind turbines	66.00	m
Roughness coefficient	0.20	
Wind year (high=2012, low=2011)		
Average wind speed 2012	6.74	m/sec
Average wind speed 2011	5.57	m/sec
PV technical parameters		
Annual irradiation on horizontal	2 024.69	kWh/m²
Module Peak Capacity	127.50	Wp
Area Requirement	8.00	m²/kWp
Module Area	1.02	m²
Specific annual production	2 065.18	kWh/kWp
Pump storage hydro plant technical parameters		
Head in m	300.00	m
Efficiencies		
Solid Biomass Electrical Efficiency	0.40	
Biogas or Electricity Plant	0.48	
Solid Waste to Energy Plant Electrical Efficiency	0.45	
Waste Gasification to Energy electrical efficiency	0.30	
Geothermal power electrical efficiency		
Pump storage pumping efficiency	0.87	
Pump storage generating efficiency	0.87	
Compression losses biogas	3.00	%
Compression losses syngas	3.00	%
Biodiesel to electricity	0.48	
Methane energy content per m3	9.94	kWh/m3
Syngas energy content per m3	1.24	kWh/m3
Energy per t dry matter of solid biomass		MWh/t
Energy per t of waste		MWh/t
Geothermal Power - Technical Parameters		
Temperature level available		°C

For some more sophisticated scenario variations each parameter assumption can be changed, as this has been done in the case of the typical Barbados investment costs for wind and PV or in the case of a different sheer factor.

A variation of the hourly wind data used (wind year 2011 instead of 2012) takes a more complex intervention in the model, as this can not be changed by a simple parameter in the input page, but by addressing a different wind vector in the resource calculation part of the model.

2.3 Additional explanations on a possible feed-in-tariff and its structure and the future structure of Barbados' power costs

During the workshop there was an extensive discussion of the necessary policy framework for a successful transition towards a 100% renewable energy system. As this centred around the possibilities and structures of feed-in-tariffs some of the explanations given are reported here.

Furthermore the future power cost structure of Barbados was discussed, which may have an important impact on the possibility to have a widespread community ownership of the new renewable energy technologies and to keep BL&P at least as profitable as in 2013 at the same time. The basic considerations on this point are reported below as well.

2.4 Structure of a feed-in-tariff

Feed-in-tariffs are a fixed price per kilowatt hour (kWh) at which the grid operator has to buy all electricity produced from renewable energy sources from every power producer. The price is ordinarily guaranteed for 20 years, once it has been granted. Normally the sale of renewable electricity is granted priority access to the grid. The cost of the renewable power purchased by the grid operator is handed on to all final consumers as it is integrated into the rate base.

As the investment costs of renewable energy systems like wind or solar PV have decreased substantially over time, most feed-in-tariff systems have a built in digression over time (e.g. 1.5%/a) for installations carried out in later years. Thus, if a feed-in-tariff for wind energy is fixed at 0.10 BBD/kWh for installations made in 2015, the tariff for 2016 would be 0.0985 BBD/kWh, 0.970 BBD/kWh in 2017, 0.956 BBD/kWh in 2018, and so on. As the cost digression may not be a constant factor over time, the rates are re-evaluated after two or three years.

Figure 1 below shows the development of the German feed-in-tariff for PV systems from 2000 to 2015. It obviously started at a level too low to induce substantial investment, although there was a massive subsidy programme (100,000 roof-programme) to support PV installations in addition to the feed-in-tariff. Thus, the feed-in-tariff was substantially increased in the second half of 2004. As Figure 2 shows this has jump-started the large scale deployment of PV systems in Germany. After 2004 the feed-in-tariff was gradually reduced from 0.574 €/kWh in 2004 to 0.1231 €/kWh by the end of 2015. Due to the massive increases in PV system production induced by the initial high feed-in-tariff and the resulting cost reductions it was possible to reduce the tariff over ten years to less than 25% of its initial value.

Figure 2. Development of the German feed-in-tariff for PV systems in €/kWh from 2000 to 2015 (1€ = 2.53 BBD in 2013) (Source: own compilation based on different publications)

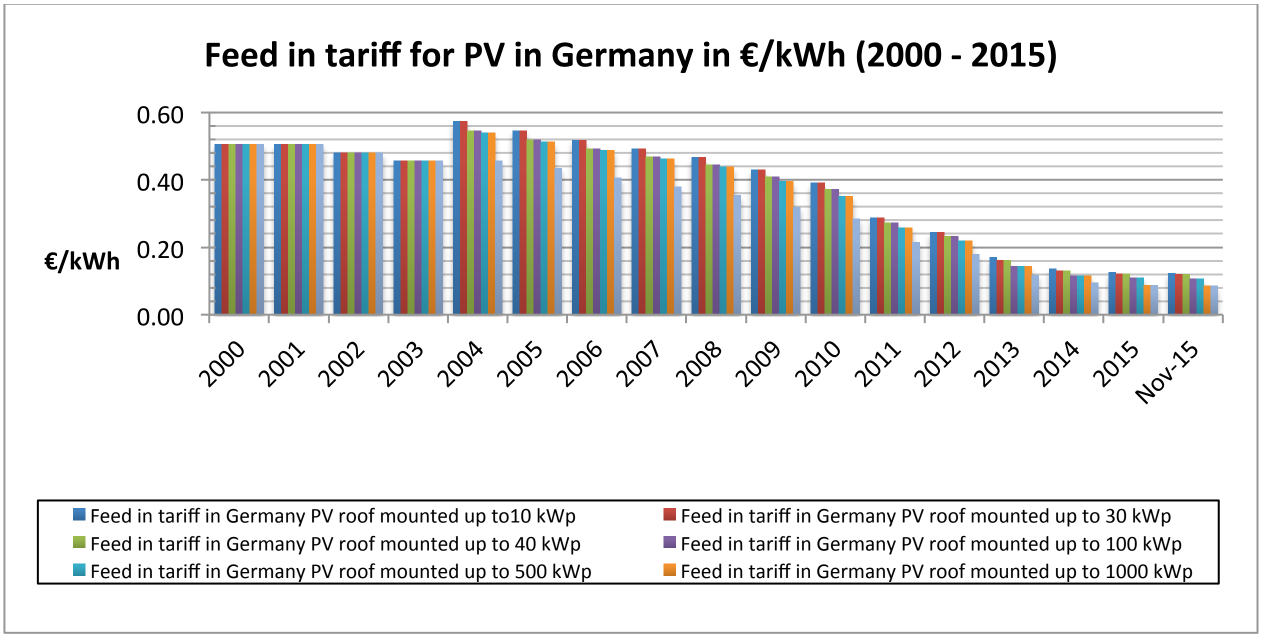
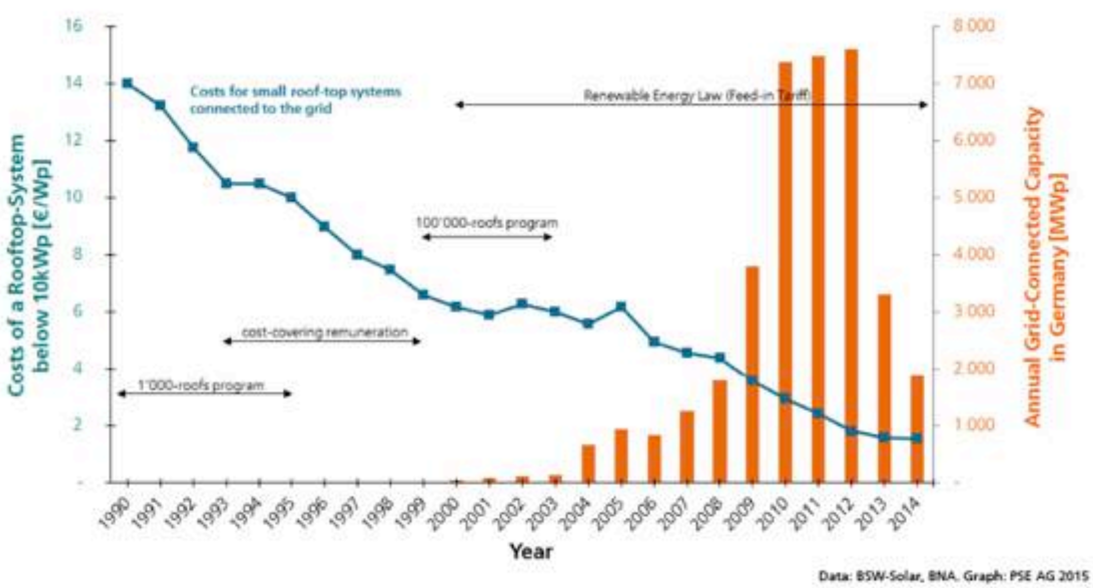


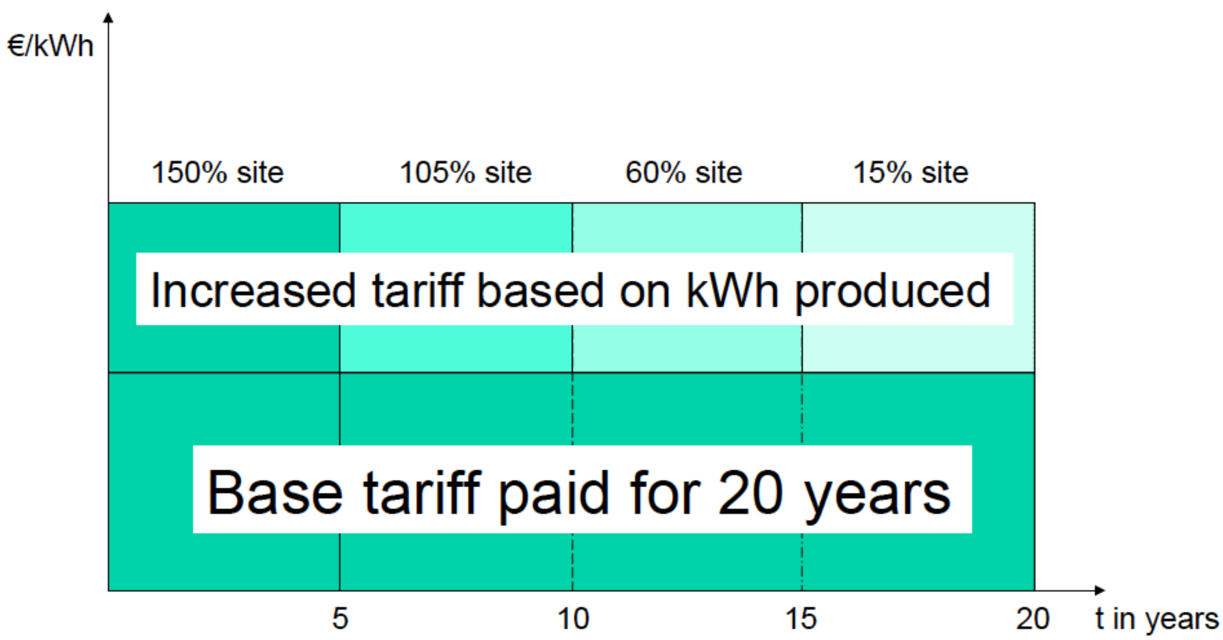
Figure 3: Development of the investment cost for small rooftop PV systems and total installed PV capacity in Germany from 1990 to 2014 (Source: PSE AG 2015)



In order to levelize the payments for wind energy under the German feed in tariff, the tariff is differentiated according to the wind speed at any given site. A very good wind site is taken as a reference site. For this site the feed-in-tariff is calculated to guarantee a fair but modest return on the investment based on the specific wind energy production at a site producing 150% of the annual output of the reference site. In 2004 a basic feed-in-tariff of 5.9 c€/kWh was paid for twenty years. For the 150% site an additional initial payment 3.0 c€/kWh was paid for the first five years of operation to allow a fast amortisation of the investment. For all other sites the payment of the additional payment was extended by 2 month for every 0.75% of power production lower than the production from the 150% site. Thus, for every 9% lower output the additional payment of 3.0 c€/kWh was extended by one year. A site with 105% of the reference site's output would get it for 10 years, a site with 60% for 15 years, and a site with 15% of the output would get it for the entire 20 years. The structure of the tariff is shown in Figure 4.

This is a rather cumbersome method to achieve a similar return on the initial investment independent of the quality of the site. A similar, but simpler method would be to calculate the number of kilowatt-hours necessary to pay back the initial investment for a good reference site. The high initial payment is granted for this period. After this period the tariff is reduced to the lower long-term rate for the reference site. For every other site, the higher payment is granted for the same number of kilowatt-hours per kilowatt installed. Afterwards the payment will be reduced to the lower long-term rate, which is oriented towards paying the operation and maintenance costs plus a fair profit.

Figure 4. Structure of a split feed-in-tariff (German wind energy FIT of 2004)



2.5 Future power cost structure for Barbados

As the discussion of the potential for wind energy on Barbados and the visualization of the siting of the wind turbines on possible sites around the island showed, public acceptance will be a central condition for the success of a transition process towards a low cost renewable energy future for Barbados. International experience has shown that the acceptance of renewable energy strategies largely based on wind and solar energy is strongly correlated with citizen ownership of at least a major share of the installed capacities in their neighbourhood. This implies that under the given space constraints of

Barbados, where wind and solar installations can only be placed relatively close to human activities, citizen ownership will be essential for the transition to a 100% renewable power supply.

At the same time Barbados Light and Power (BL&P) needs to remain a healthy utility company to guarantee the safe and reliable operation of Barbados' electricity system. Thus, the citizen ownership of a major share of renewable energy production technologies may not endanger the solid economic operation of BL&P. At the workshop a model was discussed that will guarantee both high levels of citizen involvement and investment, as well as a solid economic operation of BL&P.

This model assumes that BL&P will receive the same payment as in 2013, which was 139.8 million BBD/a or 0.156 BBD/kWh for the operation of the system including the present depreciation on its equipment as well as its profits. It is the amount remaining once the expenses for fuels of 376.7 million BBD/a or 0.413 BBD/kWh are subtracted from the total production costs of 516.5 million BBD/a or 0.566 BBD/kWh. Thus, an annual payment of 140 million BBD should cover all other system costs beyond the costs for generating and storing the power from renewable energy systems. There may be a need for minor future adjustments due to wage increases or other cost increases for the operation and maintenance of the electricity system besides the costs for power generation.

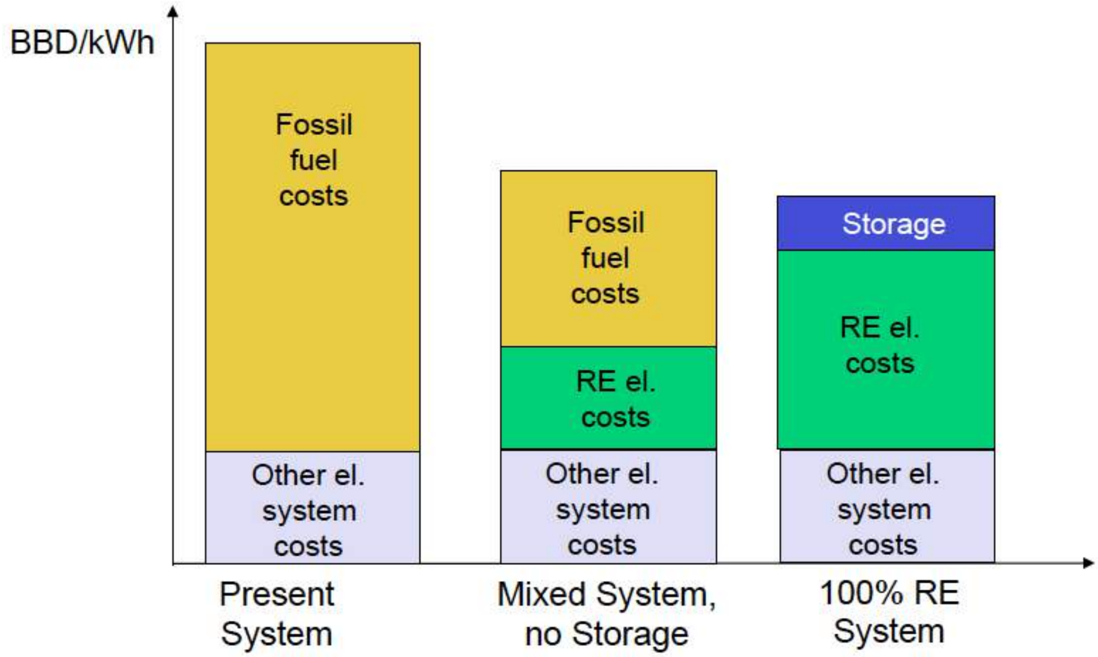
Figure 5 below shows the structure of Barbados' electricity costs on the basis of fossil fuels in 2013, the cost structure with a 50% renewable and 50% fossil power supply without storage, and a 100% renewable power supply with storage.

The approach guarantees that even if 100% of the renewable power production would be owned directly by the citizens of Barbados, BL&P would still have a solid economic base and no smaller profits than in 2013.

In case BL&P would also own and operate some share of the renewable power generation facilities these would guarantee the same long-term rate of return to BL&P as to every other investor. The net profits from such investment or operation would then increase the income of BL&P. Whether this will be seen by BL&P as a sufficient rate of return on the new investment has to be decided by its management.

Furthermore, there may be an interesting business case for BL&P in the professional operation and maintenance of wind turbines for private investors, which might want to put this into the hands of professionals.

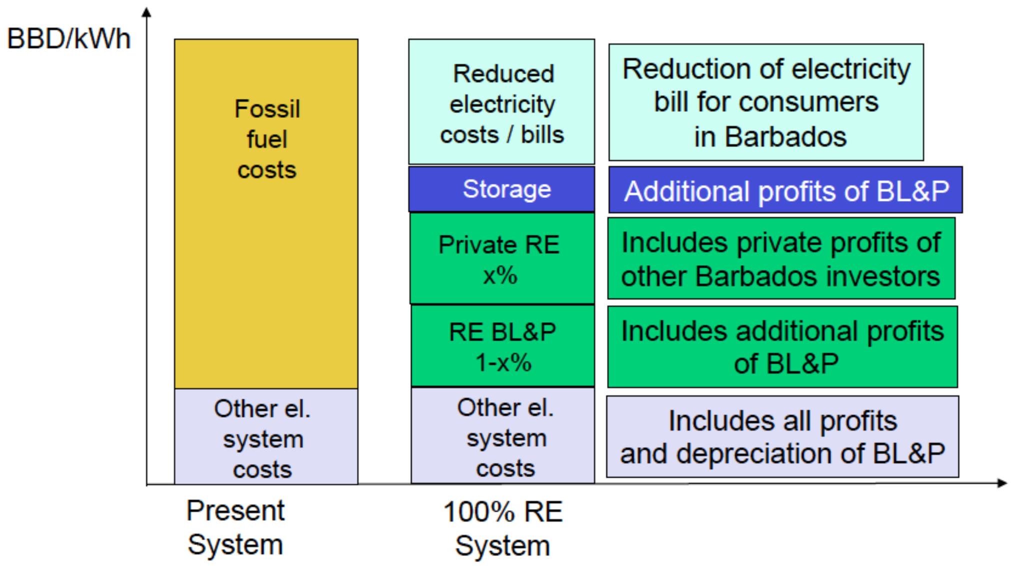
Figure 5. Barbados' power supply cost structure 2013, with 50% and 100% renewable energy production



In addition, BL&P may opt for the investment into the necessary storage facilities, which most likely will be pump-storage hydro facilities in the range of 50 to 250 MW capacity and 1,000 to 3,000 MWh of storage volume. Any profit made form the investment, operation and maintenance of such facilities could add to the profits of BL&P.

Figure 6 below shows the distribution of possible income streams and electricity consumer benefits of the discussed ownership model. It is fundamentally different from the fossil fuel based present situation, where the major profits are made by the oil companies selling fossil fuels to Barbados.

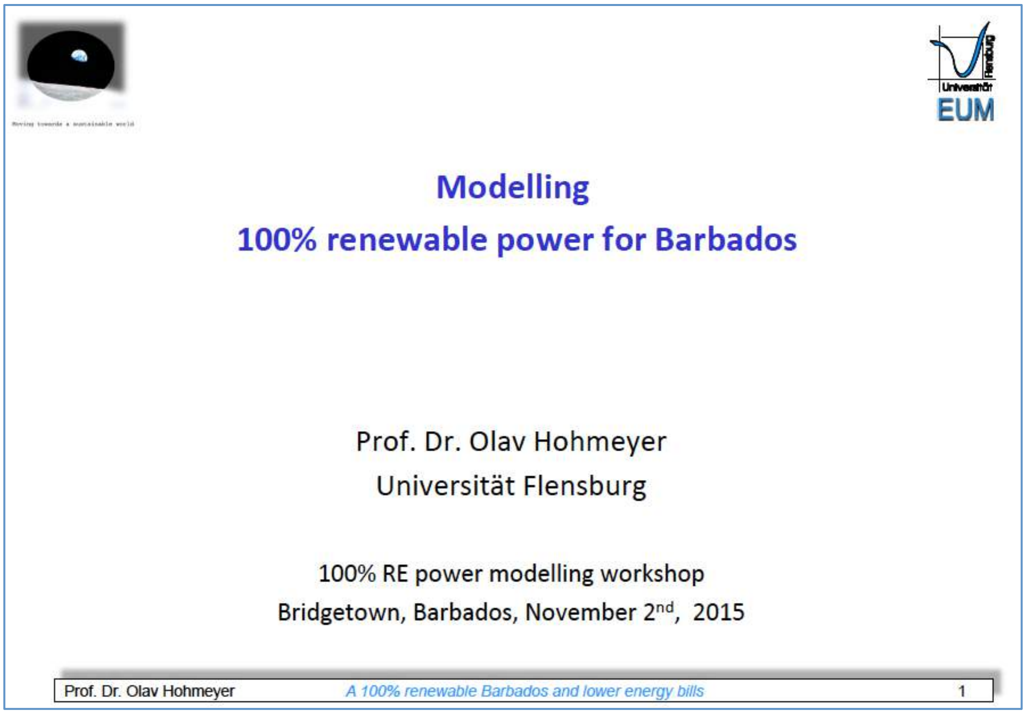
Figure 6. Basic distribution of income possibilities from Barbados' power production based on fossil fuels in the past and renewable energy in the future

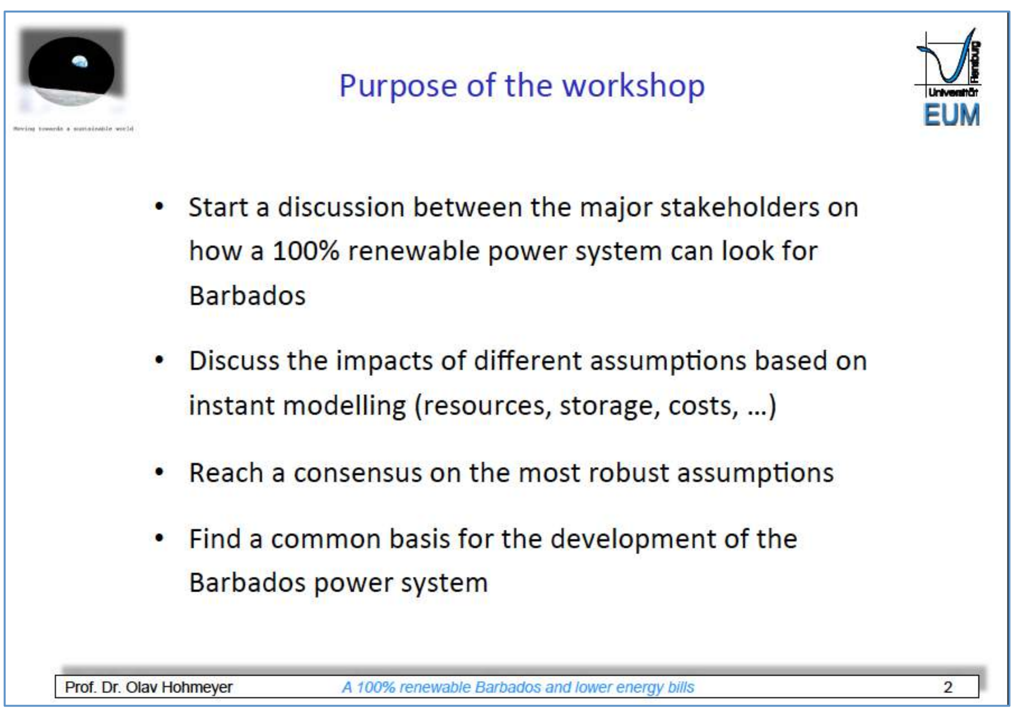


More than 70% of the money spent of electricity in 2013 was spent on imported fuels and was drained from Barbados' national economy (except for the taxes and duties paid on the imported fuels). The transition towards a 100% renewable power supply can benefit every citizen of Barbados through stable low electricity prices, guarantee a solid future for BL&P and pave the way for a broad scale participation of Barbados' citizens in the investment in and the earnings from Barbados' low cost, low risk sustainable energy future.

3 Appendices

3.1 Presentation by Professor Hohmeyer





Structure of the workshop

1. Short recap of the 100% results from 2014
2. Summary of the key assumptions made
3. Introduction of most recent wind power assessment
4. Three rounds of discussion of assumptions resulting in new specifications and calculations
5. Discussion of results of each round of modelling with new modifications of the assumptions
6. Hopefully a consensus on the most plausible assumptions will be reached

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2013 electricity demand and supply

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)

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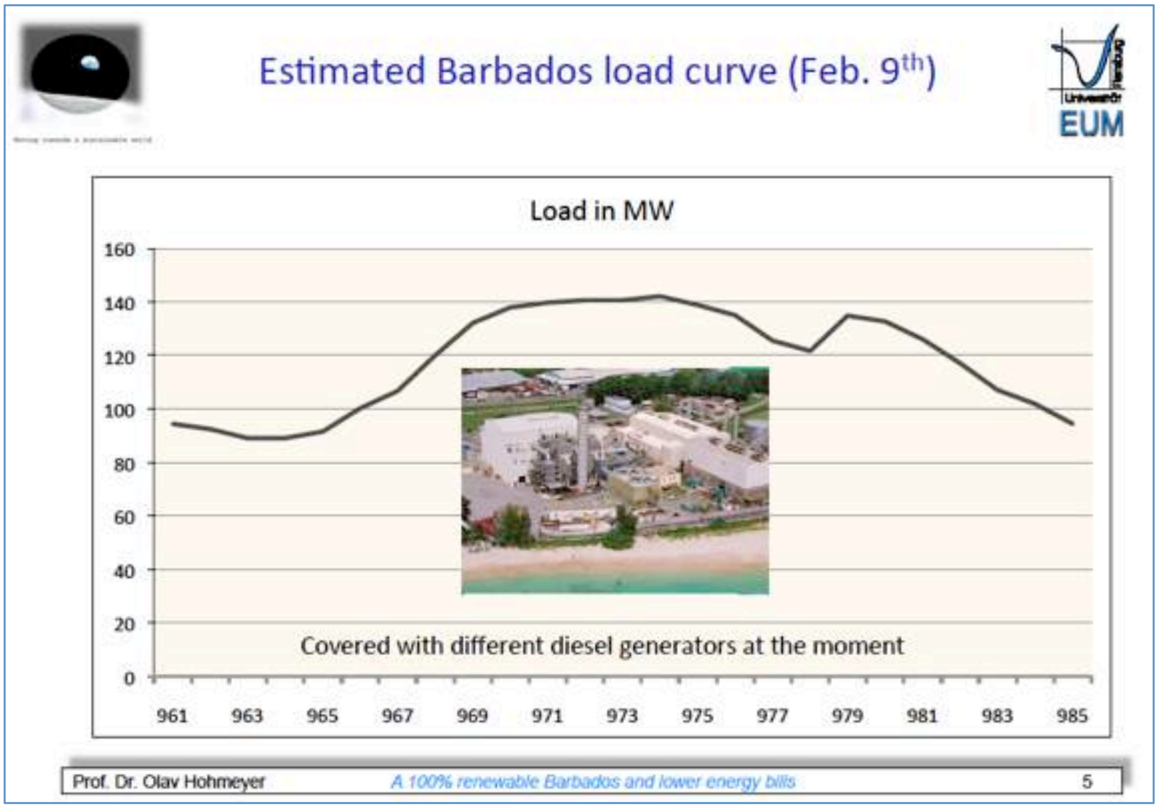
Estimated Barbados load curve (Feb. 9th)
EUM
Load in MW
160
140
120
100
80
60
40
20
0
961
963
965
967
969
971
973
975
977
979
981
983
985
Covered with different diesel generators at the moment
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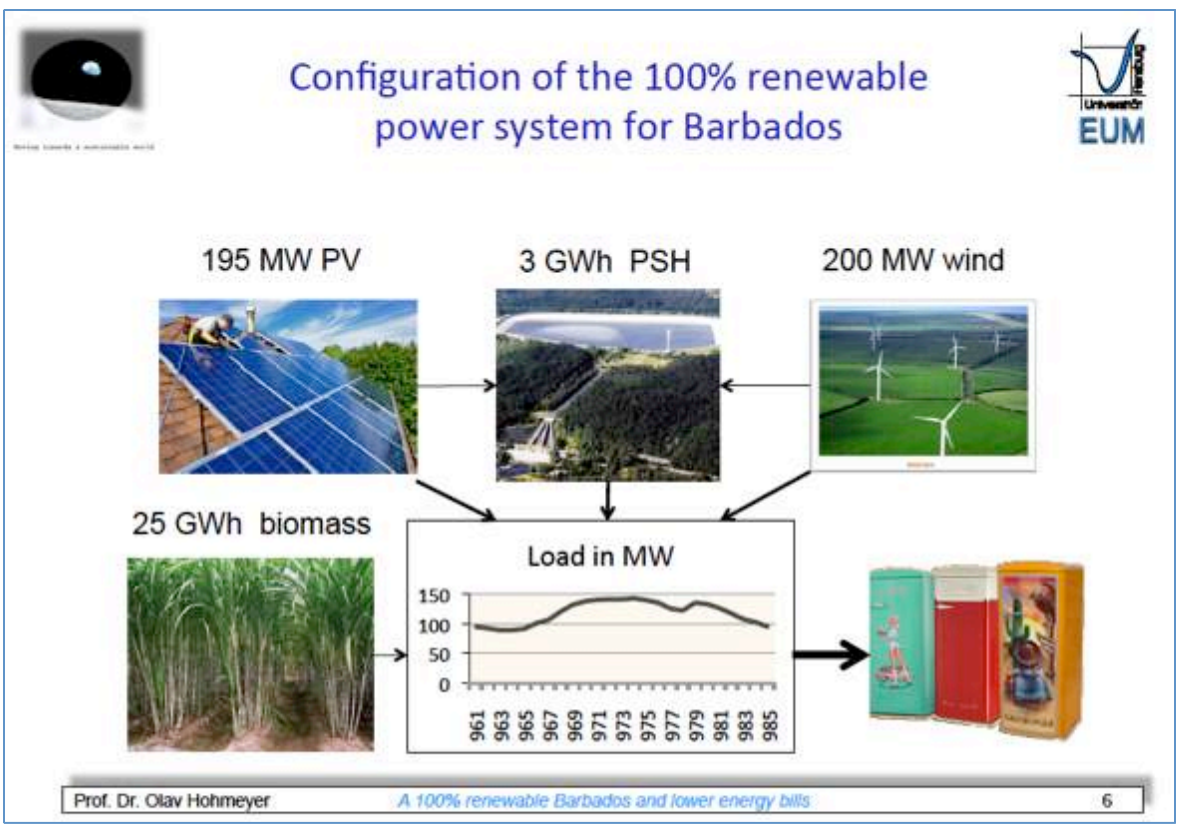
Configuration of the 100% renewable power system for Barbados
EUM
195 MW PV
3 GWh PSH
200 MW wind
25 GWh biomass
Load in MW
150
100
50
0
961
963
965
967
969
971
973
975
977
979
981
983
985
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The concept of residual load and the sequence of calculation

1. Starting point is the hourly load (demand) curve
2. All non controlled production (wind and PV) is subtracted from the load
3. All base load production is subtracted
4. Storage is used to meet the remaining load or to store overproduction
5. Fast starting production units are used to meet the load remaining after storage is empty
6. This will be existing conventional units using fossil fuels or liquid biofuels

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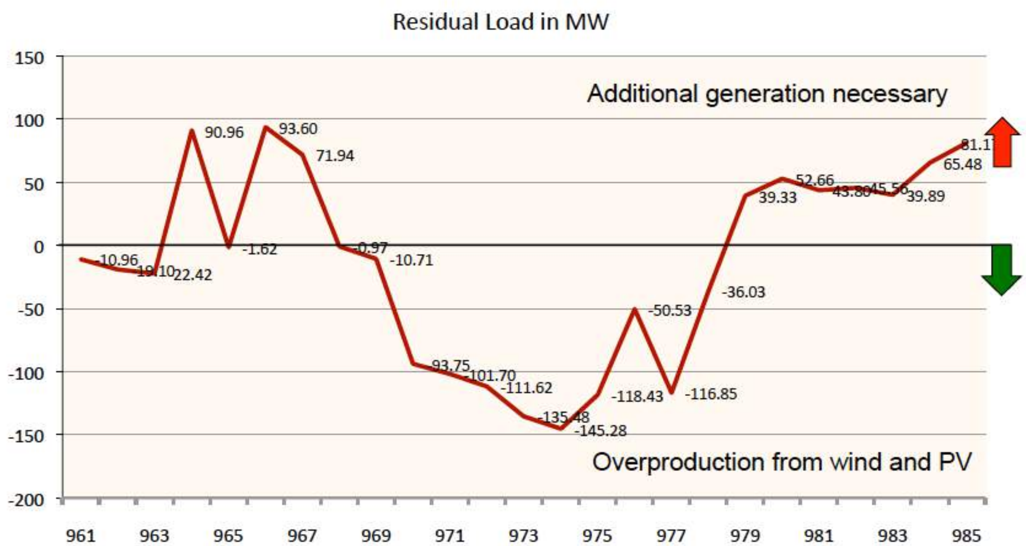
Residual load for 100% REN Barbados (load – wind – PV) (Feb. 9th)



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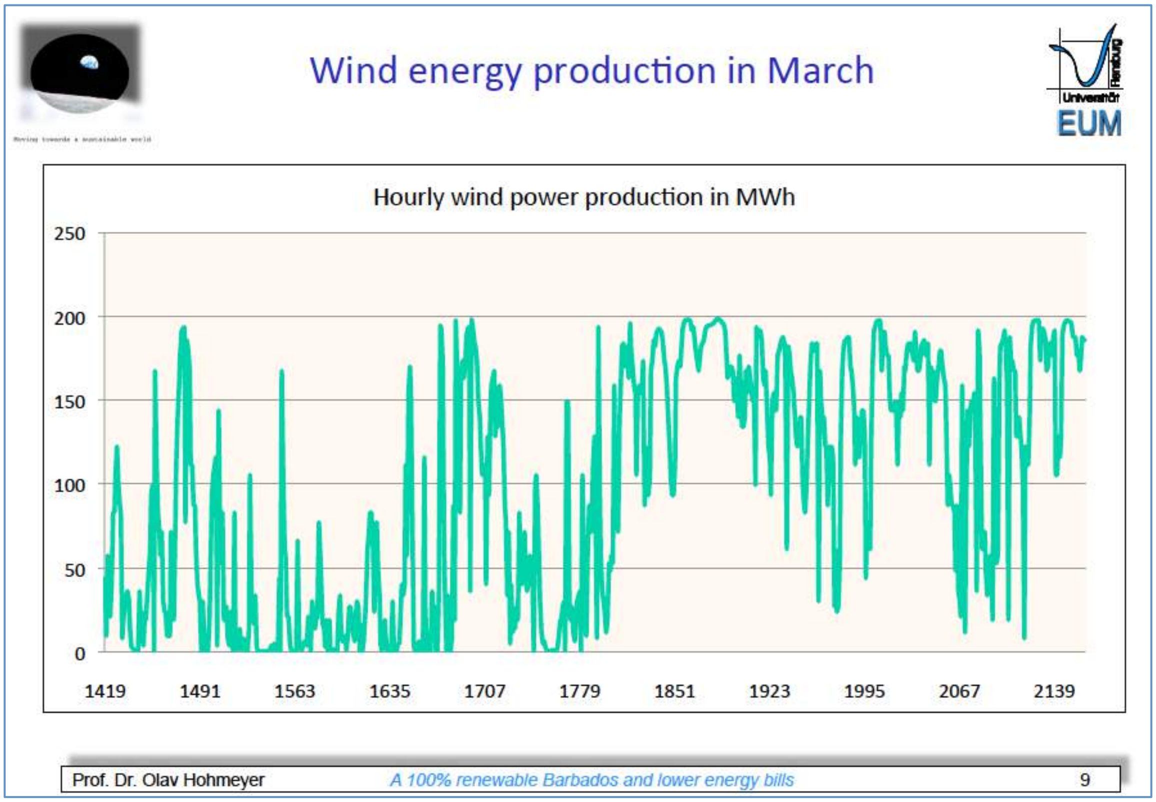
Wind energy production in March
Universität Flensburg
EUM
Hourly wind power production in MWh
250
200
150
100
50
0
1419
1491
1563
1635
1707
1779
1851
1923
1995
2067
2139
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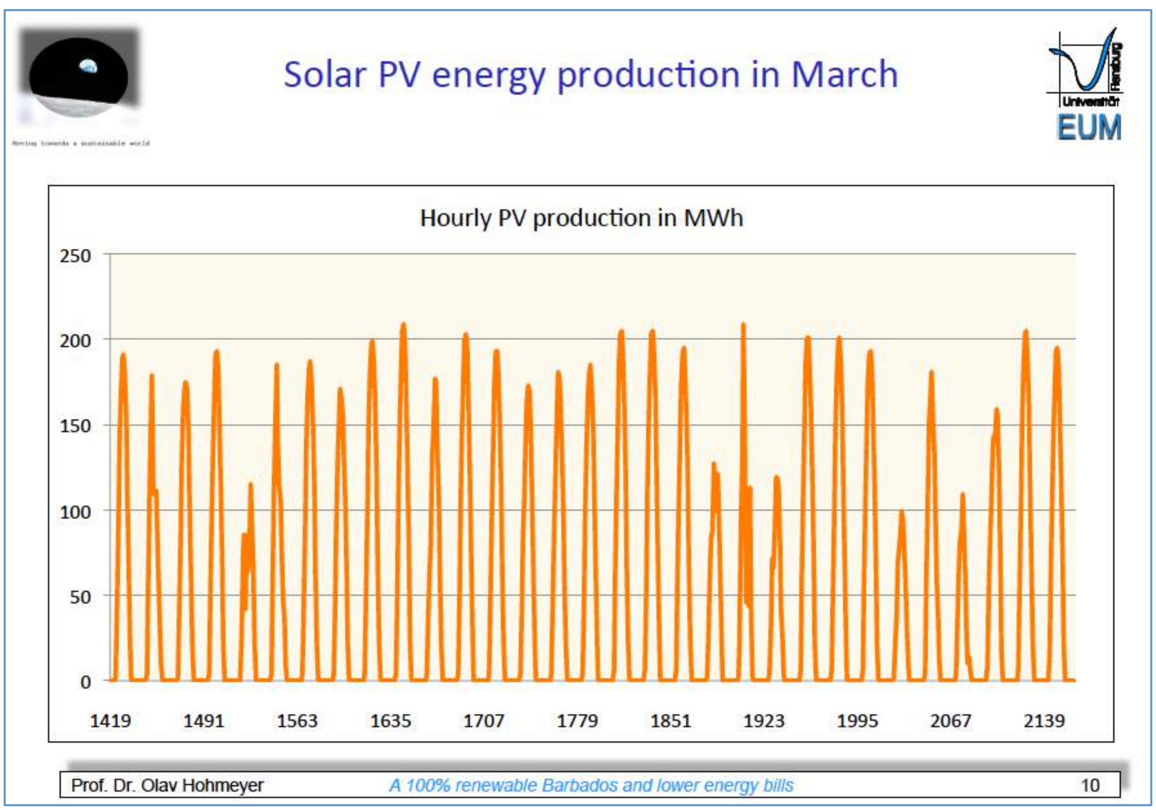
Solar PV energy production in March
Universität Flensburg
EUM
Hourly PV production in MWh
250
200
150
100
50
0
1419
1491
1563
1635
1707
1779
1851
1923
1995
2067
2139
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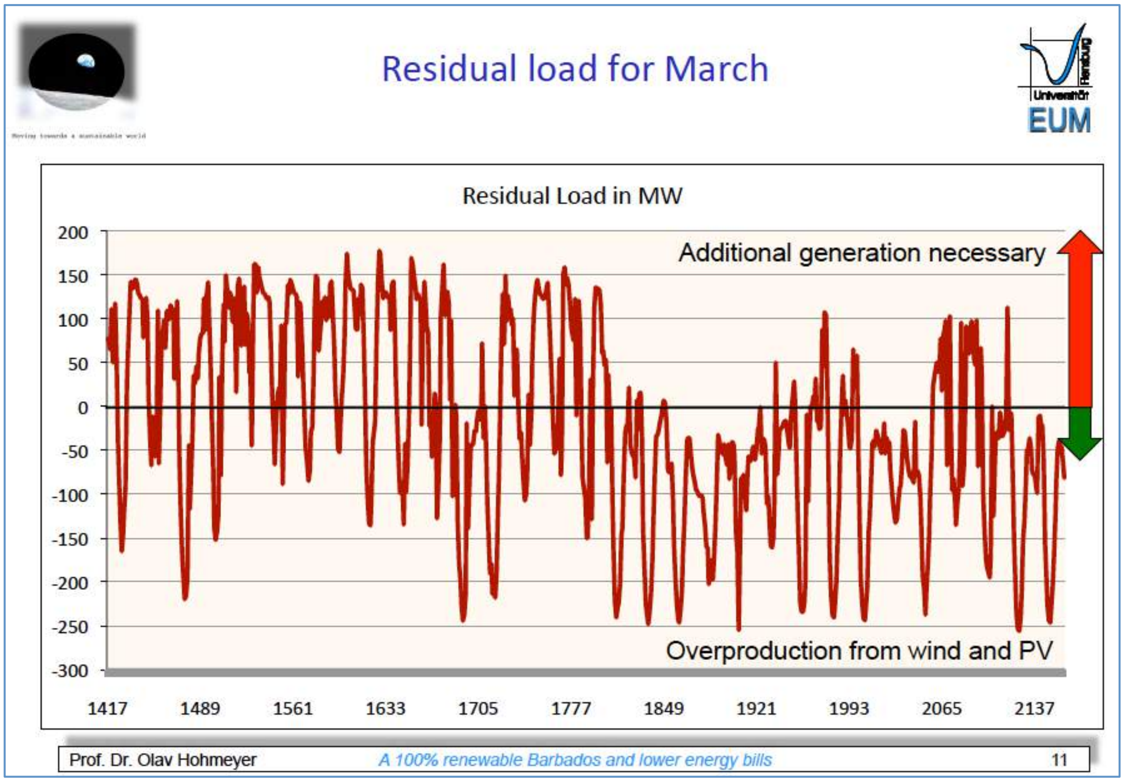
Residual load for March
Universität Flensburg
EUM
Residual Load in MW
200
150
100
50
0
-50
-100
-150
-200
-250
-300
Additional generation necessary
Overproduction from wind and PV
1417
1489
1561
1633
1705
1777
1849
1921
1993
2065
2137
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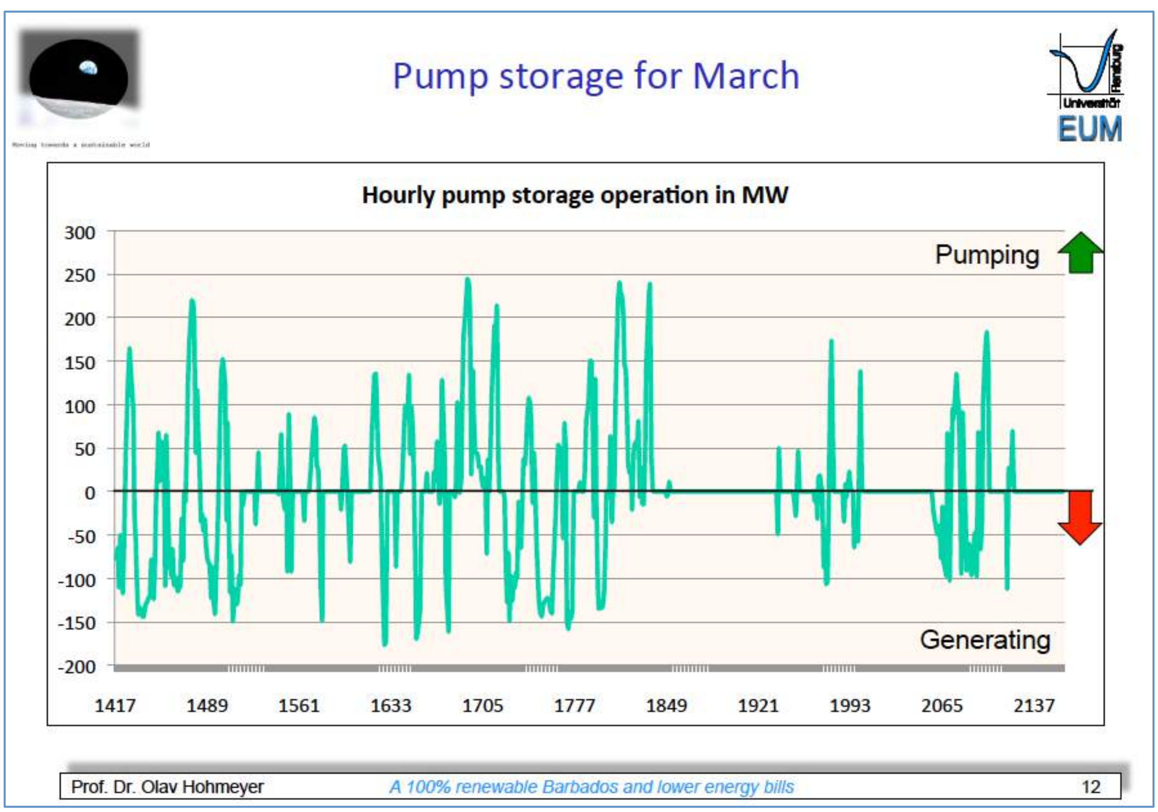
Pump storage for March
Universität Flensburg
EUM
Hourly pump storage operation in MW
300
250
200
150
100
50
0
-50
-100
-150
-200
Pumping
Generating
1417
1489
1561
1633
1705
1777
1849
1921
1993
2065
2137
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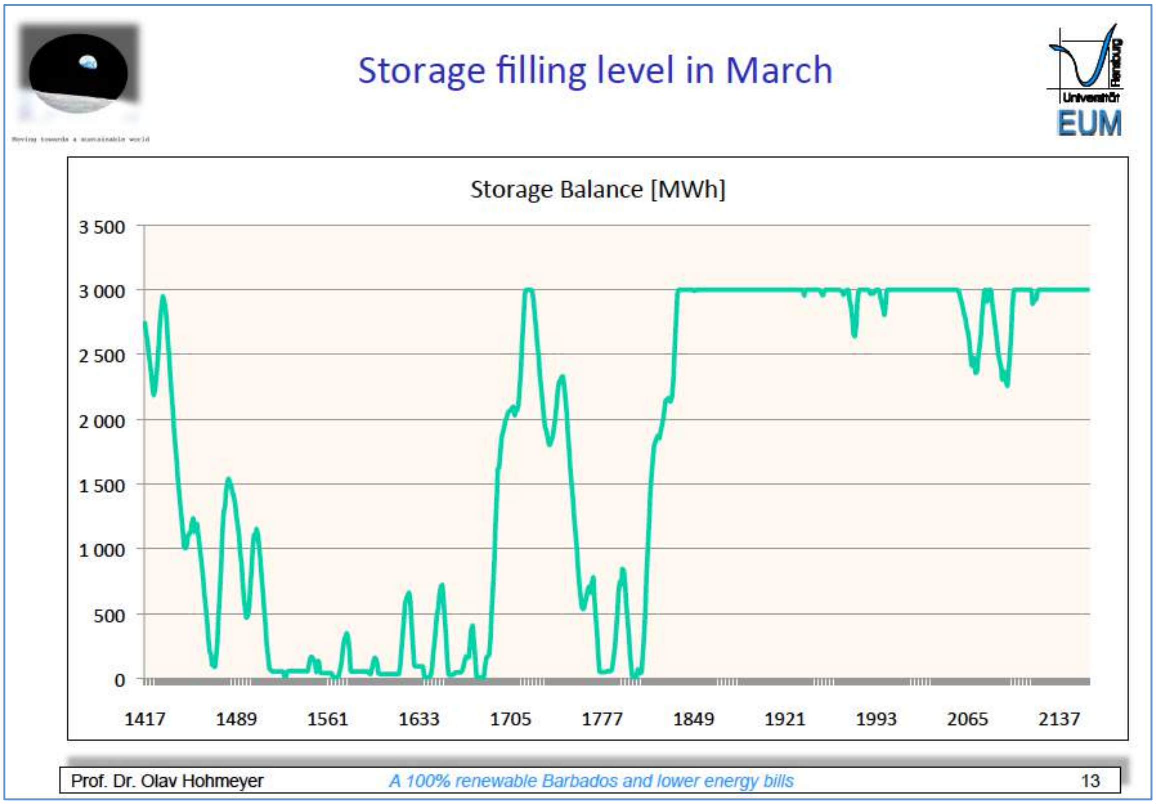
Storage filling level in March
Storage Balance [MWh]
3 500
3 000
2 500
2 000
1 500
1 000
500
0
1417
1489
1561
1633
1705
1777
1849
1921
1993
2065
2137
EUM
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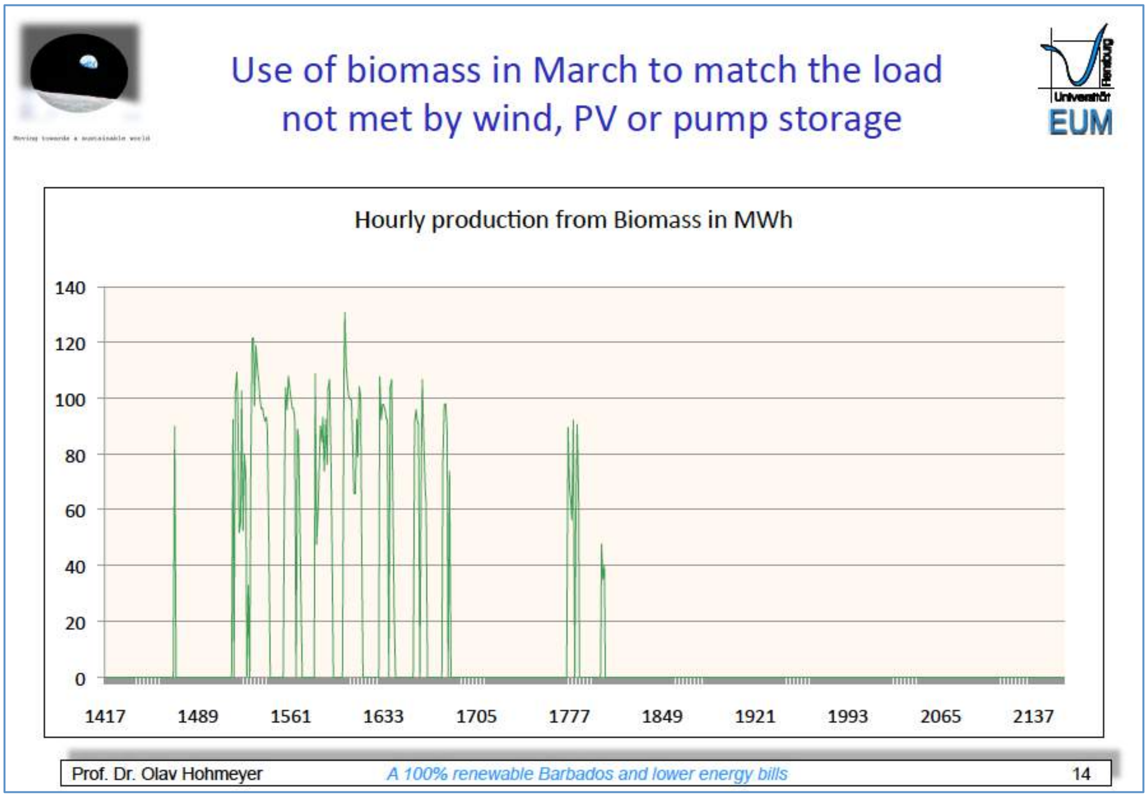
13


Use of biomass in March to match the load not met by wind, PV or pump storage
Hourly production from Biomass in MWh
140
120
100
80
60
40
20
0
1417
1489
1561
1633
1705
1777
1849
1921
1993
2065
2137
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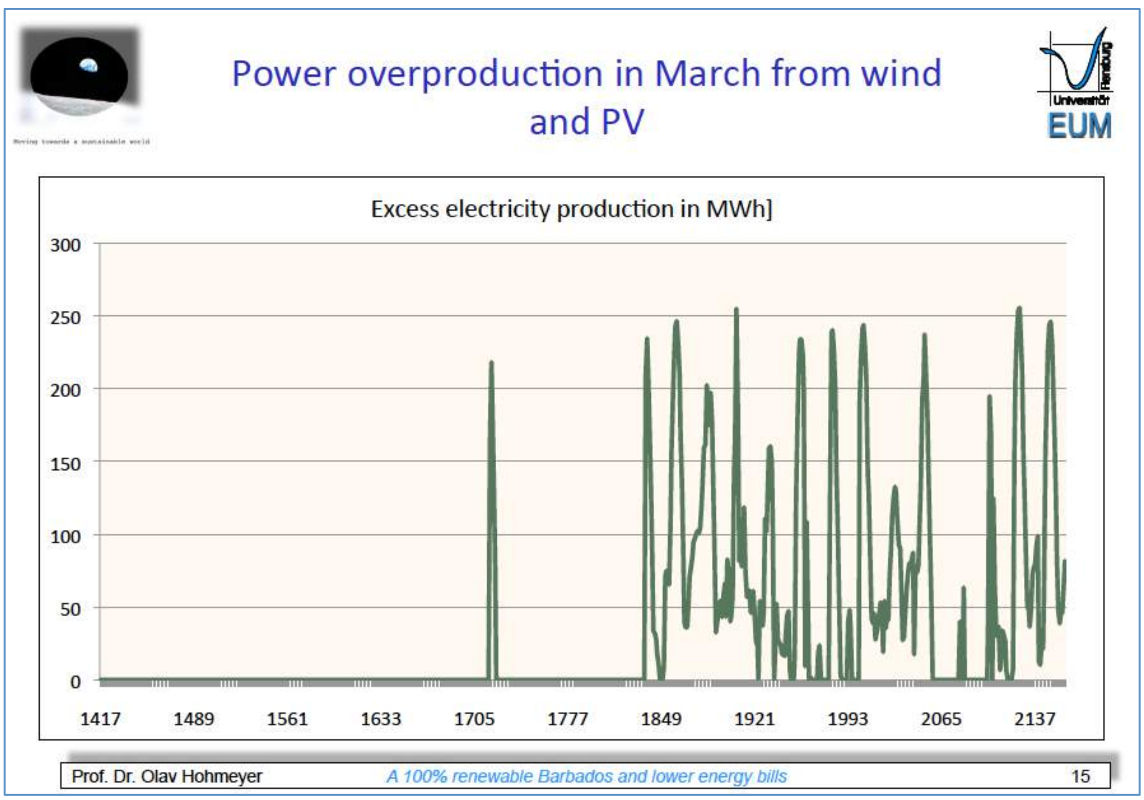
Power overproduction in March from wind and PV
Excess electricity production in MWh]
300
250
200
150
100
50
0
1417
1489
1561
1633
1705
1777
1849
1921
1993
2065
2137
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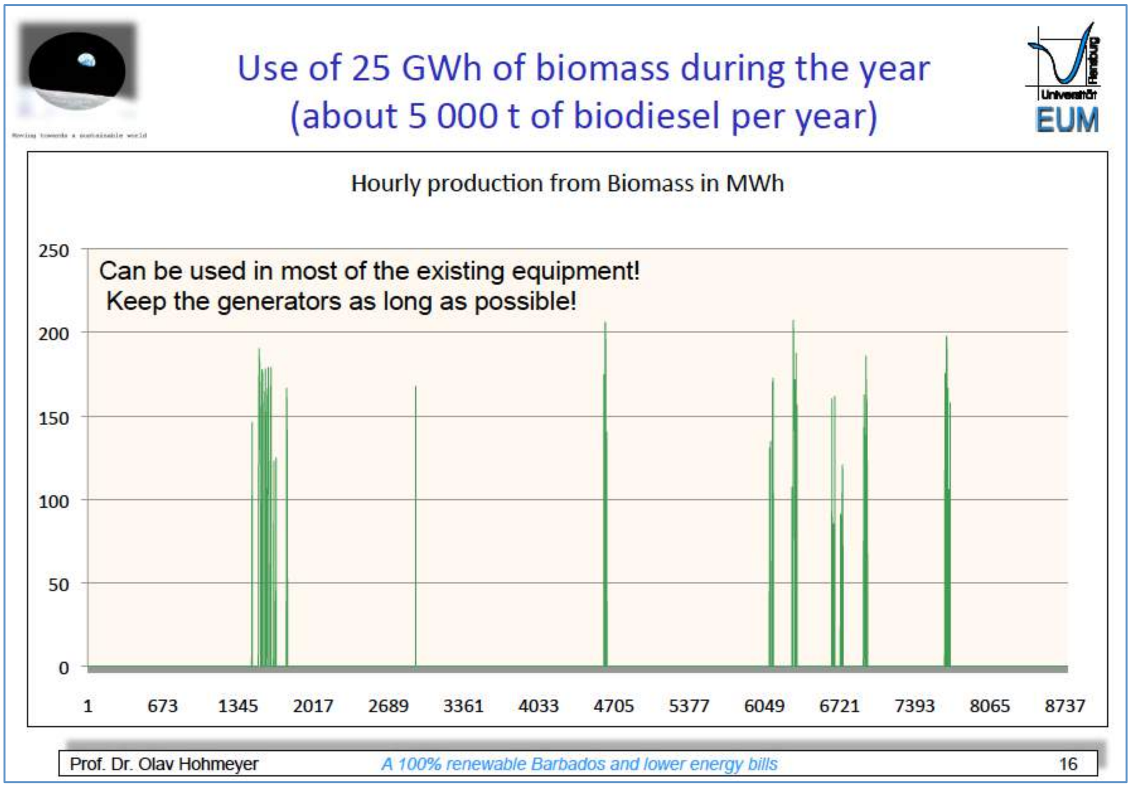
15


Use of 25 GWh of biomass during the year
(about 5 000 t of biodiesel per year)
EUM
Hourly production from Biomass in MWh
Can be used in most of the existing equipment!
Keep the generators as long as possible!
250
200
150
100
50
0
1
673
1345
2017
2689
3361
4033
4705
5377
6049
6721
7393
8065
8737
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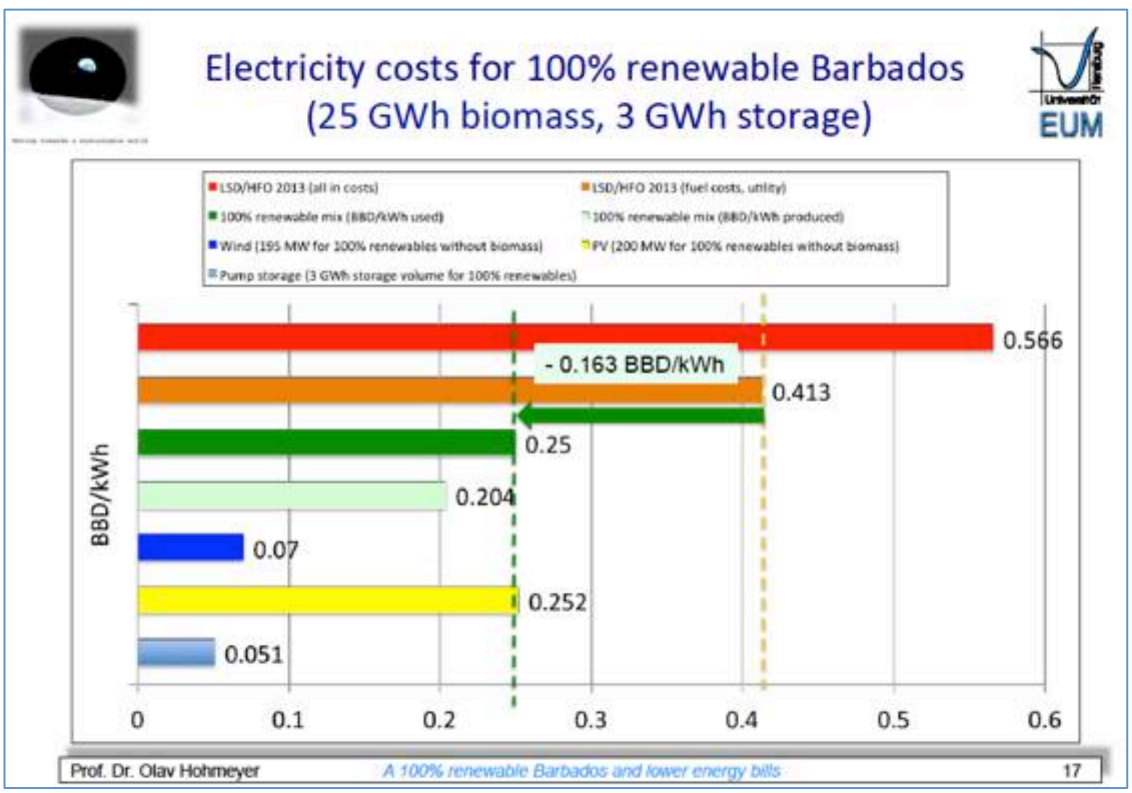
16


Electricity costs for 100% renewable Barbados
(25 GWh biomass, 3 GWh storage)
EUM
LSD/HFO 2013 (all in costs)
LSD/HFO 2013 (fuel costs, utility)
100% renewable mix (BBD/kWh used)
100% renewable mix (BBD/kWh produced)
Wind (195 MW for 100% renewables without biomass)
PV (200 MW for 100% renewables without biomass)
Pump storage (3 GWh storage volume for 100% renewables)
- 0.163 BBD/kWh
0.566
0.413
0.25
0.204
0.07
0.252
0.051
BBD/kWh
0
0.1
0.2
0.3
0.4
0.5
0.6
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17

Main assumptions made I

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

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Main assumptions made II

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

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Main assumptions made III

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

Exchange rate 2013 used: 1 € = 2.534 BBD

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Model input
Capacities installed

CAPACITIES (AGGREGATED)	Wind year	2 012
Wind Power	230	MW
PV	205	MW
Solid Biomass Capacity installed	0.0	MW
Geothermal Capacity installed	0	MW
Waste to Energy Combustion	0	MW
Run of River Hydropower	0	MW
Biogas to Power Capacity installed	0.0	MW el
Waste to Energy Gasification installed	0.0	MW el
Start Volume Storage	1 000	MWh
Max Storage	3 000	MWh
Storage efficiency (one way)	0.866	

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Model input
Financial parameters 1

FINANCIAL PARAMETERS		
Lifetime Wind Turbine	20	a
Lifetime PV Plant	20	a
Lifetime Solid Biomass Plant	25	a
Lifetime Geothermal Power Plant	25	a
Lifetime Solid Waste to Energy Plant	25	a
Lifegeime Run of River Hydropower	50	a
Lifetime Biogas to Power Capacity	20	a
Lifetime Waste to Energy Gasification	15	a
Biodiesel generator	25	a
Lifetime Pump Storage Hydro Plant	50	a
Lifetime Gasstorage (gas field)	50	a

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Model input
Financial parameters 2

Investment cost Wind Power	1 050.00	€/kW
Investment cost solar PV	1 500.00	€/kWp
Investment cost Solid Biomass Plant	8 418.84	€/kW
Investment cost Geothermal Plant	5 000.00	€/kW
Investment cost Solid Waste to Energy Plant	4 000.00	€/kW
Investment cost Run of River Hydropower	5 000.00	€/kW
Investment cost Biogas to Power	2 500.00	€/kW
Investment cost Waste to Energy Gasification	10 523.55	€/kW
Investment Biodiesel generator	2 500.00	€/kWh
Investment cost Pump Storage Hydro Plant	120 000.00	€/MWh
Investment cost Gas storage (old gas field)	100	€/MWh gas

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Model input
Financial parameters 3

Operation and Maintenance cost (O&M) Wind Power	5	%/a of invest
O&M (PV)	5	%/a of invest
O&M Solid Biomass Power Plant	10	%/a of invest
O&M Geothermal Power Plant	5	%/a of invest
O&M Solid Waste to Energy Plant	5	%/a of invest
O&M Run of River Hydropower	3	%/a of invest
O&M Biogas to Power	5	%/a of invest
O&M Waste to Energy Gasification	10	%/a of invest
O&M Biodiesel Generator	5	%/a of invest
O&M Pump Storage Hydro Plant	4 000.00	€/MW Pumpe
O&M Gasstorage	1	%/a of invest

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Model input
Financial parameters 4

Fuel Costs Solid Biomass	25	€/MWh (input)
Fuel Costs Waste	1	€/MWh (input)
Substrate cost Biomass	25	€/MWh (input)
Interest rate	6	%
Cost of Biodiesel in €/t	520.00	€/t
Cost of Biodiesel €/MWh	200.00	€/MWh

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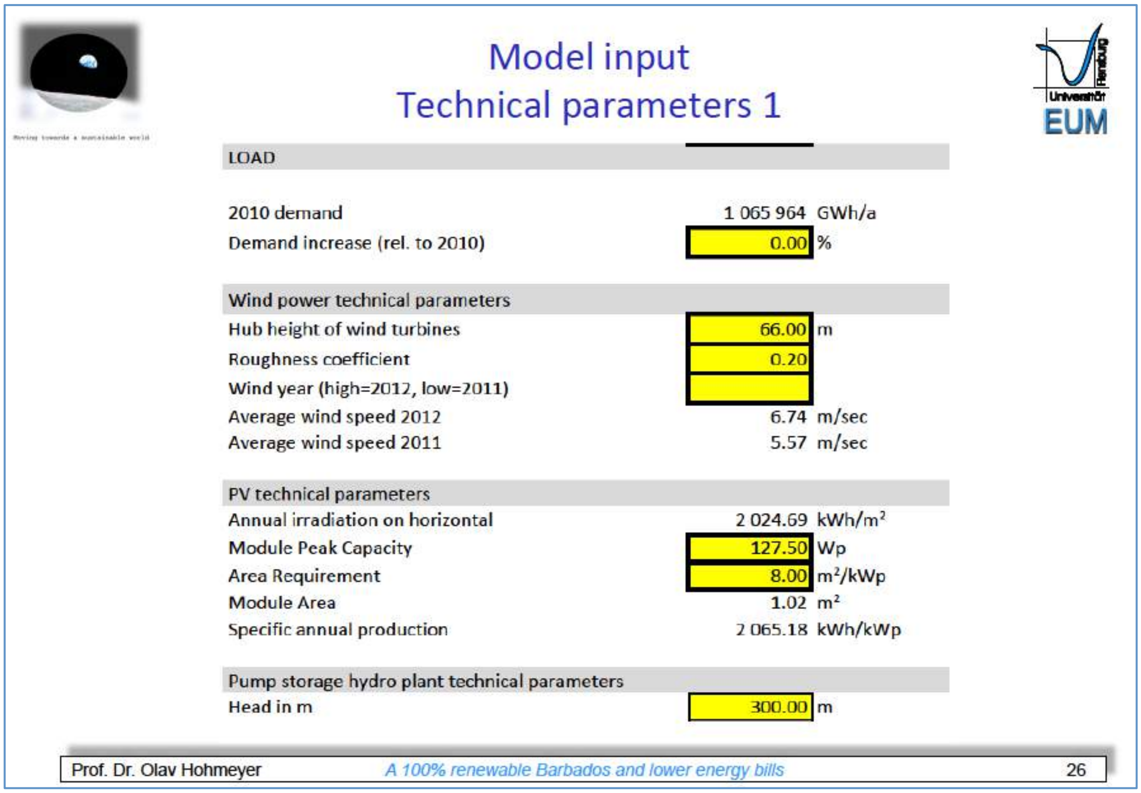

Model input
Technical parameters 1

LOAD		
2010 demand	1 065 964	GWh/a
Demand increase (rel. to 2010)	0.00	%
Wind power technical parameters		
Hub height of wind turbines	66.00	m
Roughness coefficient	0.20	
Wind year (high=2012, low=2011)		
Average wind speed 2012	6.74	m/sec
Average wind speed 2011	5.57	m/sec
PV technical parameters		
Annual irradiation on horizontal	2 024.69	kWh/m²
Module Peak Capacity	127.50	Wp
Area Requirement	8.00	m²/kWp
Module Area	1.02	m²
Specific annual production	2 065.18	kWh/kWp
Pump storage hydro plant technical parameters		
Head in m	300.00	m

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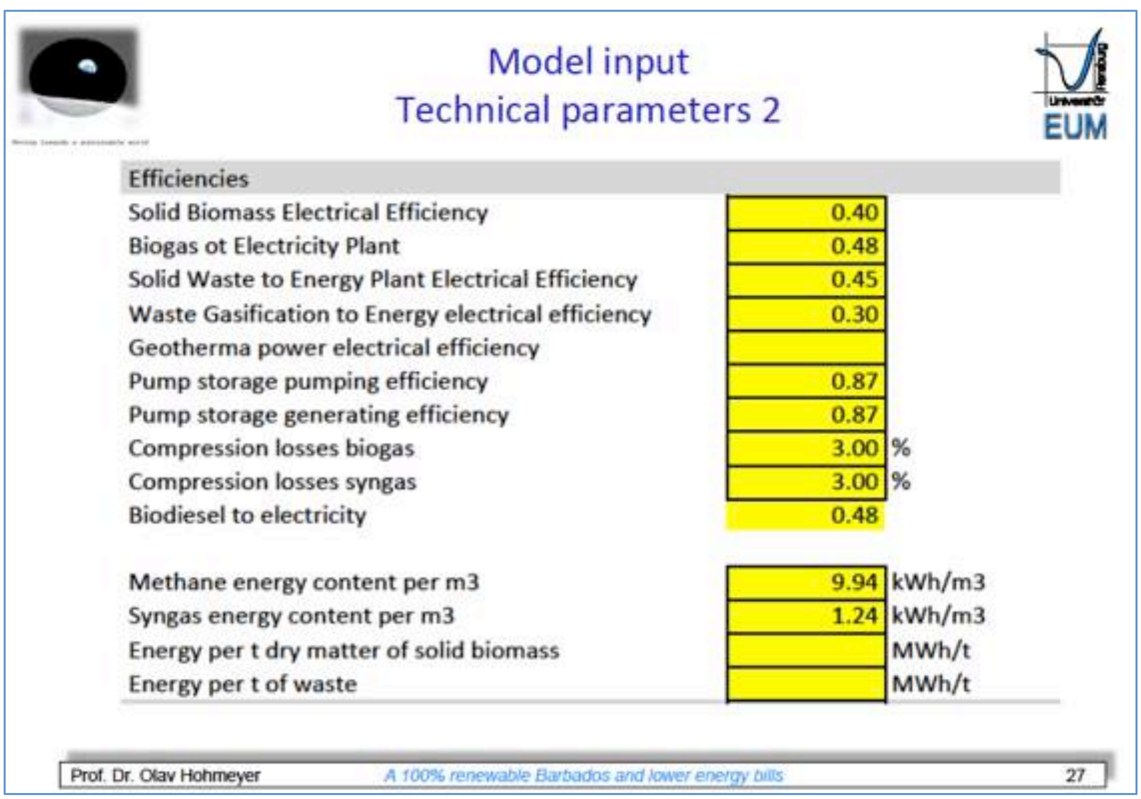

Model input
Technical parameters 2

Efficiencies		
Solid Biomass Electrical Efficiency	0.40	
Biogas ot Electricity Plant	0.48	
Solid Waste to Energy Plant Electrical Efficiency	0.45	
Waste Gasification to Energy electrical efficiency	0.30	
Geotherma power electrical efficiency		
Pump storage pumping efficiency	0.87	
Pump storage generating efficiency	0.87	
Compression losses biogas	3.00	%
Compression losses syngas	3.00	%
Biodiesel to electricity	0.48	
Methane energy content per m3	9.94	kWh/m3
Syngas energy content per m3	1.24	kWh/m3
Energy per t dry matter of solid biomass		MWh/t
Energy per t of waste		MWh/t

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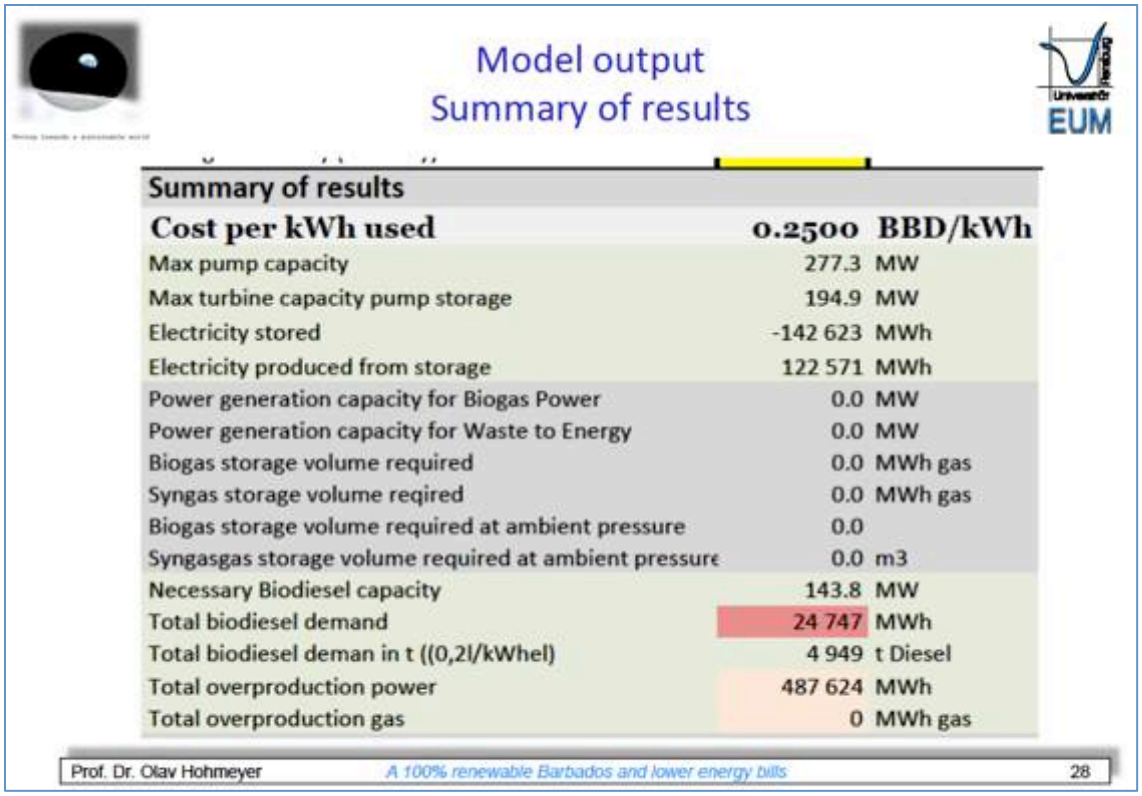
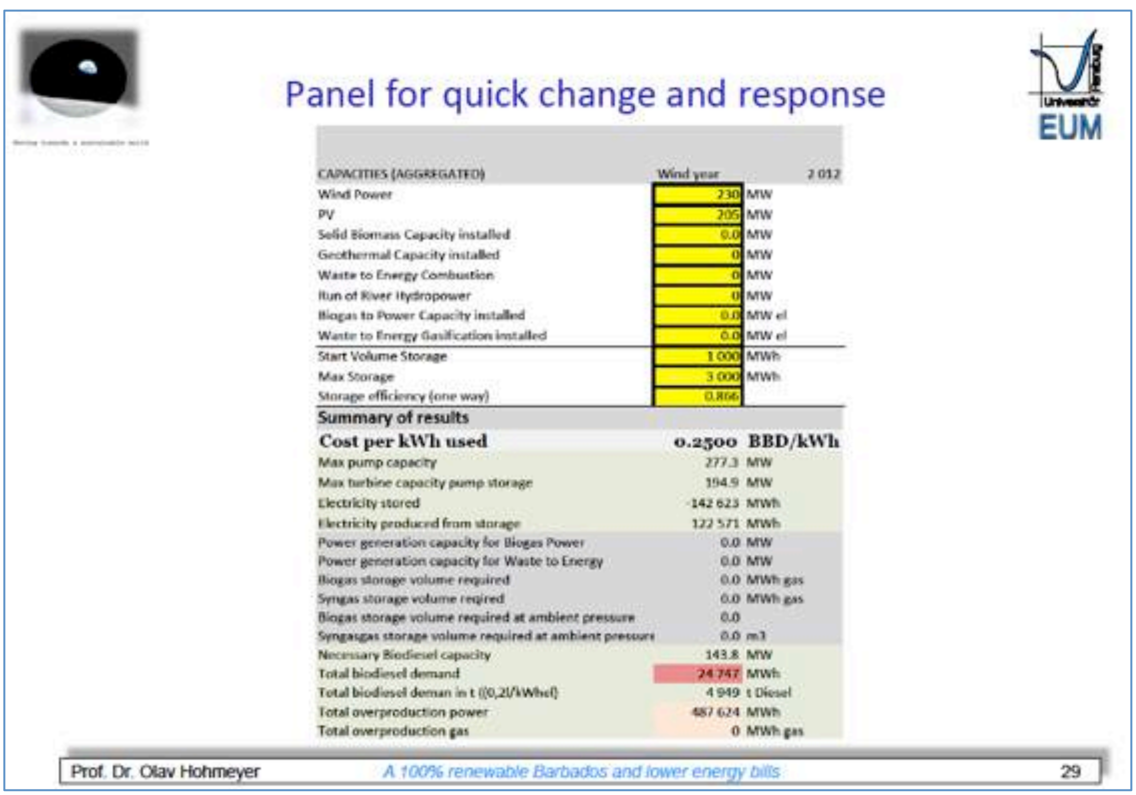


Summary of results		
Cost per kWh used	**0.2500**	**BBD/kWh**
Max pump capacity	277.3	MW
Max turbine capacity pump storage	194.9	MW
Electricity stored	-142 623	MWh
Electricity produced from storage	122 571	MWh
Power generation capacity for Biogas Power	0.0	MW
Power generation capacity for Waste to Energy	0.0	MW
Biogas storage volume required	0.0	MWh gas
Syngas storage volume reqired	0.0	MWh gas
Biogas storage volume required at ambient pressure	0.0	
Syngasgas storage volume required at ambient pressure	0.0	m3
Necessary Biodiesel capacity	143.8	MW
Total biodiesel demand	24 747	MWh
Total biodiesel deman in t ((0,2l/kWhel)	4 949	t Diesel
Total overproduction power	487 624	MWh
Total overproduction gas	0	MWh gas



CAPACITIES (AGGREGATED)	Wind year	2 012
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Run of River Hydropower	0	MW
Biogas to Power Capacity installed	0.0	MW el
Waste to Energy Gasification installed	0.0	MW el
Start Volume Storage	1 000	MWh
Max Storage	3 000	MWh
Storage efficiency (one way)	0.866	
Summary of results		
Cost per kWh used	**0.2500**	**BBD/kWh**
Max pump capacity	277.3	MW
Max turbine capacity pump storage	194.9	MW
Electricity stored	-142 623	MWh
Electricity produced from storage	122 571	MWh
Power generation capacity for Biogas Power	0.0	MW
Power generation capacity for Waste to Energy	0.0	MW
Biogas storage volume required	0.0	MWh gas
Syngas storage volume reqired	0.0	MWh gas
Biogas storage volume required at ambient pressure	0.0	
Syngasgas storage volume required at ambient pressure	0.0	m3
Necessary Biodiesel capacity	143.8	MW
Total biodiesel demand	24 747	MWh
Total biodiesel deman in t ((0,2l/kWhel)	4 949	t Diesel
Total overproduction power	487 624	MWh
Total overproduction gas	0	MWh gas

Model output
Costs by technology

Cost analysis in BBD	Total Invest Mio. BBD	Annuity Mio. BBD/a	O&M Mio.BBD€/a	Cost Mio. BBD/a	Specific Cost BBD/kWh	Share ot total cost BBD/kWh
Wind Power	611.96	53.35	30.60	83.95	0.07	0.08
PV	779.21	67.93	38.96	106.89	0.25	0.10
Solid biomass	0.00	0.00	0.00	0.00	#DIV/0!	0.00
Geothermal power	0.00	0.00	0.00	0.00	#DIV/0!	0.00
Waste to Energy (solid)	0.00	0.00	0.00	0.00	#DIV/0!	0.00
Run of River Hydropower	0.00	0.00	0.00	0.00	#DIV/0!	0.00
Biogas to Power	0.00	0.00	0.00	0.00	0.00	0.00
Waste to Energy Gasifcation (syngas)	0.00	0.00	0.00	0.00	0.00	0.00
Cost of electricity production from Wind + PV + Solid biomass + Geothermal + R o R Hydro + Biogas to Power + Waste to Syngas	1 391.17	121.29	69.56	190.85	0.12	0.18
Pump storage hydro	912.24	57.88	2.81	60.69	0.50	0.06
Gas storage for biogas	0.00	0.00	0.00	0.00	#DIV/0!	0.00
Gas storage for syngas	0.00	0.00	0.00	0.00	#DIV/0!	0.00
Total cost of storage	912.24	57.88	2.81	60.69	0.00	0.06
Cost of electrictiy from biodiesel in BBD/kWh	0.00	0.00	0.00	12.54	0.51	0.01
Production plus storage and biodiesel	2 303.41	179.16	72.37	264.08	0.00	0.25
Other power system costs in BBD/kWh (BL&P 2013)						0.153
Total power costs in BBD/kWh						0.40

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Model output

	Energy MWh	N N
Load	1 056 156	
Solid biomass	0	
Geothermal power	0	
Waste to Energy	0	
Run of River Hydropower	0	
Wind Power	1 233 468	
PV	423 363	
Wind Power + PV + Solid biomass + Geothermal power + Waste to Ener	1 656 831	
Load not met (R1)	146 204	
Power stored	-142 623	
Power produced from storage	-122 571	
Residual Load 2 not met	24 747	
Power produced from Biogas	0	
Residual Load 3 not met	24 747	
Power produced from Waste to Energy Syngas	0	
Residal Load 4 not met	24 747	
Production from Diesel or Biodiesel	24 747	
Diesel consuption in t/a	4 949 t/a	

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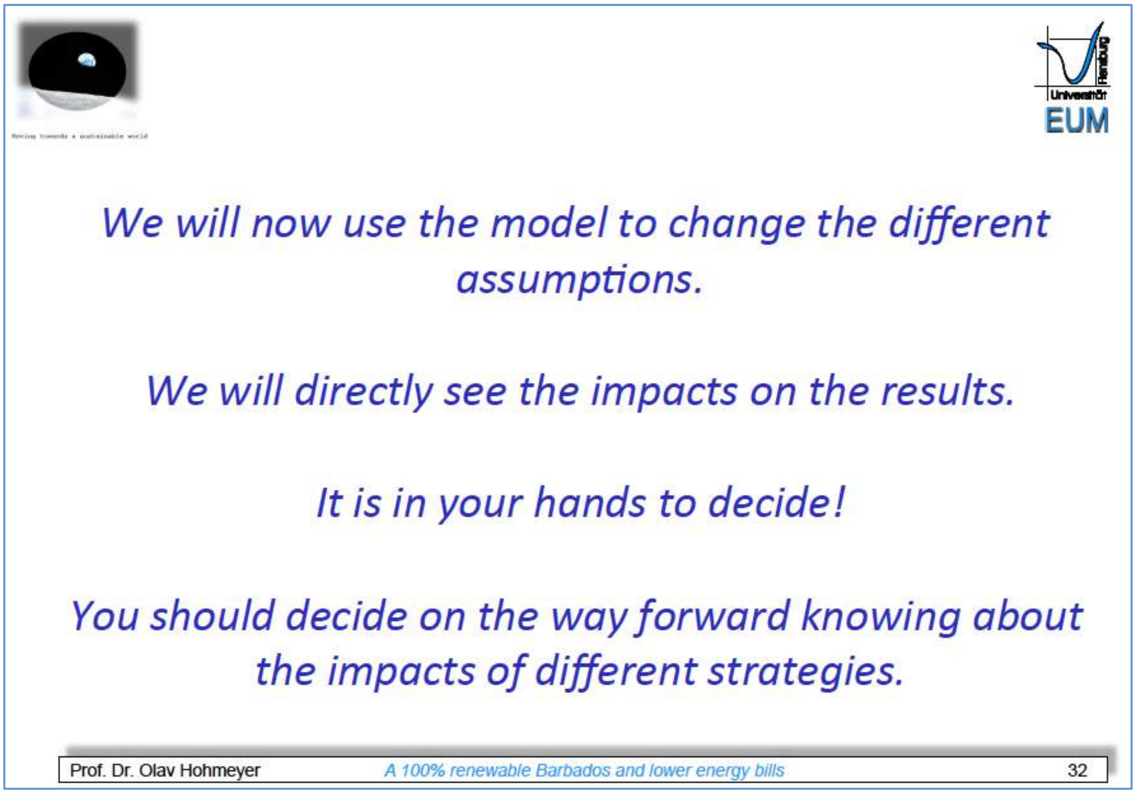
Universität Flensburg
EUM
We will now use the model to change the different assumptions.
We will directly see the impacts on the results.
It is in your hands to decide!
You should decide on the way forward knowing about the impacts of different strategies.
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32

3.2 Presentation by Dr. Rogers

Overview

- Recap of Olav's work
- Results of the desktop study
- Future work required

Recap

- GAIA hourly wind data
- Wind farms located on 5 to 10% of land in Barbados at 10MW/km^2
- Possible installed capacity – 430MW (needed 200MW for model)
- Annual energy yield – 1,845.7 GWh/year (capacity factor 49%)
- Levelised cost of electricity – $0.07/kWh (~BB$2,600/kW installed)

The desktop study

- EMD's WindPRO 3.0 software
- Used by wind farm engineers across the world

Inputs
- Weather data
- Terrain data
- Shear factor data
- Wind turbine selection and location

Outputs
- Energy yield prediction
- Financial modeling
- Electrical integration modeling
- Noise maps
- Shadow flicker maps
- Photomontages

Wind turbine selection

Enercon E-58

Hub height - 67m

Blade length - 29m

Total height - 96m

Rated capacity - 1MW (at 12m/s wind speed)

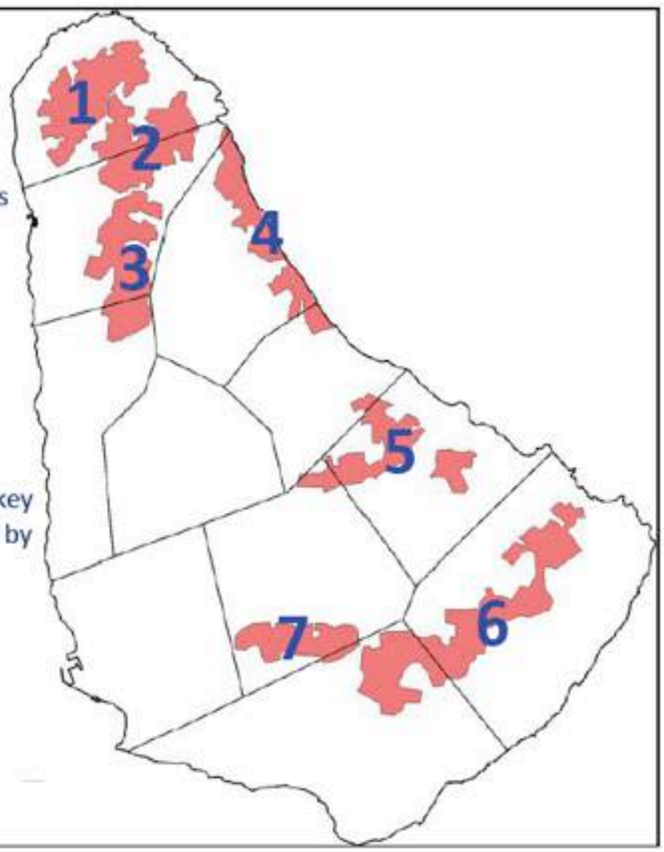
Consideration of location

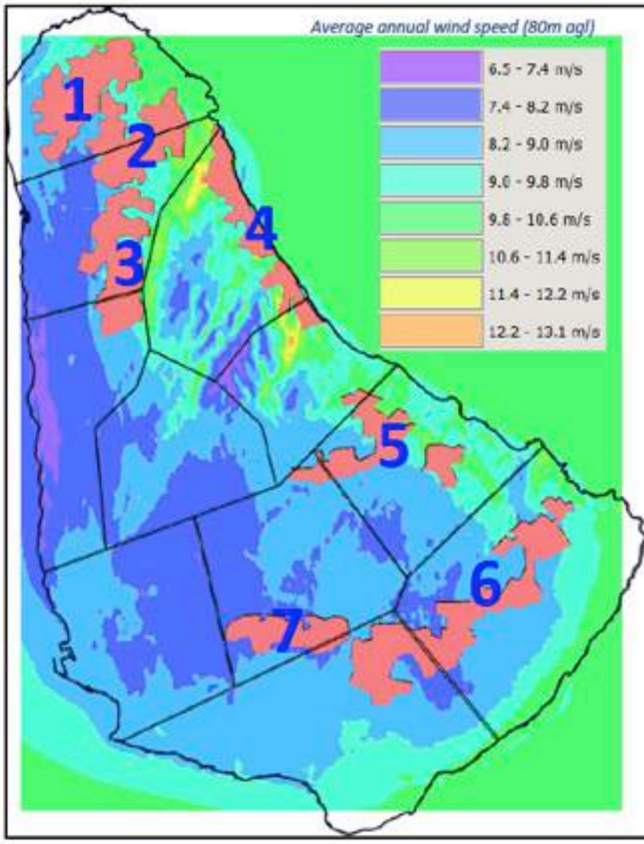
T&C Planning input
1.5 times height from roads/buildings

Noise levels – 55dB(A) daytime
45dB(A) nighttime
[Settled on 350m]

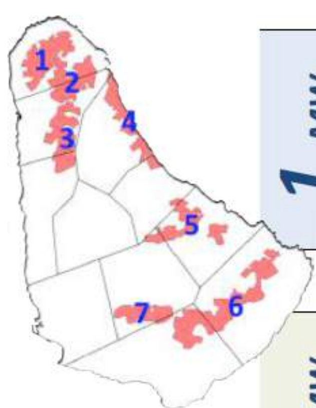
Anything over 75ft passed by BCAD

The process
Satellite imagery used to determine key locations for wind turbines, followed by site visits…





Zone	Area (km²)	No. 1MW turbines	Annual yield (GWh)
1	9.4	48	174.3
2	9.2	42	166.0
3	9.4	35	135.3
4	7.0	51	231.4
5	7.9	38	138.7
6	16.2	76	224.7
7	5.2	27	73.2
	64.2	**317**	**1,143.6**

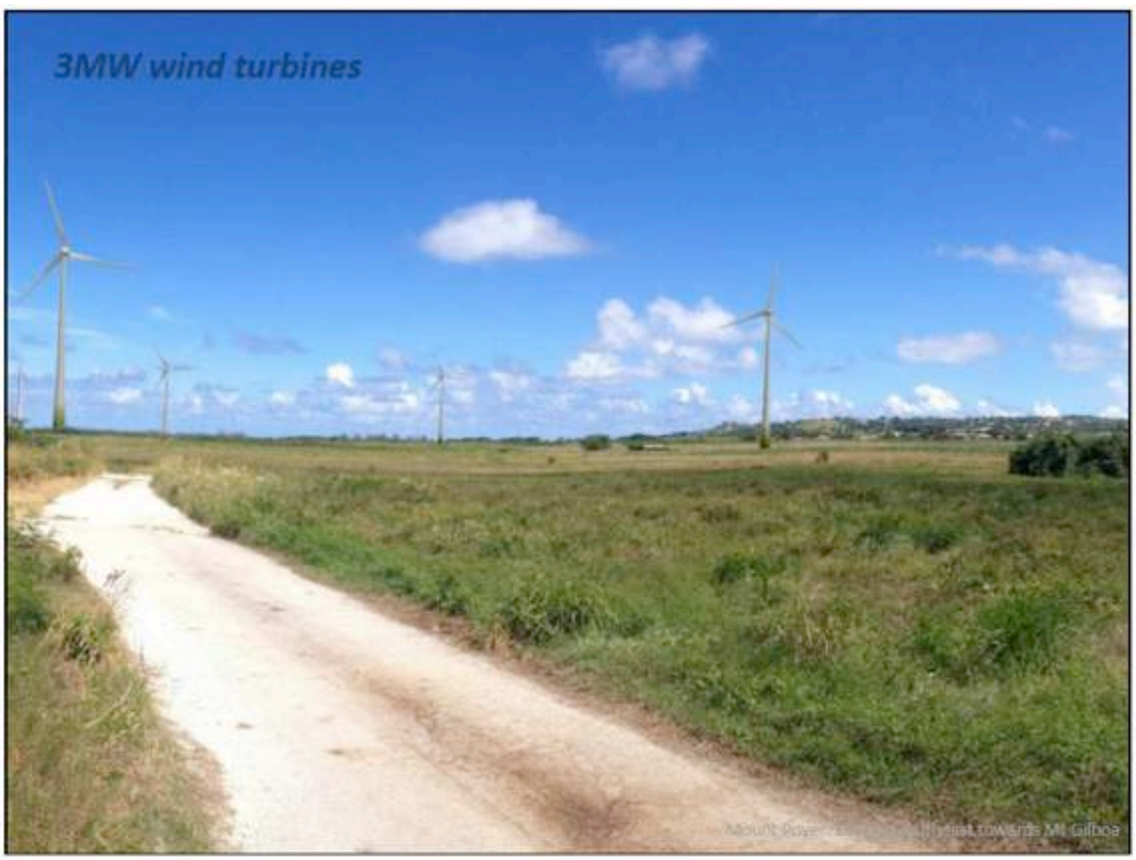


	Zone	Area (km²)	No. turbines	Installed capacity (MW)	Capacity density (MW/km²)	Energy yield (GWh/year)	Capacity factor	Yield per turbine (GWh)
1 MW	1	9.4	48	48	5.1	174.3	41.5%	3,632
	2	9.2	42	42	4.6	166.0	45.1%	3,953
	3	9.4	35	35	3.7	135.3	44.1%	3,864
	4	7.0	51	51	7.3	231.4	51.8%	4,537
	5	7.9	38	38	4.8	138.7	41.7%	3,651
	6	16.2	76	76	4.7	224.7	33.7%	2,956
	7	5.2	27	27	5.2	73.2	30.9%	2,710
		64.2	**317**	**317**	**5.1**	**1,143.6**	**41.2%**	**3,607**
3 MW	1	9.4	19	57	6.1	226.0	45.3%	11,895
	2	9.2	24	72	7.9	270.4	42.9%	11,267
	3	9.4	24	72	7.7	262.3	41.6%	10,930
	4	7.0	16	48	6.9	196.3	46.7%	12,267
	5	7.9	16	48	6.1	170.2	40.5%	10,634
	6	16.2	40	120	7.4	361.0	34.3%	9,026
	7	5.2	13	39	7.5	107.5	31.5%	8,268
		64.2	**152**	**456**	**7.1**	**1,593.7**	**39.9%**	**10,485**

Next steps

1. More detailed wind resource assessment
2. Wind power electrical integration study
3. Incorporation of wind into the next PDP
4. Radar system at GAIA
5. Public involvement in the ownership and benefits of wind


1MW wind turbines


3MW wind turbines


1MW wind turbines
Mt Gilboa. Looking north over St Lucy


3MW wind turbines
Mt Gilboa. Looking north over St Lucy


1MW wind turbines
Cherry Tree Hill, Looking down the east coast


3MW wind turbines
Cherry Tree Hill, Looking down the east coast

3.3 Paper on the original 100% scenario by Professor Hohmeyer

This appendix is omitted in the short version of the paper to reduce the size of the file to less than 10 MB for email delivery.

The paper can be downloaded from BREAs web site at www.barbadosenergy.org.

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