Shaping sustainable energy systems using simple hourly simulation models

A. The case of 100% renewable Barbados

B. Building your own hourly simulation model

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Yangon, 10.10., Vientiane 16.10. and Phnom Penh, 24.10.2017

(Based on a BREA Energy Lecture

held at Bridgetown, Barbados, November 10th, 2014)

Structure of the presentation

A: The case of a 100% renewable power supply for Barbados

1. The present electricity demand and supply of Barbados
2. The possible renewable contributions and their costs
3. How to balance the system every hour of the year?
4. A 100% power scenario for Barbados and its costs
5. Economic effects of a 100% renewable Barbados
6. Outlook: 100% renewables for electrical cars

Part II: How to build your own system model

Basic facts about Barbados

1.	Population 2010:	278 000
2.	Area:	431 km^2
3.	GDP/cap:	16 700 USD/cap
4.	HDI:	0,78
5.	Electricity demand 2013:	912 GWh/h

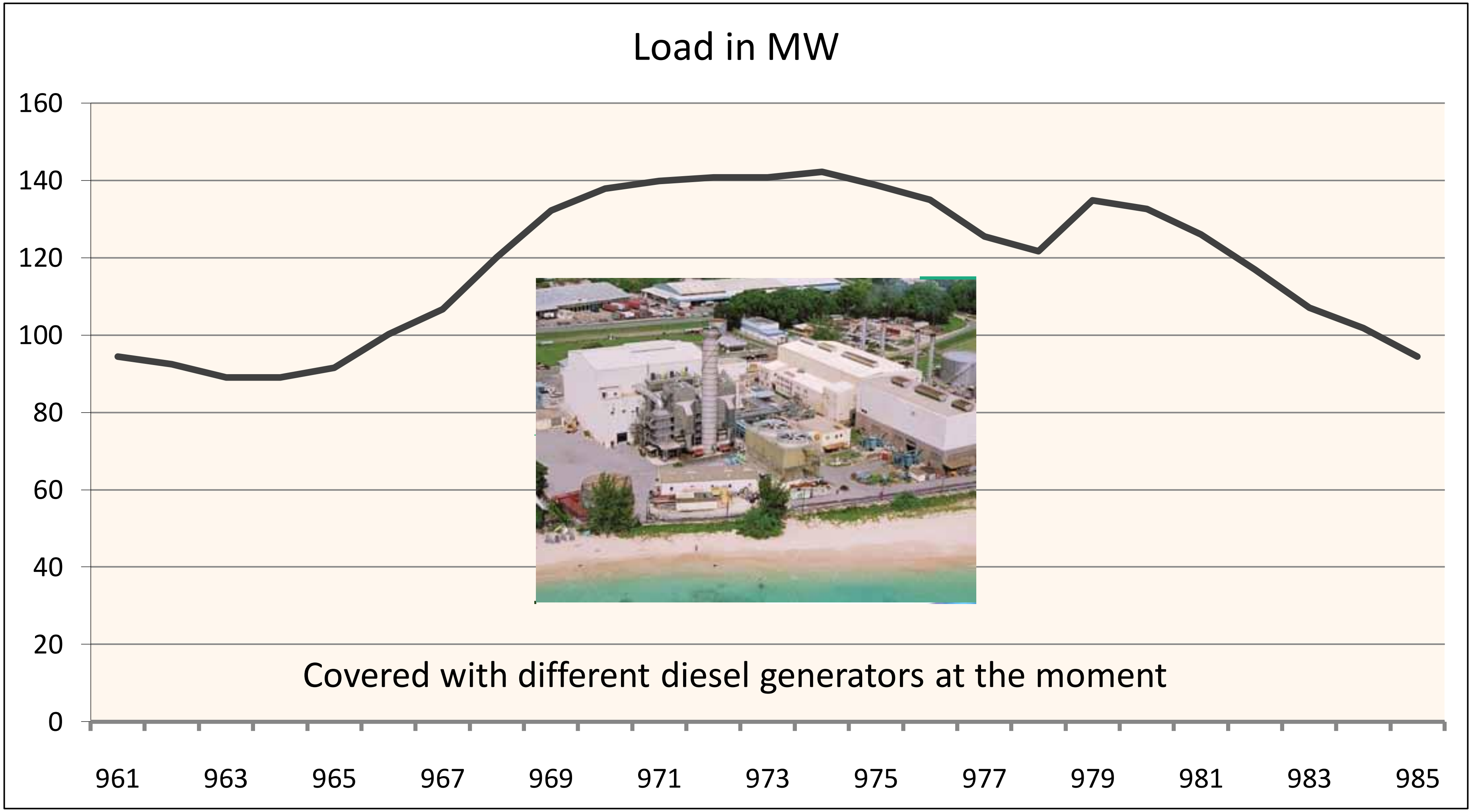
Present electricity demand and supply

1.	Demand 2013:	912 GWh/a
2.	Total production 2013:	970 GWh/a
3.	Total operating expenses:	516.5 Million BBD (2 BBD = 1 USD)
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

1. 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)

Electrical load for Barbados (Feb. 9th)



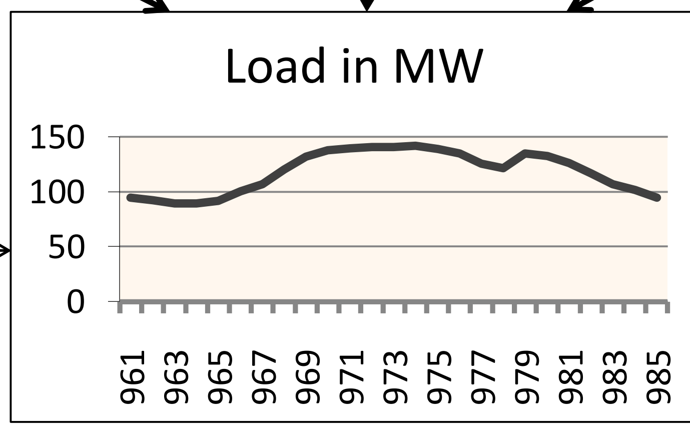
A 100% renewable power system proposed for Barbados

195 MW PV

3 GWh PSH

200 MW wind

25 GWh biomass

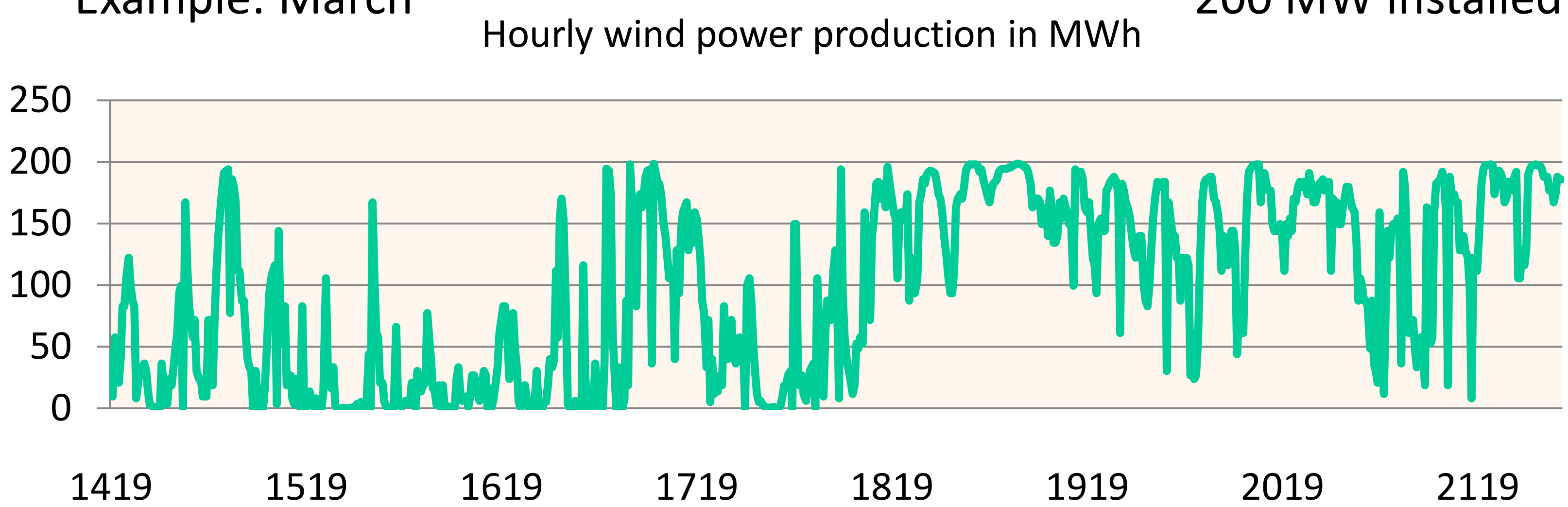


Wind energy on Barbados

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



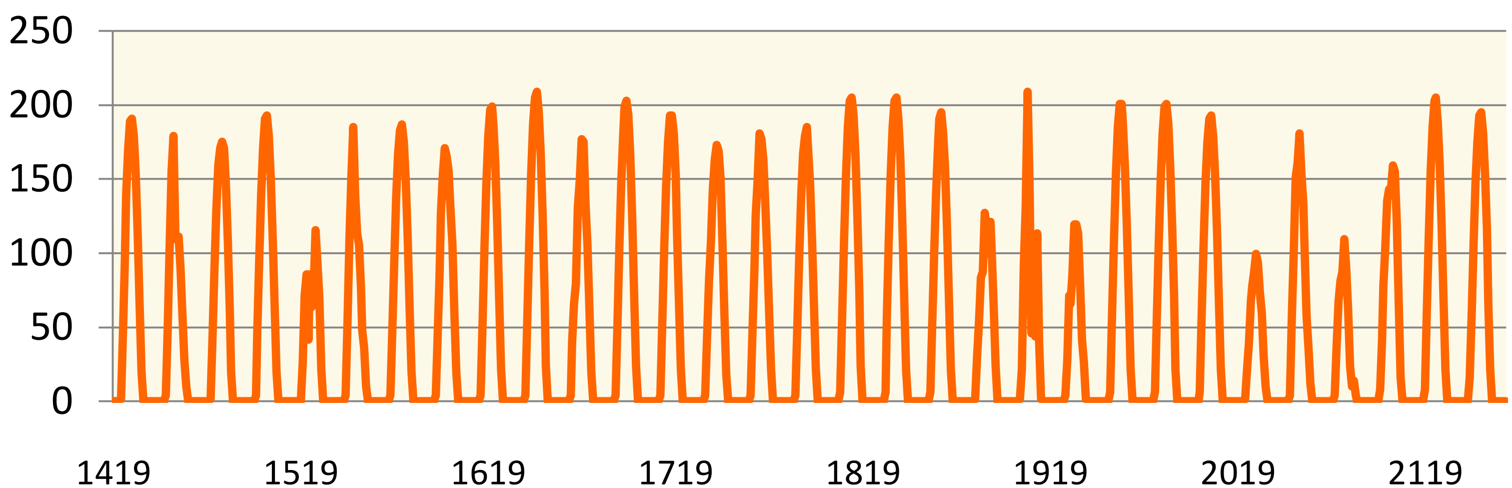
PV on Barbados

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

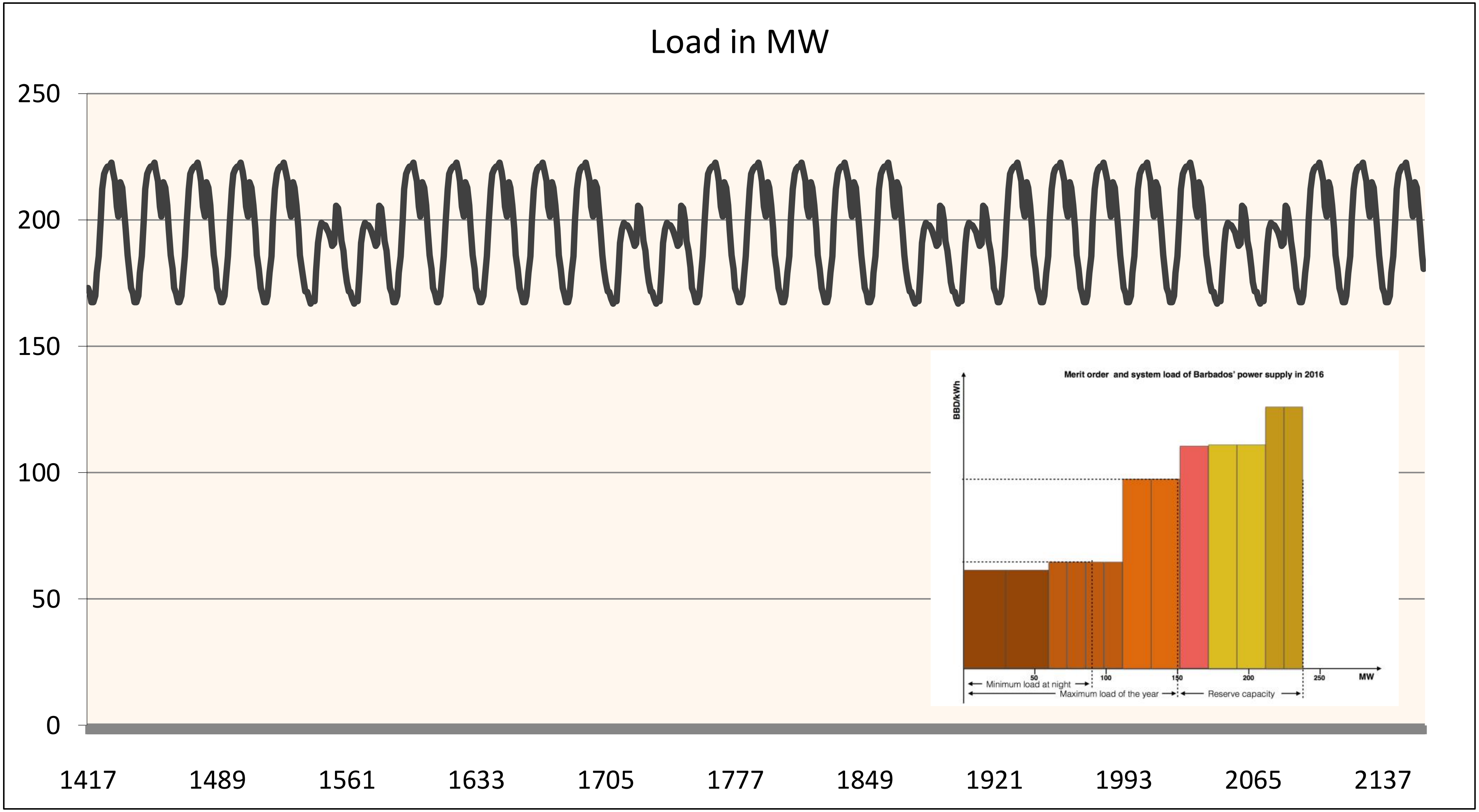
Example: March

Hourly PV production in MWh

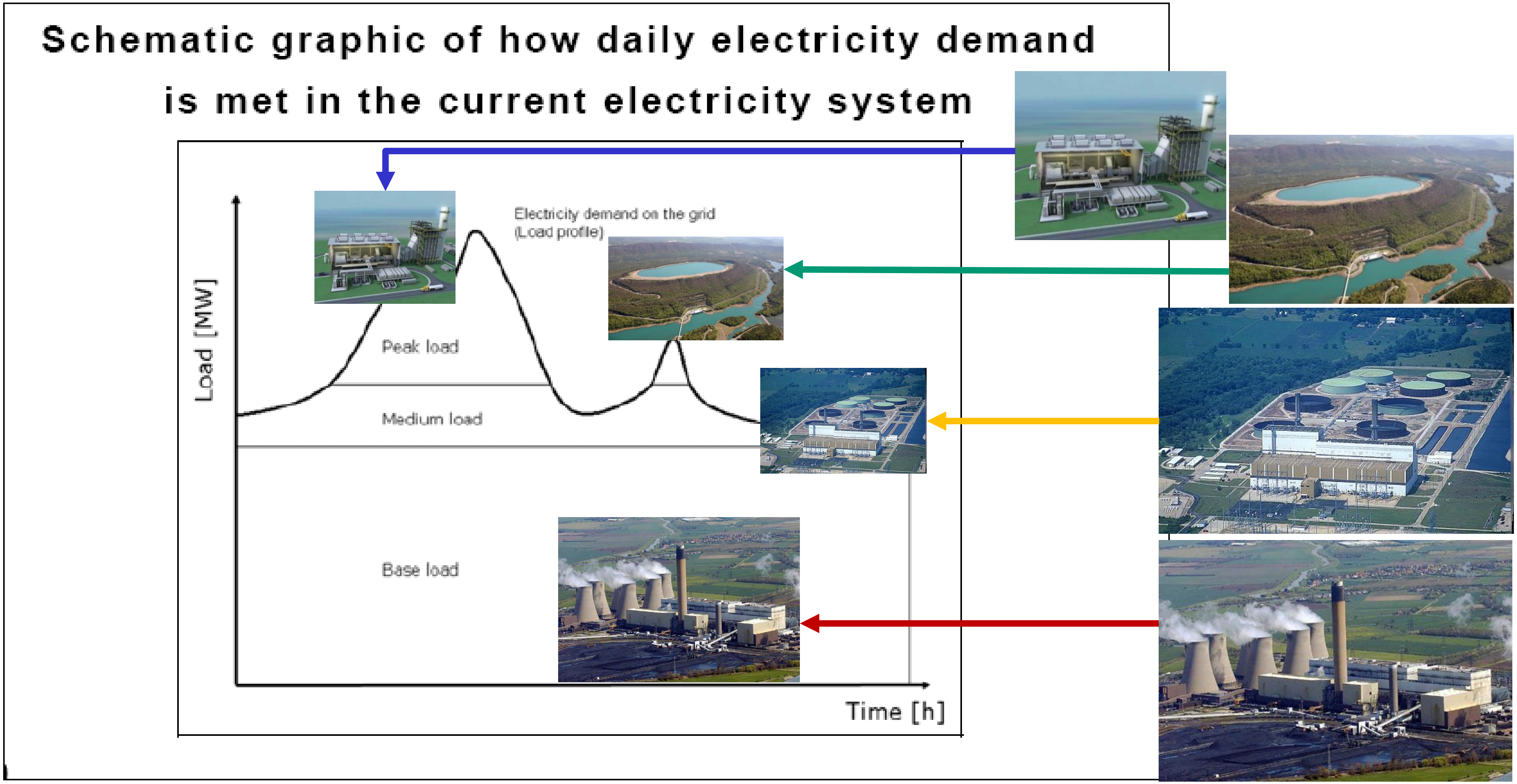
195 MW installed



Hourly load curve for Barbados in March



Dispatch and Merit Order in the Past

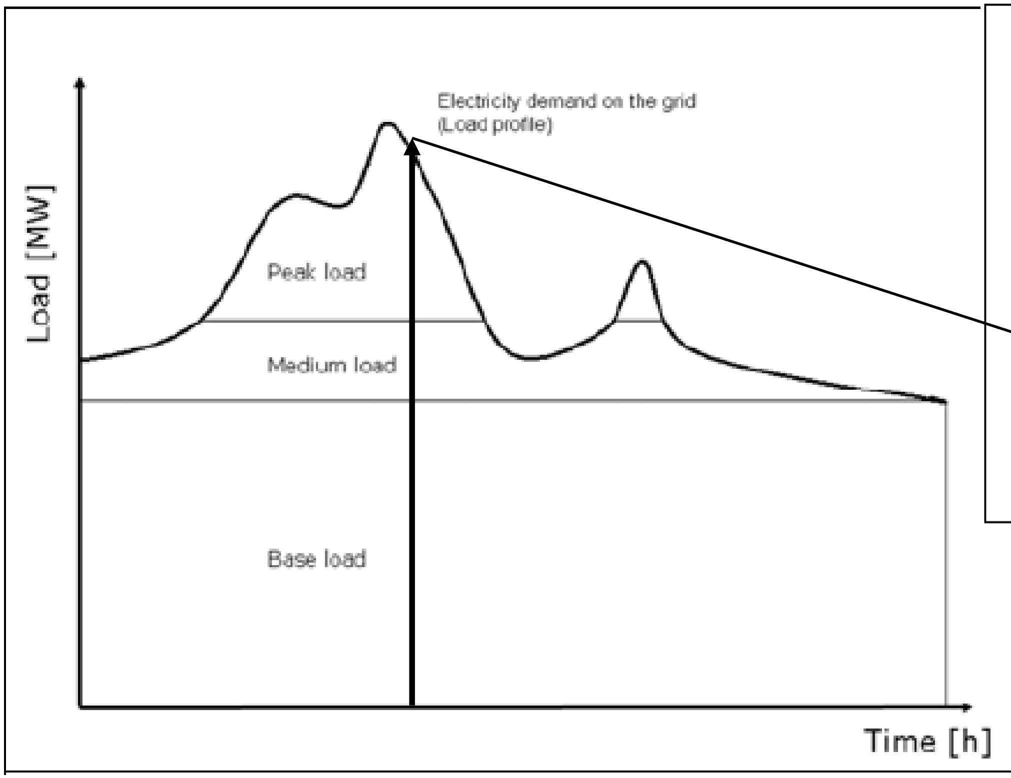


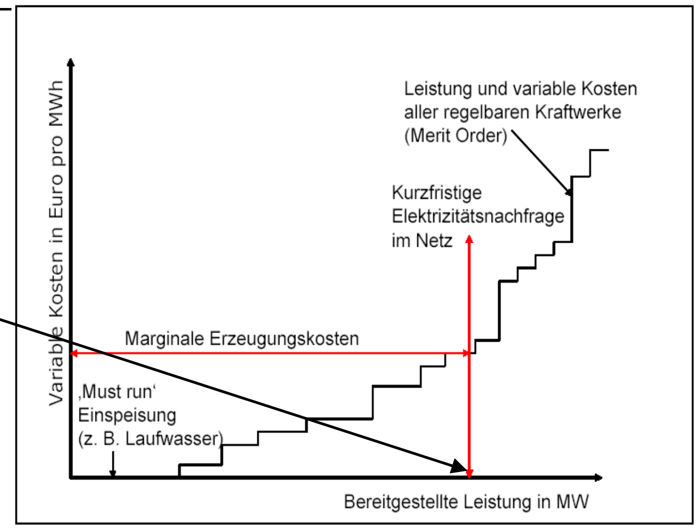
Source: SRU 2011, p.142

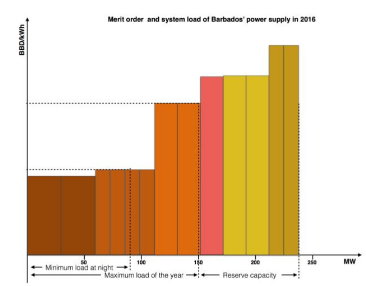
Dispatch and Merit Order in the Past

Schematic graphic of how daily electricity demand is met in the current electricity system

Merit order

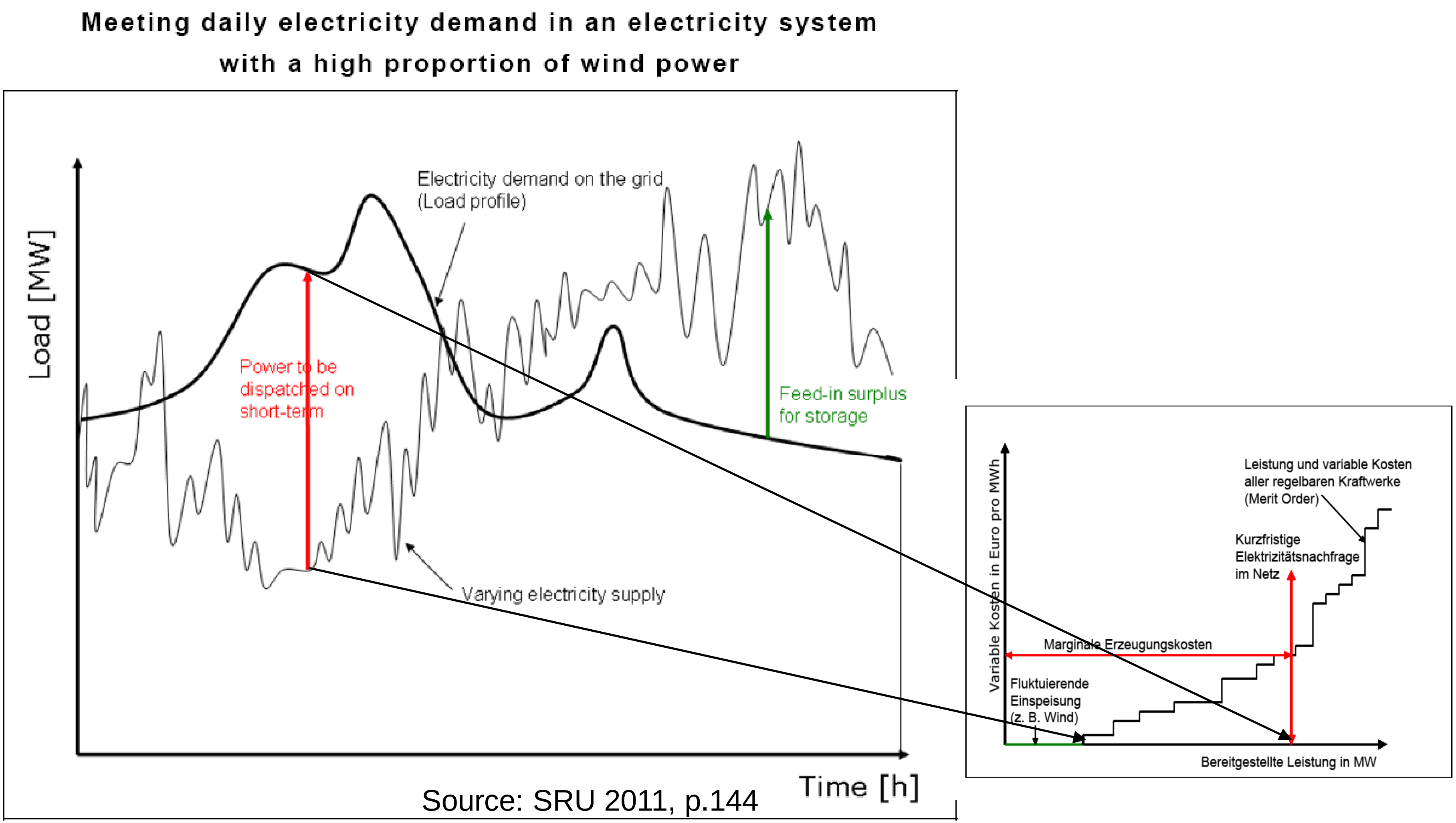






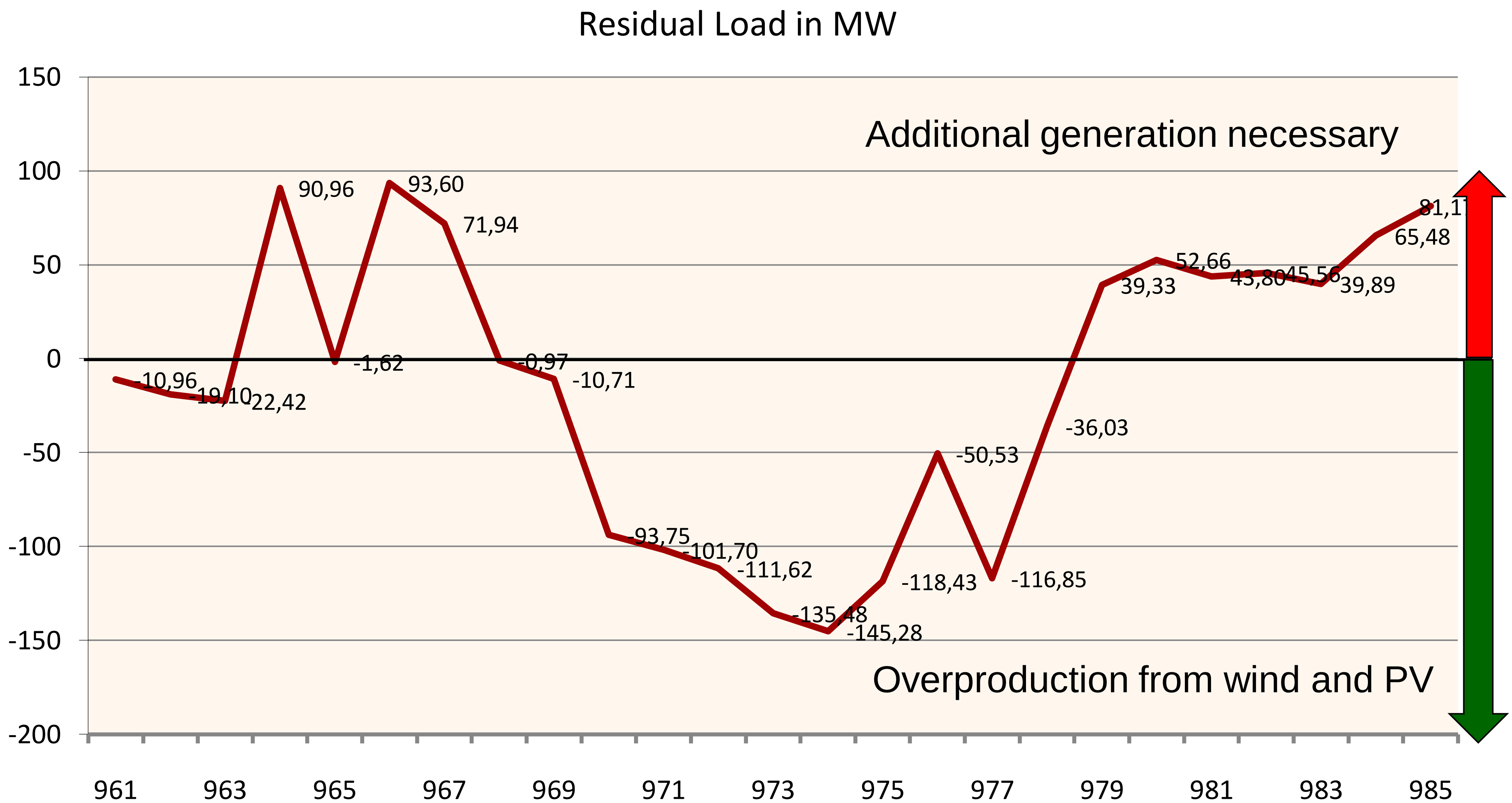
Source: SRU 2011, p.142

Future Dispatch and Merit Order



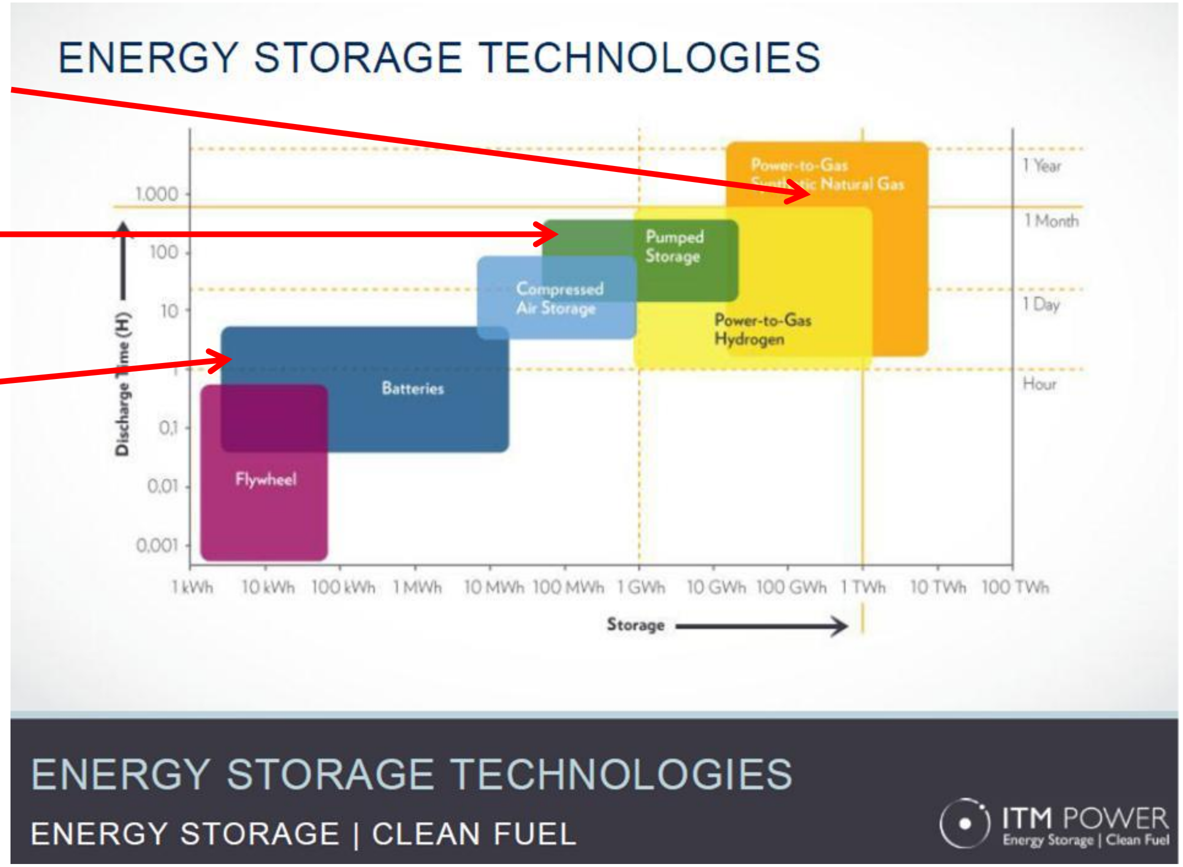
Source: SRU 2011, p.144

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



Storage options for Barbados

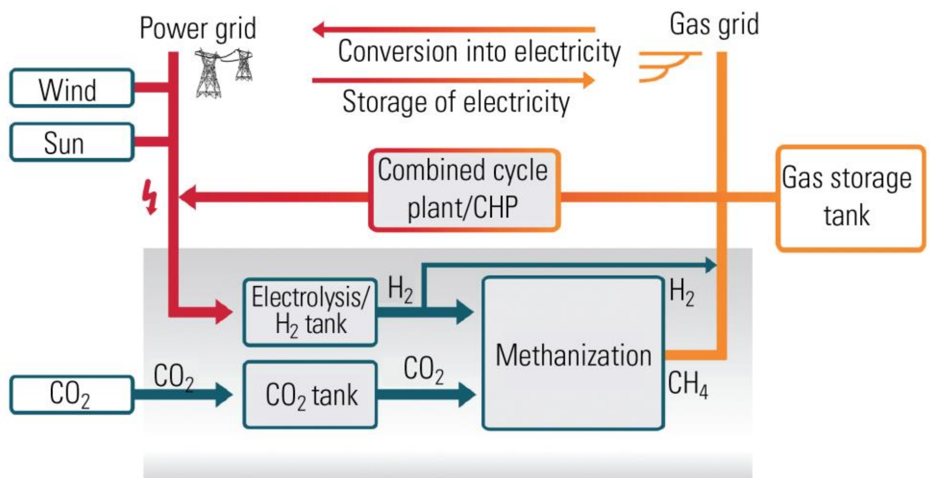
- Power to gas (to power)
- Pump storage hydropower
- Battery storage



Storage options for Barbados
Power to gas (to power)

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



Storage options for Barbados
Battery storage

Battery storage:

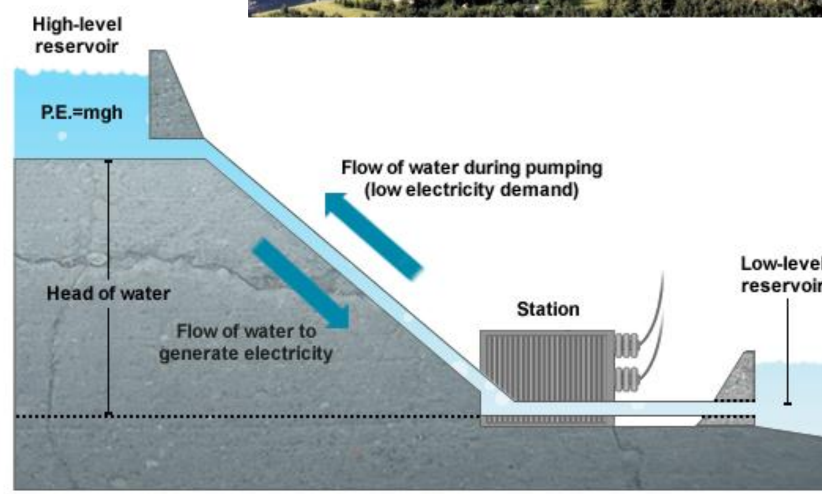
- Easy to install
- High efficiency
- Electricity loss over time
- Relatively expensive (500-600 US$/kWh storage)
- Too small for Barbados (MWh range)

Storage options for Barbados
Pump storage hydropower

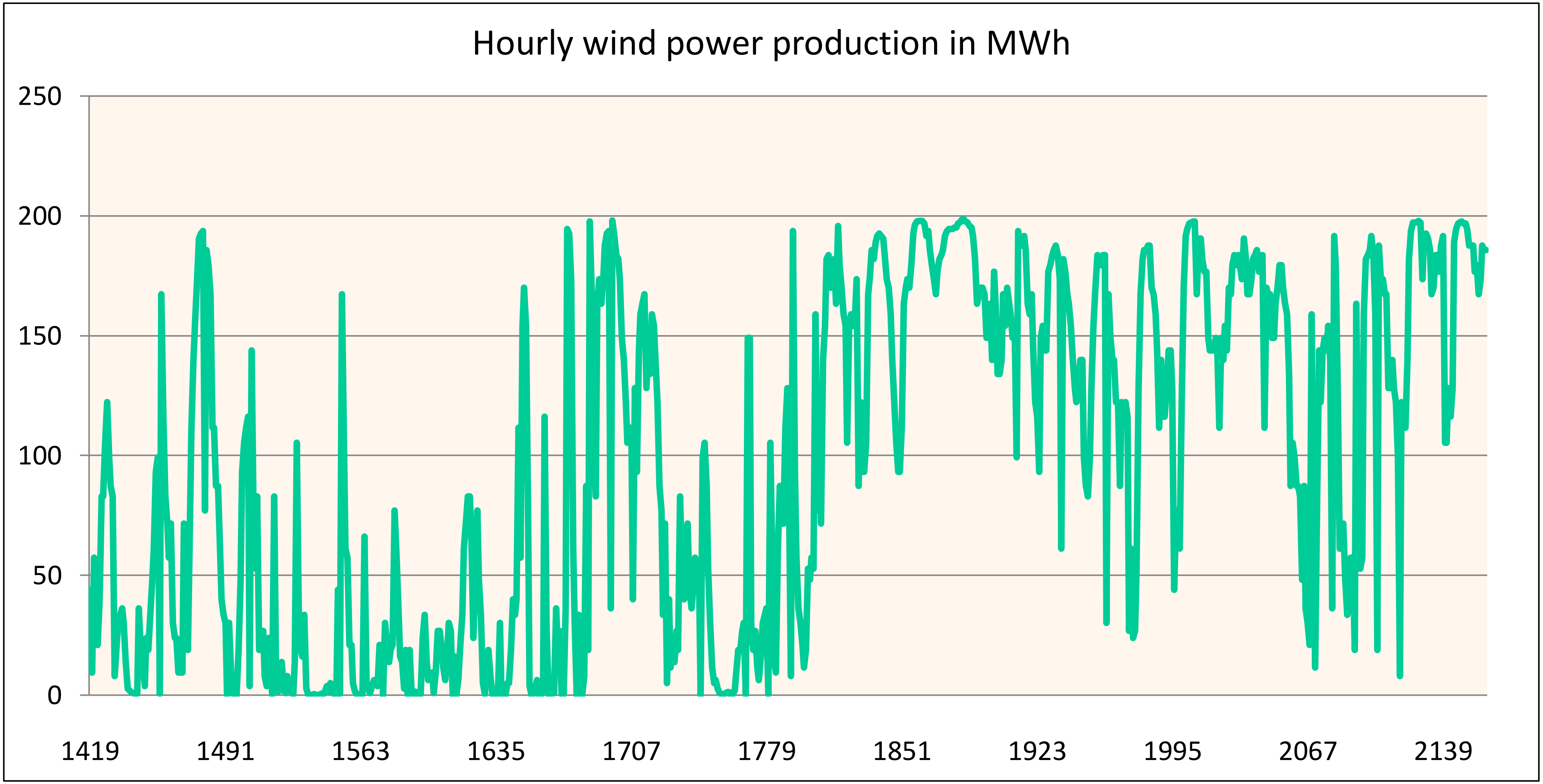
Pump storage hydropower:

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

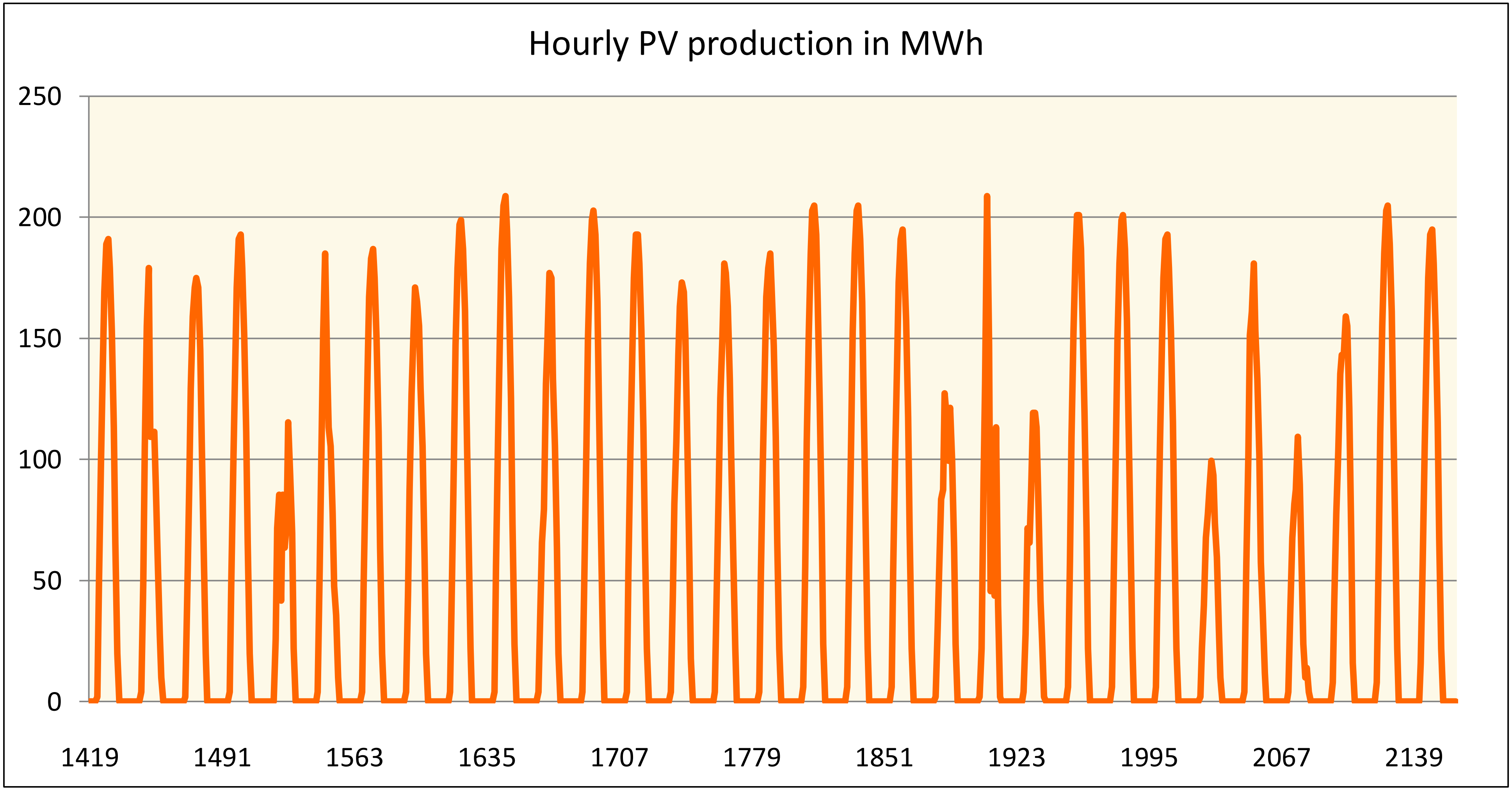
- Technology chosen for the modelling (3 GWh)



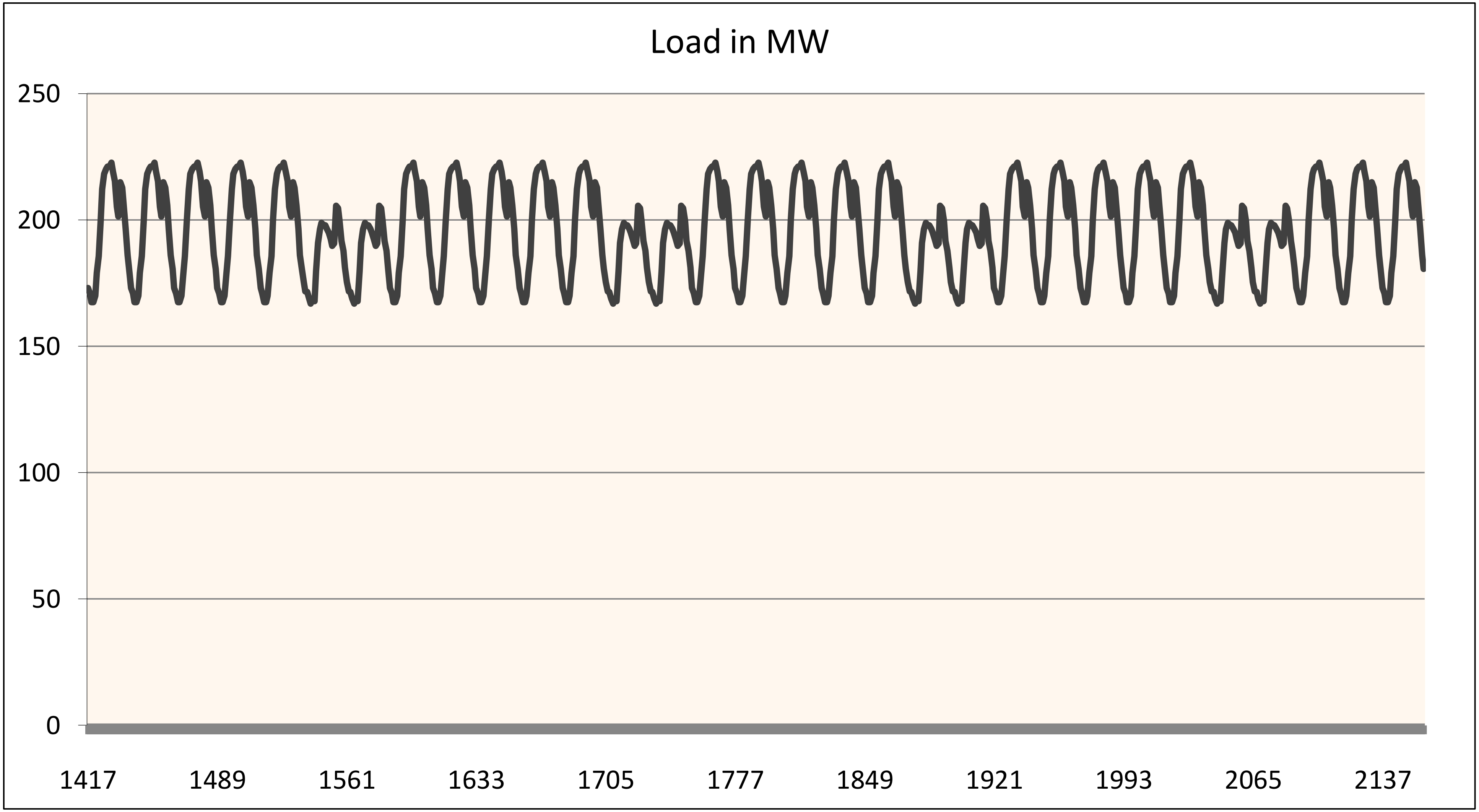
Wind energy production in March



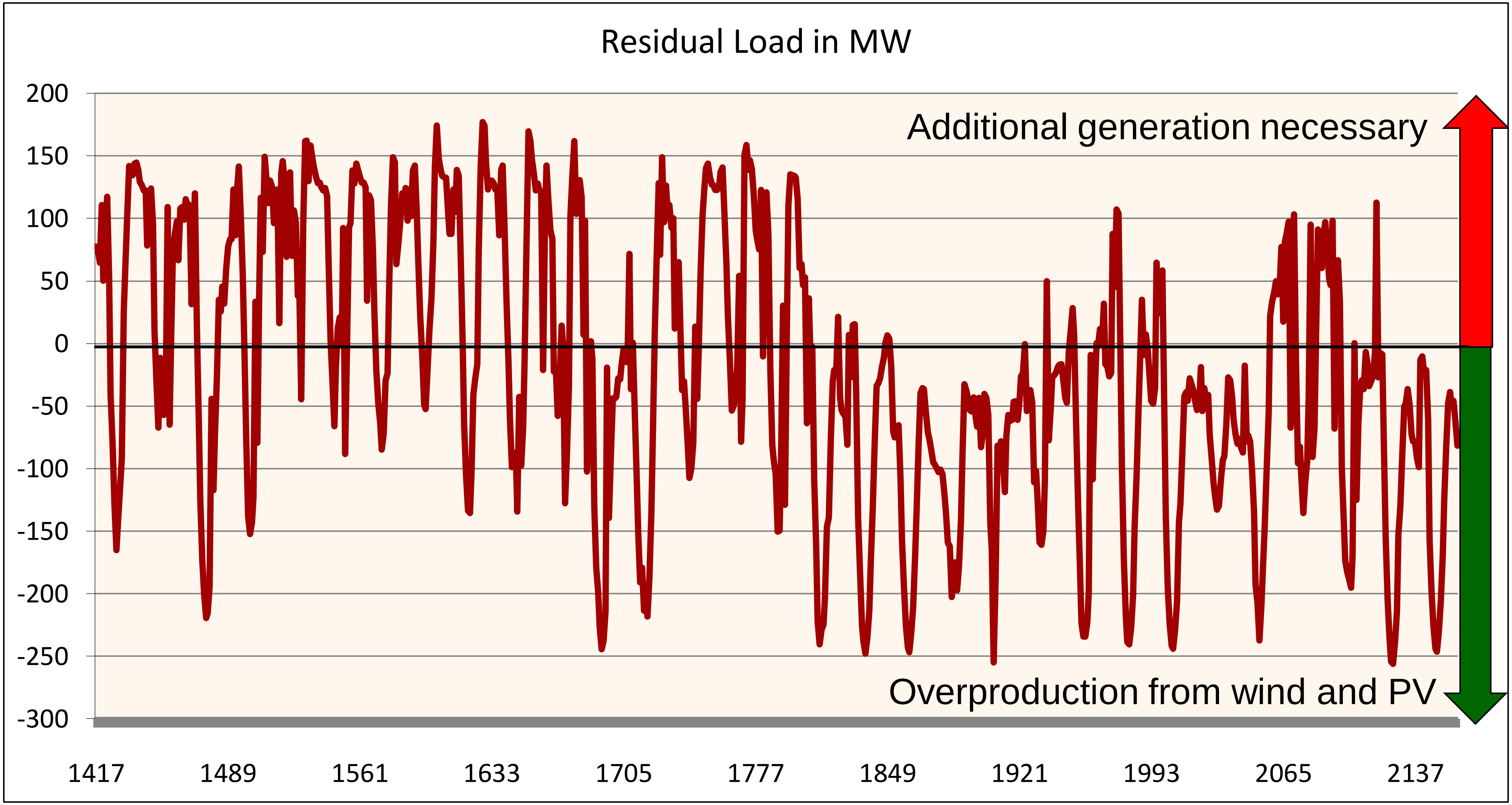
Solar PV energy production in March



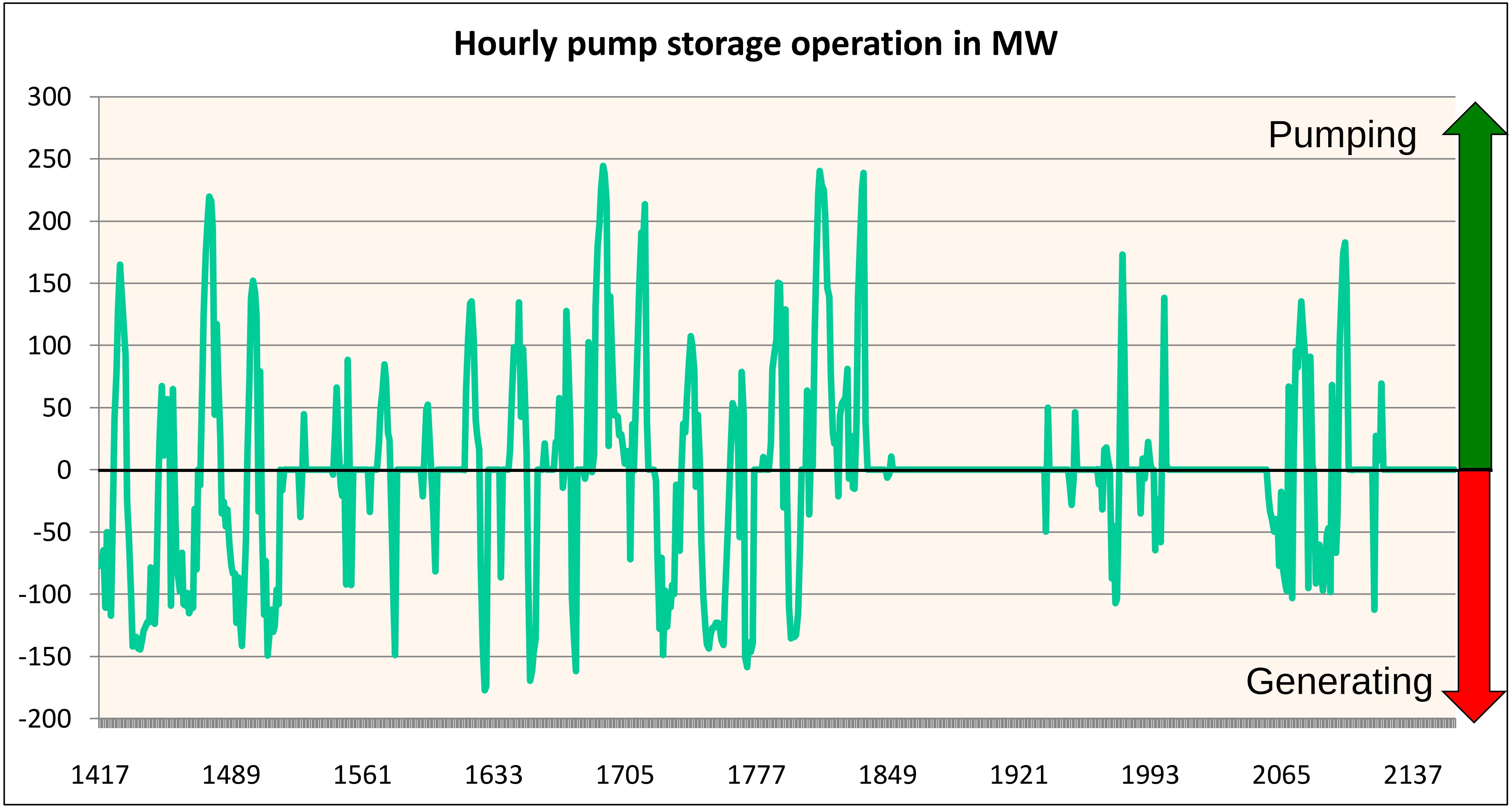
Hourly load curve for Barbados in March



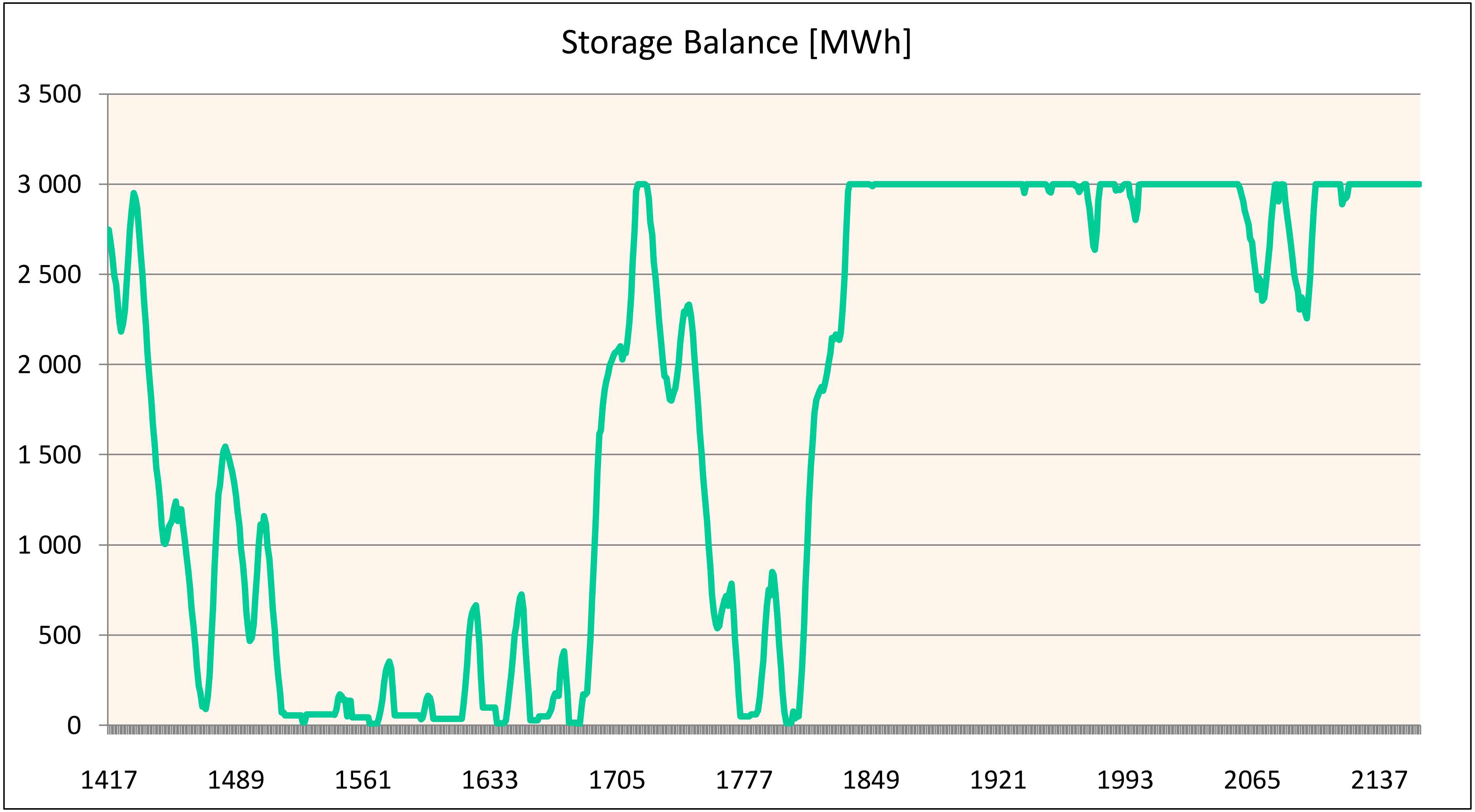
Residual load for March



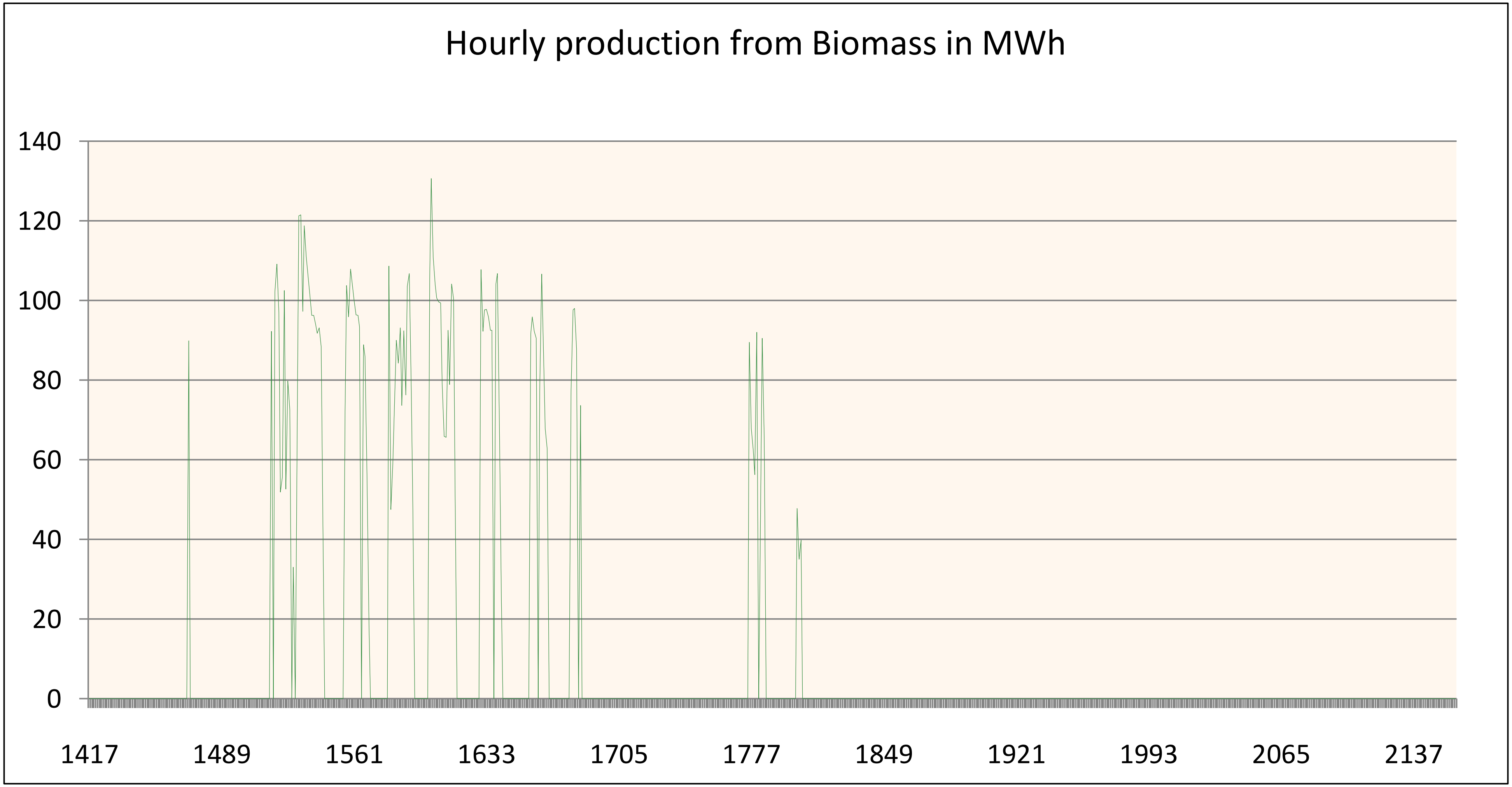
Pump storage for March



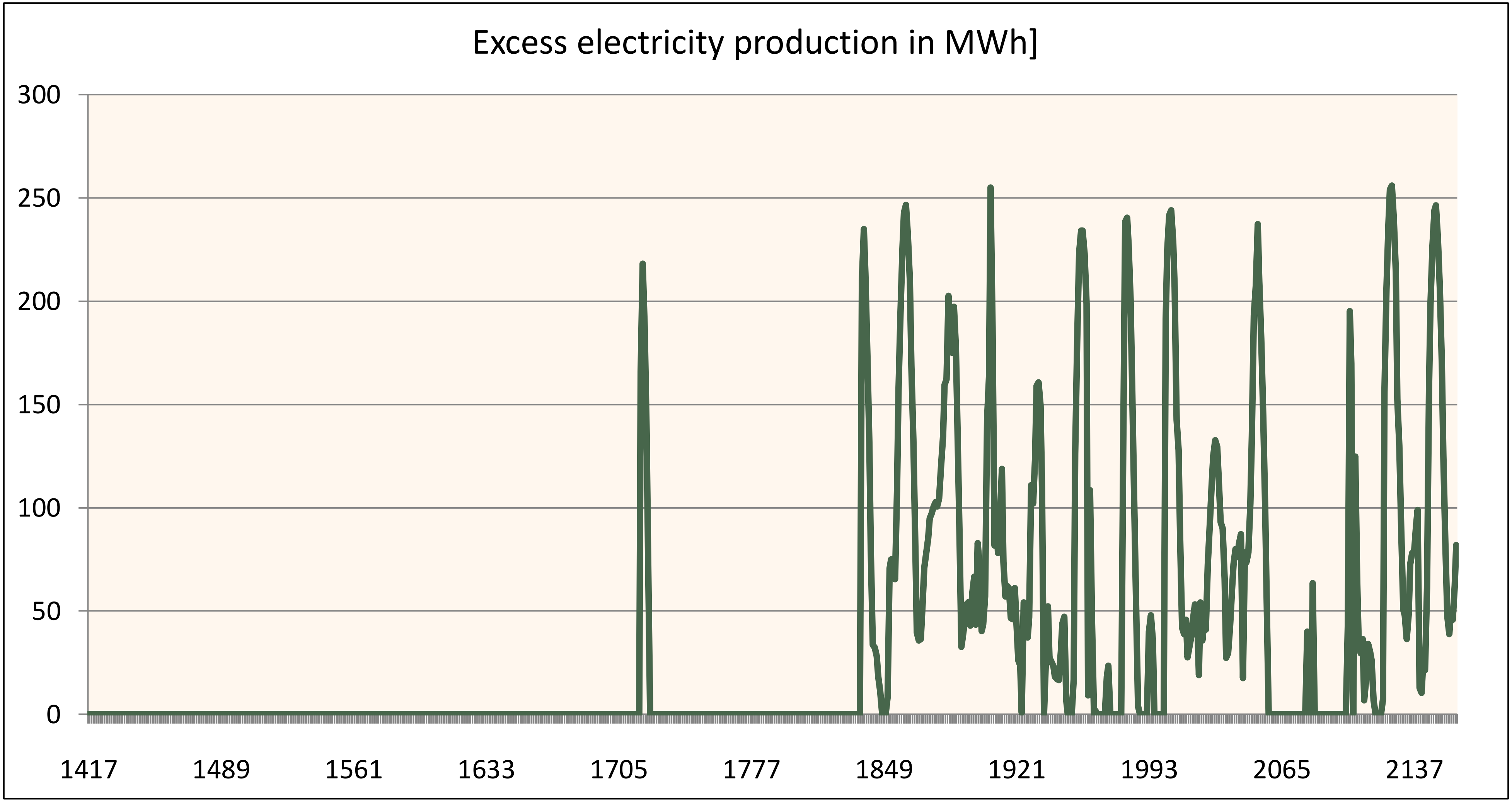
Storage filling level in March



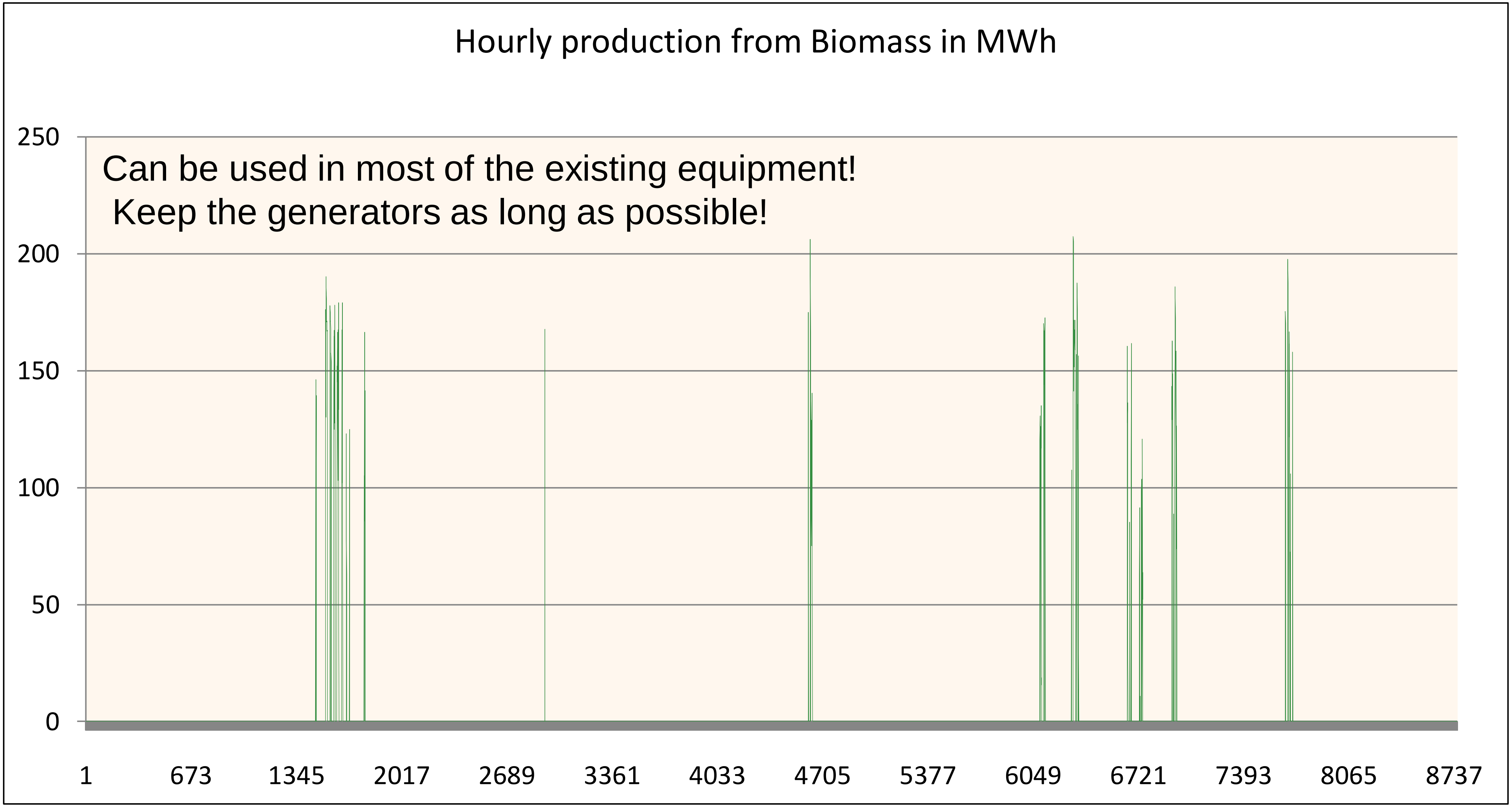
Use of biomass in March to match the load not met by wind, PV or pump storage



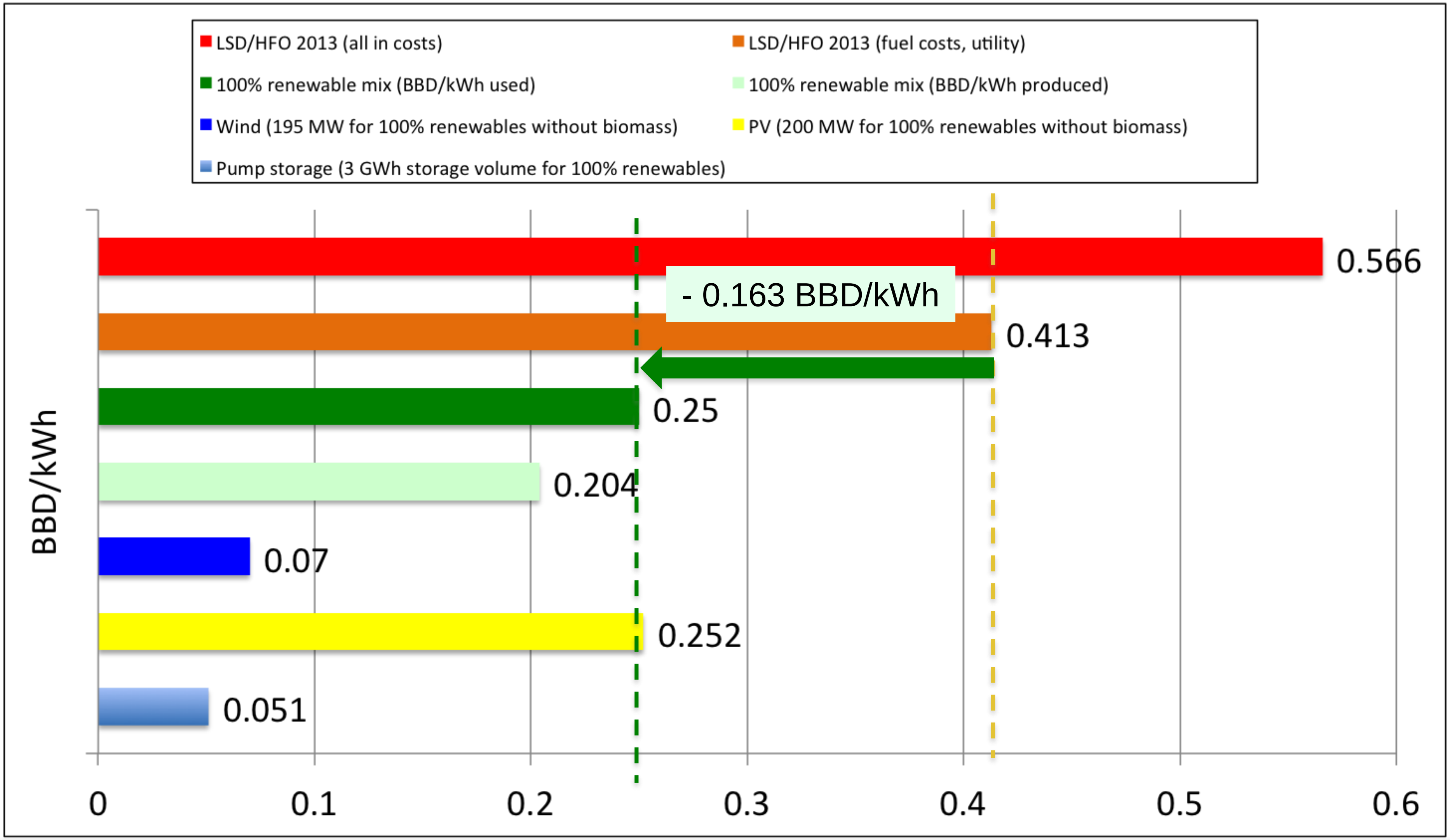
Power overproduction in March from wind and PV



Use of 25 GWh of biomass during the year (about 5 000 t of biodiesel per year)



Electricity costs for 100% renewable Barbados (25 GWh biomass, 3 GWh storage)



Results 2013

- **A 100% renewable power supply for Barbados is no problem**
- **Electricity bill lowered by 175 Million BBD/a**
- **Diesel import savings of about 375 Million BBD/a**
- **Net import reduction per year - 300 Million BBD/a**
- **Net tax increase per year + 104 Million BBD/a**

Conclusions

- 100% renewable power for Barbados is a bargain
- It can reduce Barbados' power costs by about 40%
- A 100% renewable energy strategy can boost Barbados' economy
- Barbados' tax income will significantly increase
- The drain of hard currency will stop

A look beyond

- It is possible to additionally supply even all cars on Barbados with 100% renewable electricity
- It can reduce fuel bills by about 35%
- Save another 250 to 300 Million BBD in fuel imports per year
- Reduce total imports by another 200 - 250 Million BBD/a
- and give the economy an additional boost!

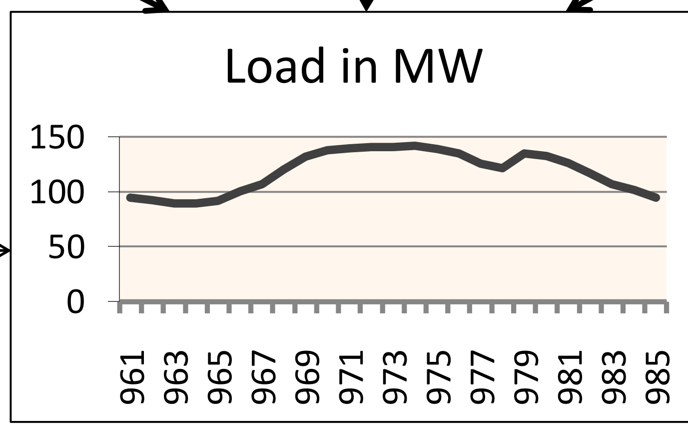
The 100% renewable power system for Barbados *including an all electrical car fleet*

376 MW PV

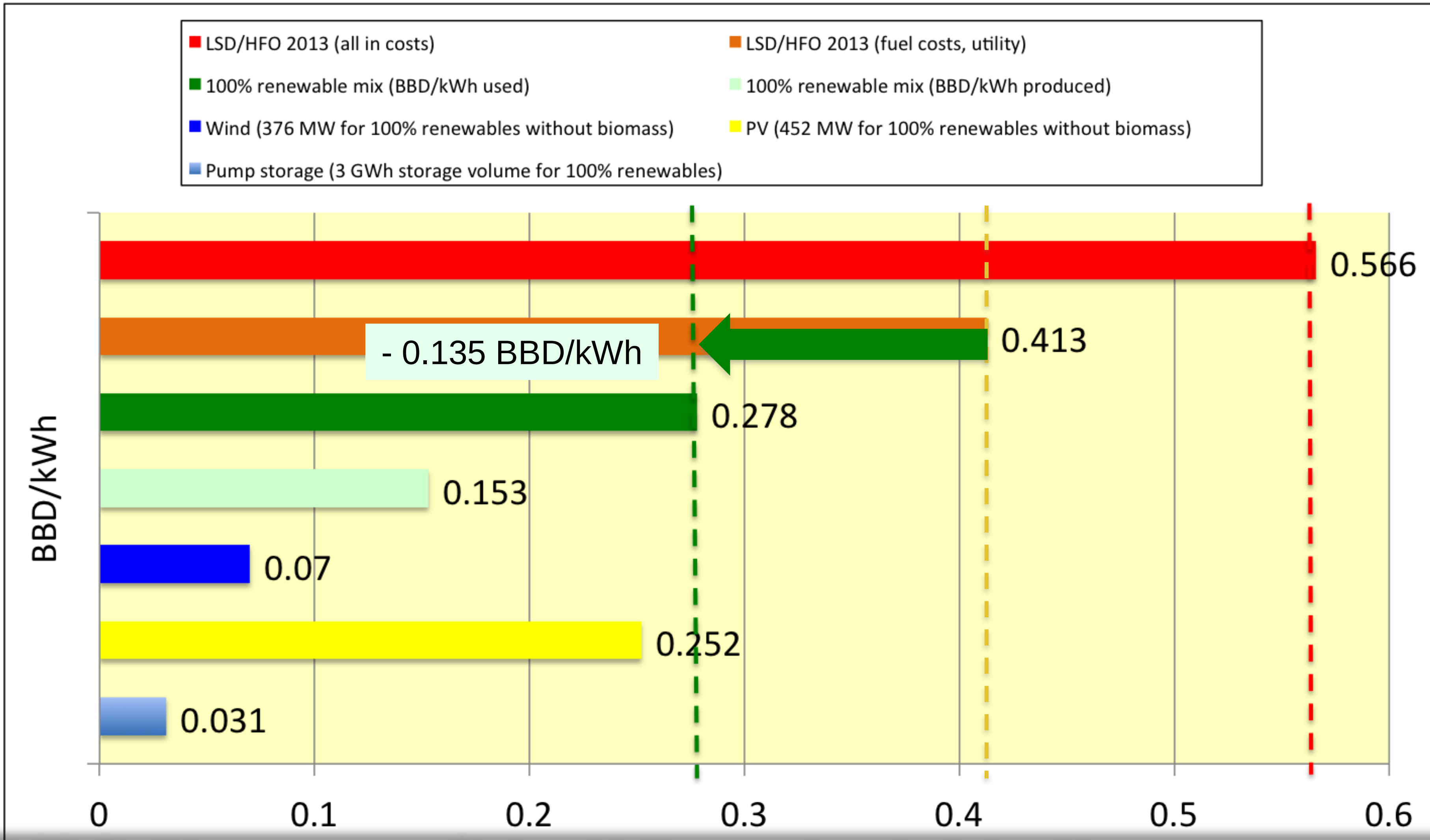
3 GWh PSH

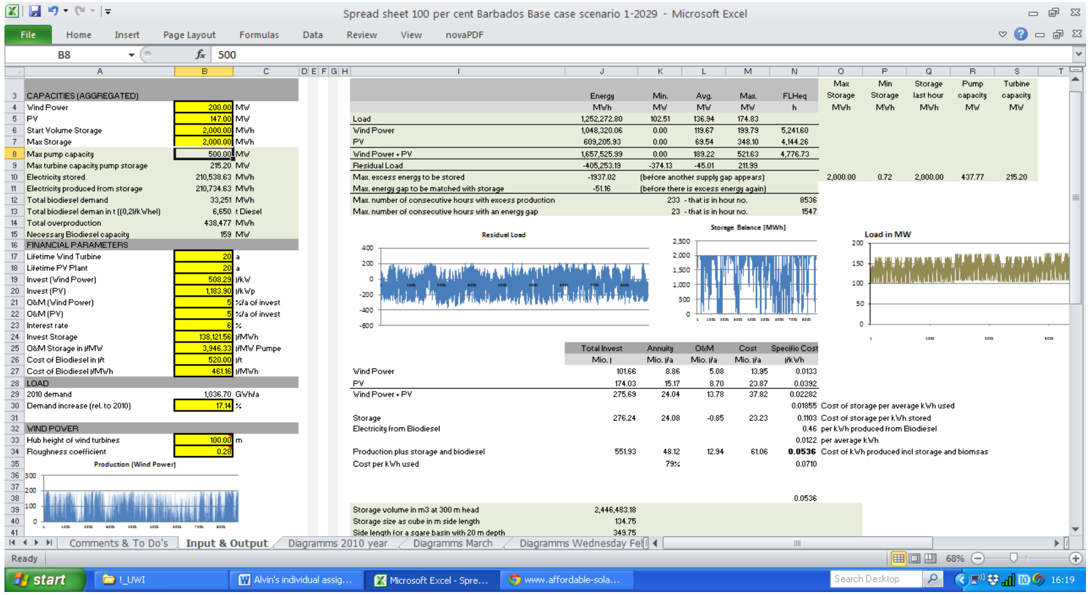
452 MW wind

25 GWh biomass



Electricity costs for 100% renewable Barbados (25 GWh biomass, 3 GWh storage, el. cars)





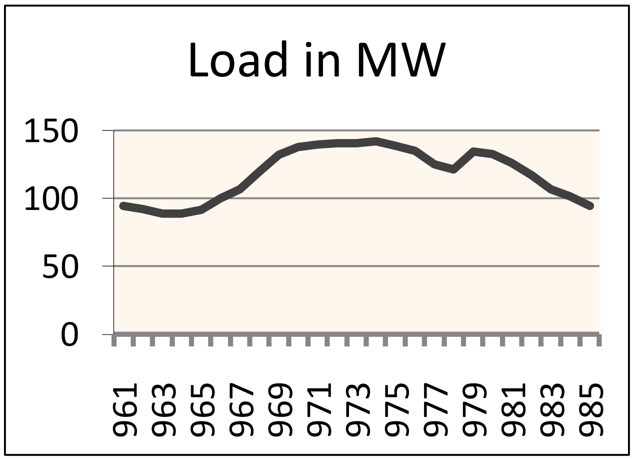
BUILDING YOUR OWN ENERGY MODEL

Moving towards a sustainable world

Building your own 100% renewable energy supply model

- Each participant can build a basic power supply model for an island system based on hourly demand, wind and solar data (until the next training session)
- The model should include demand, wind, PV, biomass, conventional (diesel based electricity) power production and storage
- It should also include a possibility to include the additional demand for e-mobility
- It needs to include a calculation of the energy costs as well
- The model should be able to run a given test-scenario

Basic model structure (hourly calculation)

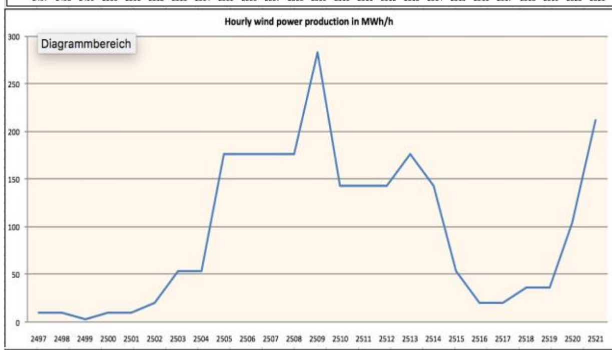


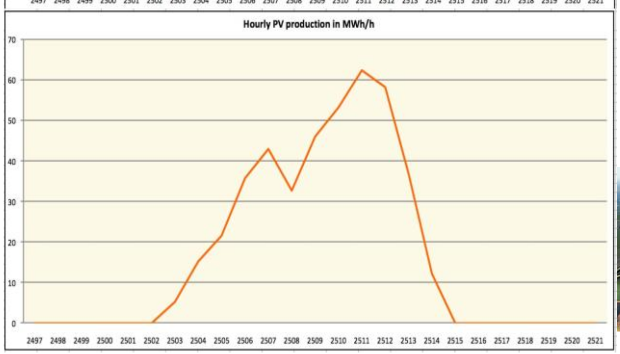
1.

Basic model structure (hourly calculation)

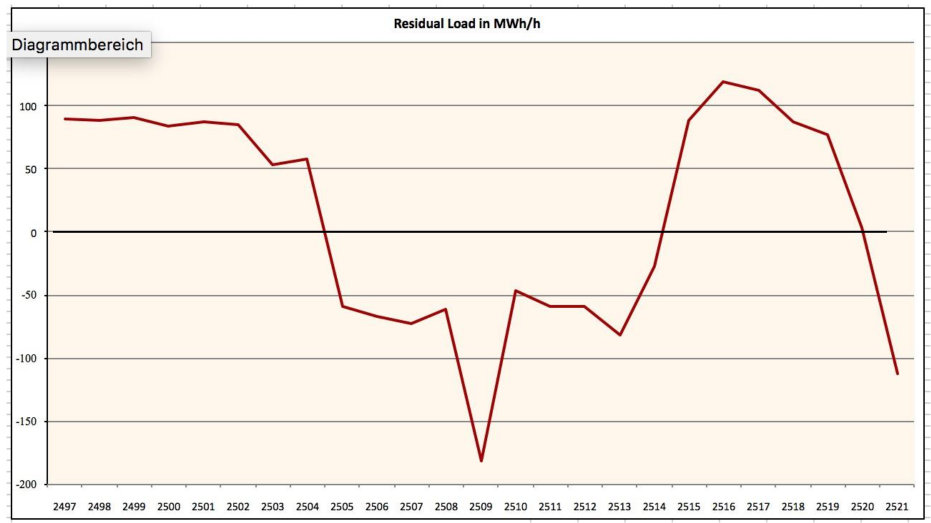
1.

2.





Load – wind – PV = Residual load

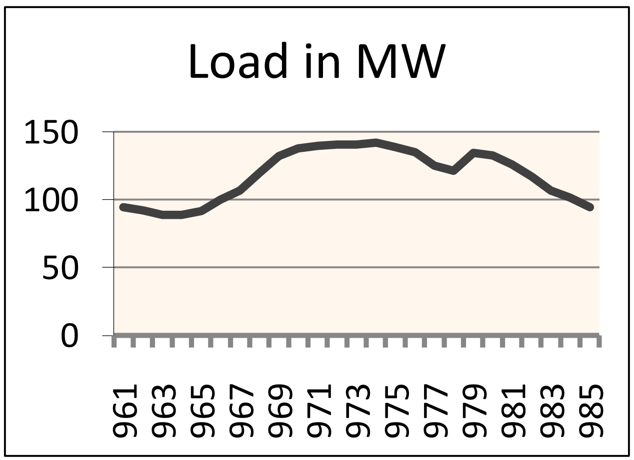


Basic model structure (hourly calculation)

2.

3.

2.



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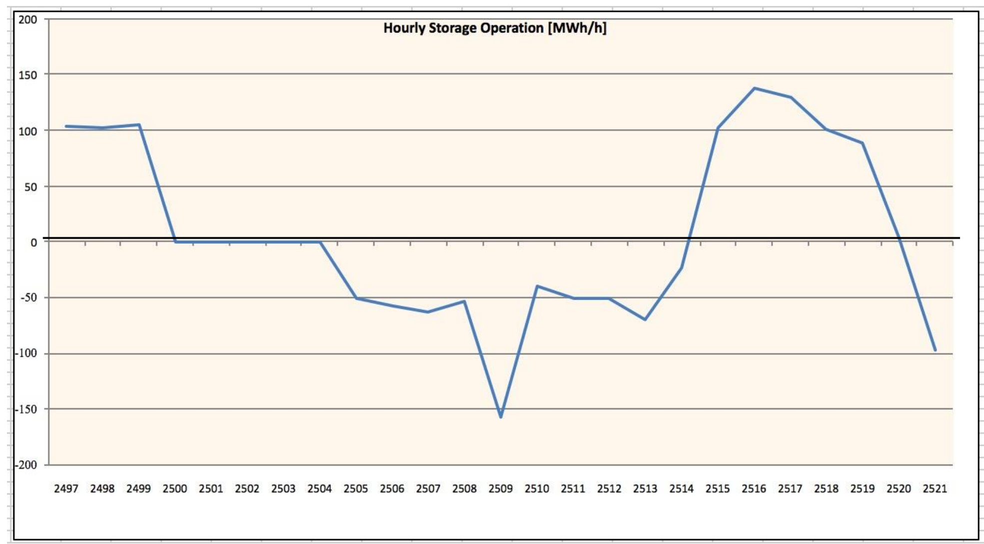

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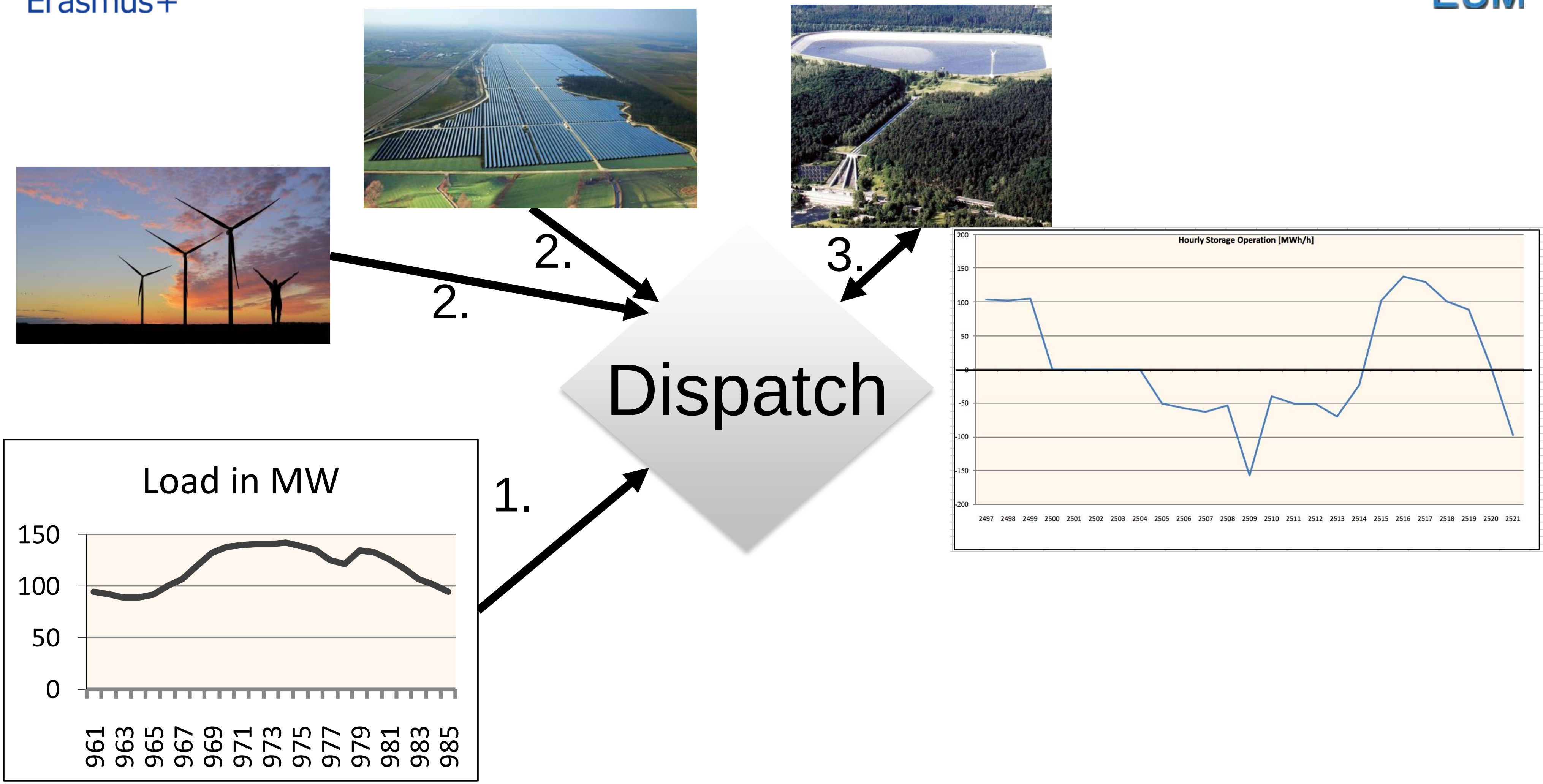

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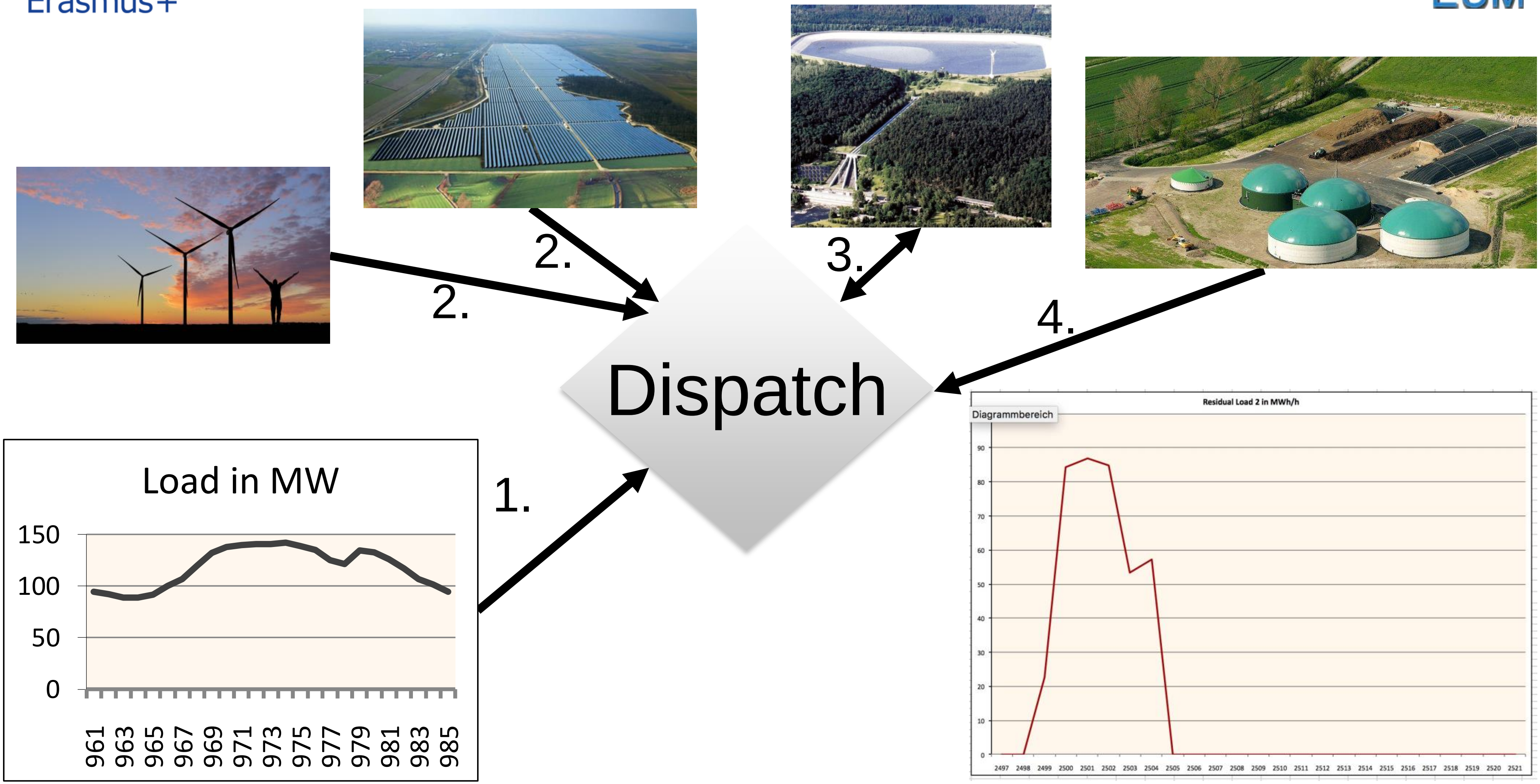

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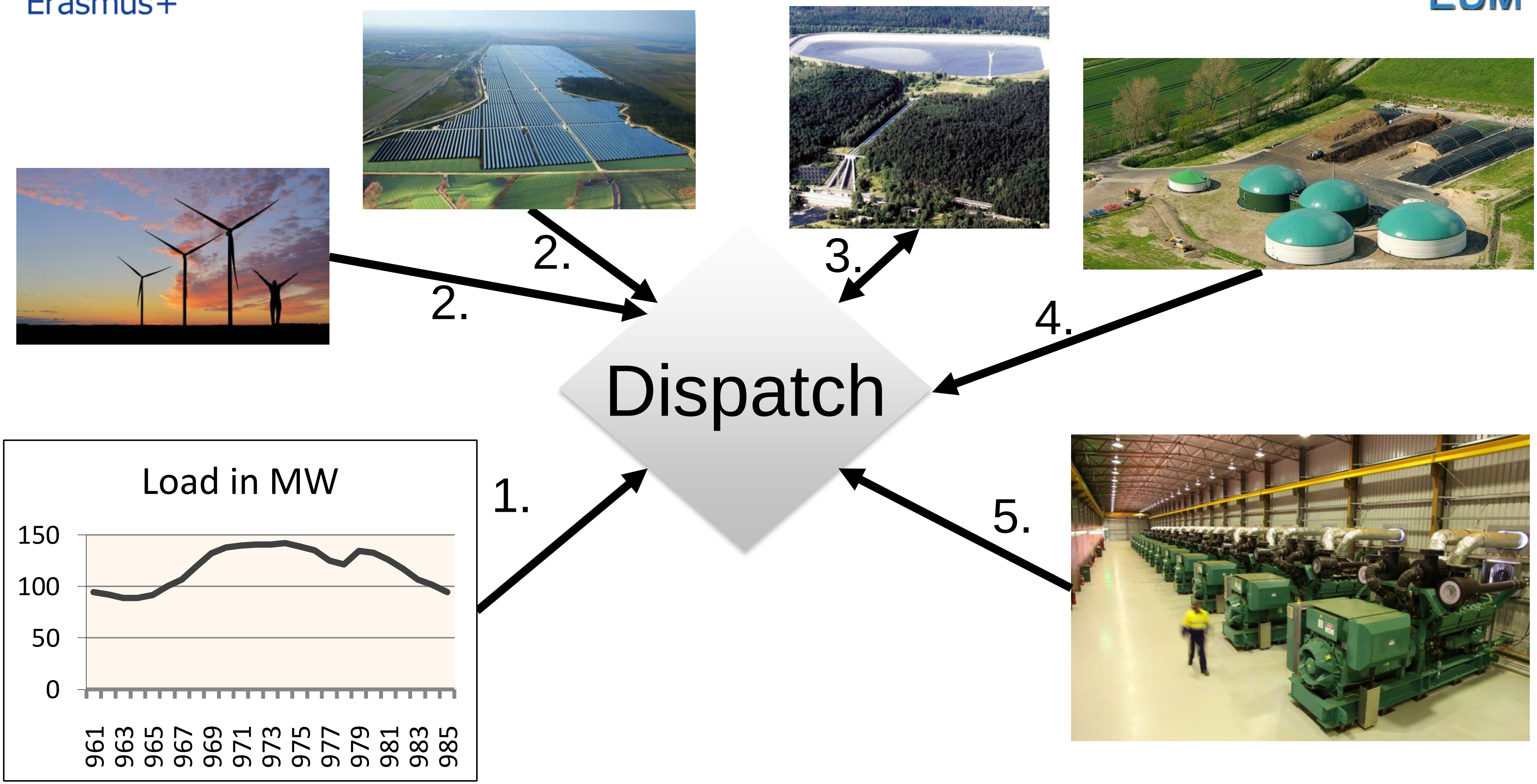

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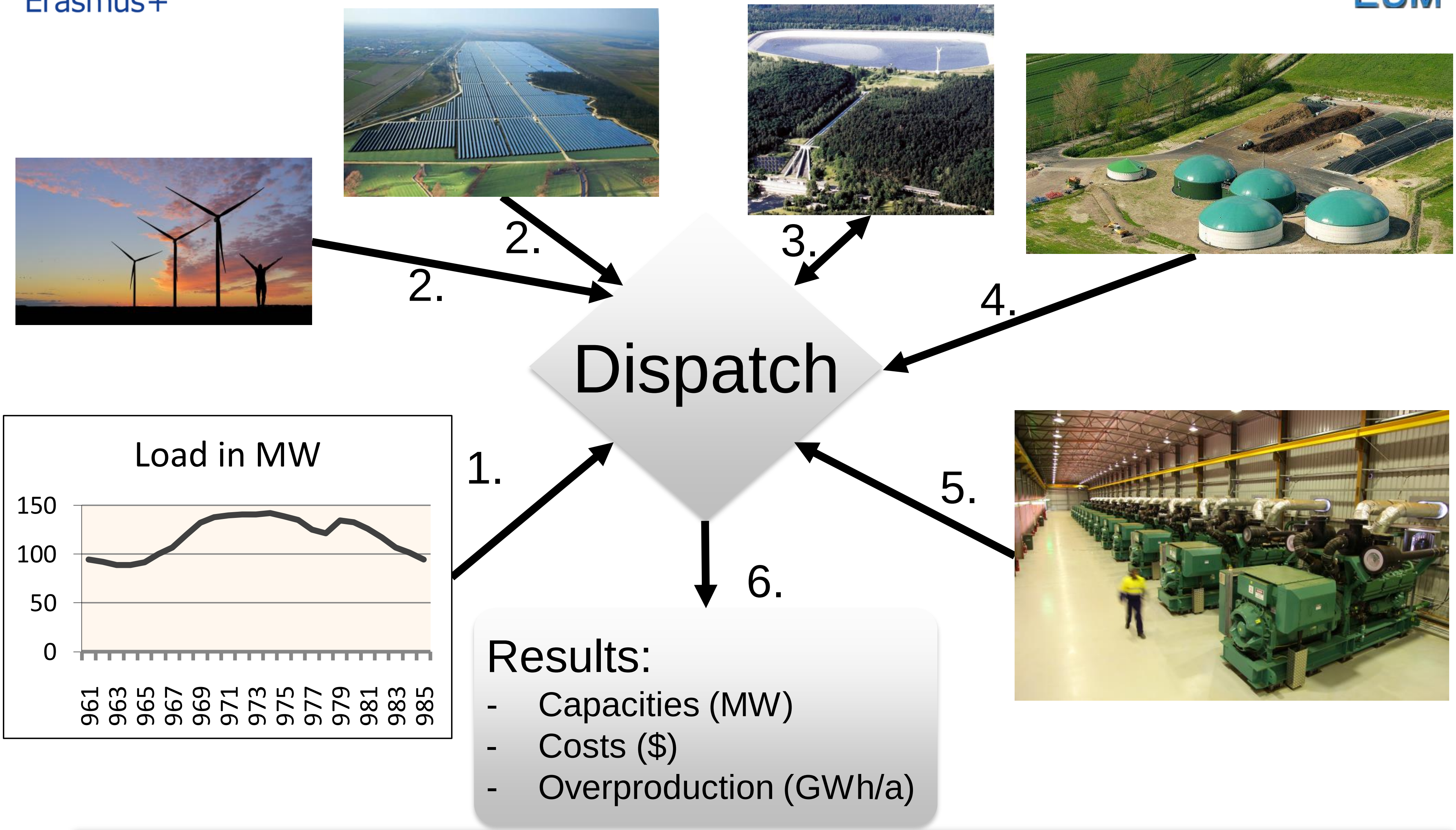

Basic model calculations

Residual load$_t$ = $load_t - PV_t - wind_t$

Basic model calculations

Residual load$_t$ = load$_t$ – PV$_t$ – wind$_t$

Case 1: Wind and solar are not enough to cover the load

If Residual load$_t$ > 0, and storage$_t$ > residual load,
then storage$_{(t+1)}$= storage$_t$ – Residual load$_t$
And Residual load t$_2$ = 0

Basic model calculations

Residual load$_t$ = load$_t$ – PV$_t$ – wind$_t$

Case 1: Wind and solar are not enough to cover the load

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and Residual laod 2$_t$ = 0

If Residual load$_t$ > 0, and storage$_t$ < residual load$_t$,
then **Residual load 2$_t$** = Residual load$_t$ – storage$_t$,
Storage$_{(t+1)}$ = 0,
and **Biomass Prod$_t$ = Residual load 2$_t$** (or conventional production = Residual load 2) (we need dispatachable production to cover the rest of the demand)

Basic model calculations

Residual load$_t$ = load$_t$ – PV$_t$ – wind$_t$

Case 2: Wind and solar production are higher than demand

If Residual load$_t$ < 0, and storage maximum - storage$_t$ >= residual load$_t$
then storage$_{(t+1)}$= storage$_t$ + residual load$_t$

All excess production fits into the storage!

Basic model calculations

Residual load$_t$ = load$_t$ – PV$_t$ – wind$_t$

Case 2: Wind and solar production are higher than demand

If Residual load$_t$ < 0, and storage maximum - storage$_t$ **>=** residual load$_t$
then storage$_{(t+1)}$= storage$_t$ + residual load$_t$
All excess production fits into the storage!

If Residual load$_t$ < 0, and storage maximum – storage$_t$ **<** residual load$_t$
then
down regulated power$_t$ = residual load$_t$ – (strorage maximum – storage$_t$)

Basic model calculations

Residual load$_t$ = load$_t$ – PV$_t$ – wind$_t$

If Residual load$_t$ > 0, and storage$_t$ > residual load,
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If Residual load$_t$ < 0, and storage maximum – storage$_t$ < residual load$_t$
then
down regulated power$_t$ = residual load$_t$ – (strorage maximum – storage$_t$)

Basic model calculations

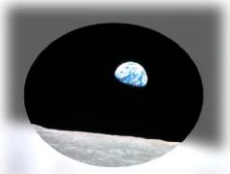
$R1_t = L_t – PV_t – Wind_t$

If $R1_t > 0$, and $S_t > R1$, then $S_{(t+1)} = S_t – R1_t$

If $R1_t > 0$, and $S_t < R1_t$, then $R2_t = R1_t – S_t$,
$S_{(t+1)} = 0$,
and $Biom_t = R2_t$

If $R1_t < 0$, and $S_{max} - S_t >= R1_t$ then $S_{(t+1)} = S_t + R1_t$

If $R1_t < 0$, and $S_{max} – S_t < R1_t$, then $DRP_t = R1_t – (Smax – S_t)$



Moving towards a sustainable world

Basic modules of the model: Input module

- Data to be entered into the input module:
  - Scenario assumptions
    - How much wind capacity is installed
    - How much PV capacity is installed
    - How much storage volume is installed
    - Head of pump storage in m
    - Initial filling level of the storage
    - Hub hight of wind turbines
    - Shear factor for wind
    - Efficiency of PV systems
    - Efficiency of storage …
  - Cost assumptions

Model input for Barbados
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	

Model input for Barbados
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

Model input for Barbados
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

Model input for Barbados
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

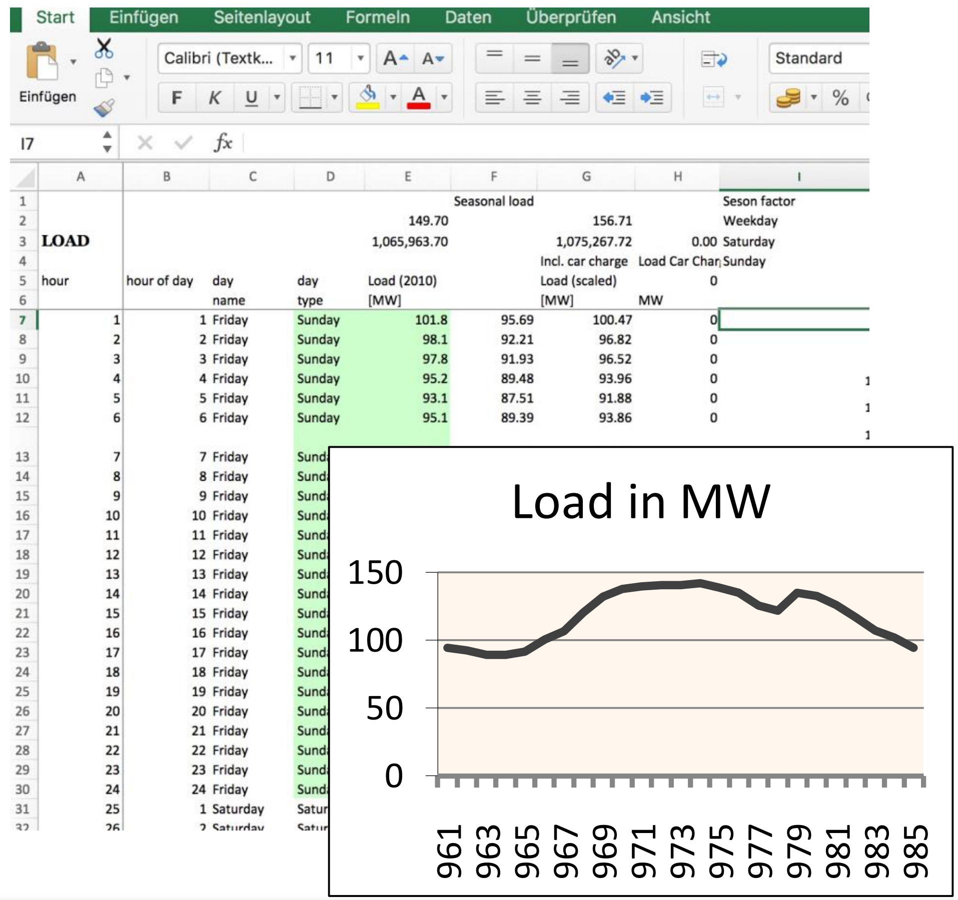
Model input for Barbados
Technical parameters 1

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

Basic modules of the model: Demand module

Data and calculations in the demand module:

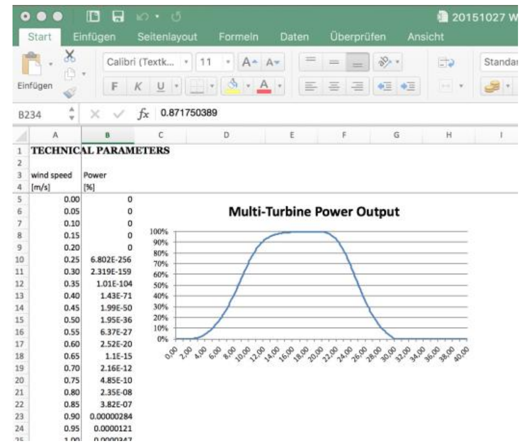
- **Hourly power demand for an entire year**
- Possibly a substructure of the power demand
  - Air conditioning
  - dispatchable loads
  - **e-vehicle charging cycles**
  - Lighting demand
  - Cooking demand
  - Typical household demand
  - Typical hotel demand (seasonality)

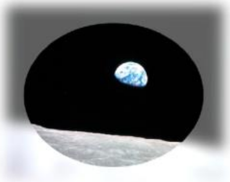


Basic modules of the model: Wind module

Data and calculations in the wind module

- Power curve for wind turbine(s) (Supplied by Prof. Hohmeyer)
- Hourly wind speeds for at least one site and year (airport?)
- Hight of measurements, roughness class of site
- Hub hight of average turbine
- Recalculation algorithm for wind speed at hub hight (shear factor) (Supplied by Prof. Hohmeyer) ($v_1 = v_2 * (Z_1/Z_2)^n$)
- cost of wind turbine investment and operation
- Life time of investment
- Result: Hourly wind power production per MW installed





Basic modules of the model: Wind module

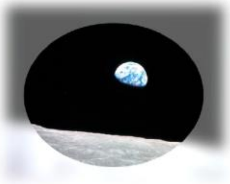
Recalculation algorithm for wind speed at hub hight (shear coefficient)

$$V_1 = V_2 * (Z_1/Z_2)^n$$

- V_1: wind speed at hub height
- V_2: wind speed at measuring height (10m)
- Z_1: hub height
- Z_2: measuring hight
- n: shear coefficient

Table 1: Wind shear coefficient of various terrains [3].

Terrain type	
Lake, ocean, and smooth-hard ground	0.1
Foot-high grass on level ground	0.15
Tall crops, hedges, and shrubs	0.2
Wooded country with many trees	0.25
Small town with some trees and shrubs	0.3
City area with tall buildings	0.4



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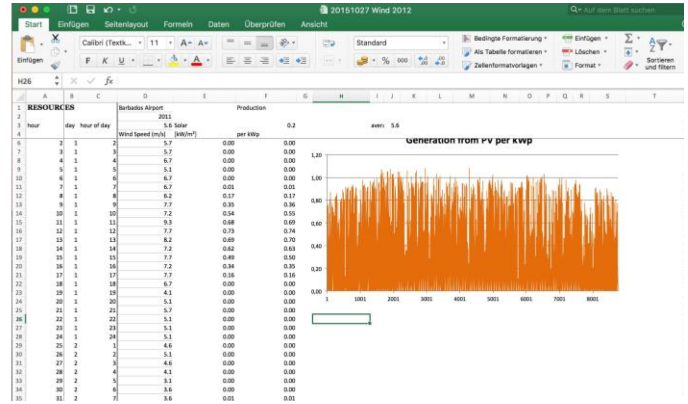
Basic modules of the model: PV module

Data and calculations in the PV module:



- System efficiency data
- Hourly solar radiation data
- Calculation algorithm for output per kW of installed power
- cost of PV system for investment and operation
- Life time of investment
- Result: Hourly solar power production per MW installed

Basic modules of the model: PV calculation

$output_t$ (kWh/kW_p) =

$irradiation_t$ * module area per kW_p * module capacity at 1 kW $irradiation_t$ (kWh/m^2) (m^2/kWp) (kW/kWp)

Example: output in hour 13 of the year

$0.35\ kWh/m^2 * 8\ m2/kW_p * 0.1275\ kW/kW_p = 0.357\ kWh/kW_p$

if 195 MW are installed this is going to produce

0.357 * 195 MW = 69.62 MWh/h

in hour 13 of the year

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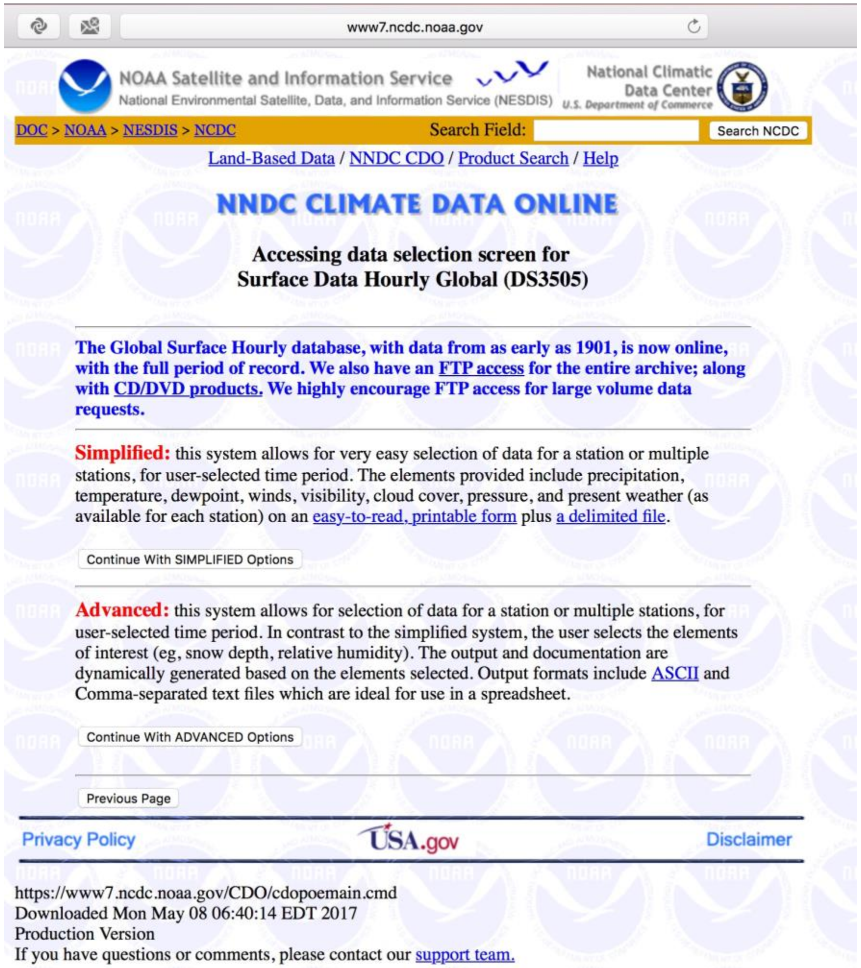
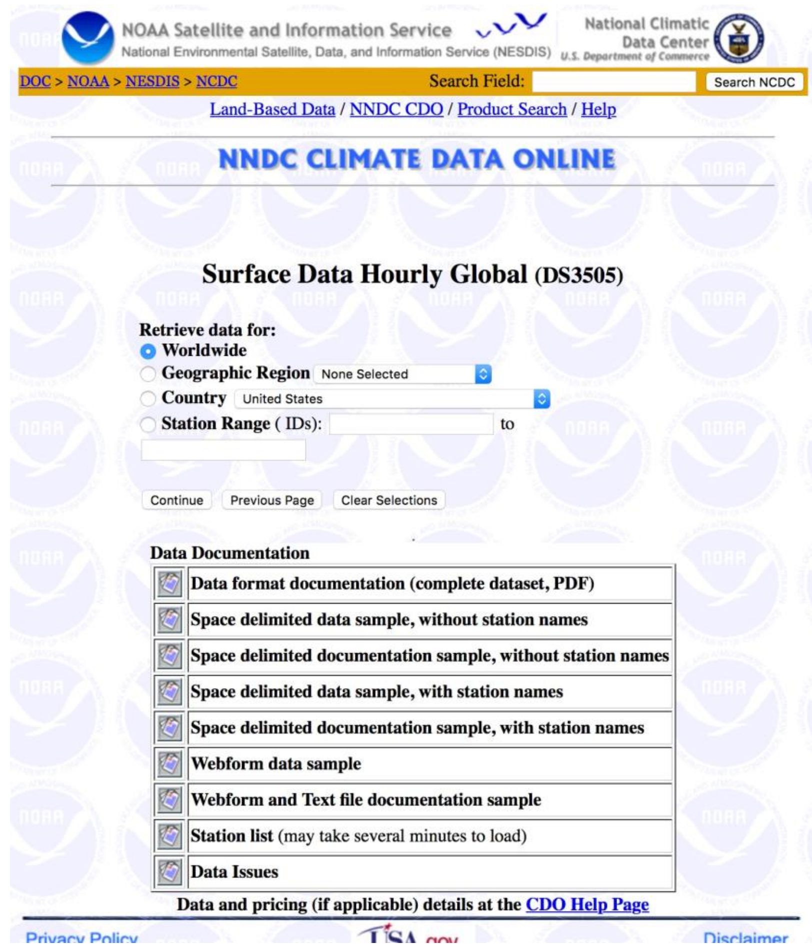
Hourly wind and solar data can be obtained from NOAA





https://www7.ncdc.noaa.gov/CDO/cdopoemain.cmd?datasetabbv=DS3505&countryabbv=&georegionabbv=&resolution=40

Basic modules of the model: Storage module

Data and calculations in the storage module:

- Efficiency of storage technology
- Installed capacity
  - pumps in MW
  - generators in MW
  - Storage volume in MWh
- Cost of storage
  - Investment (per volume and per installed capacity)
  - operation and maintenance
  - Life time of investment
- Result: Hourly storage operation per MW installed

Basic modules of the model: Biomass module

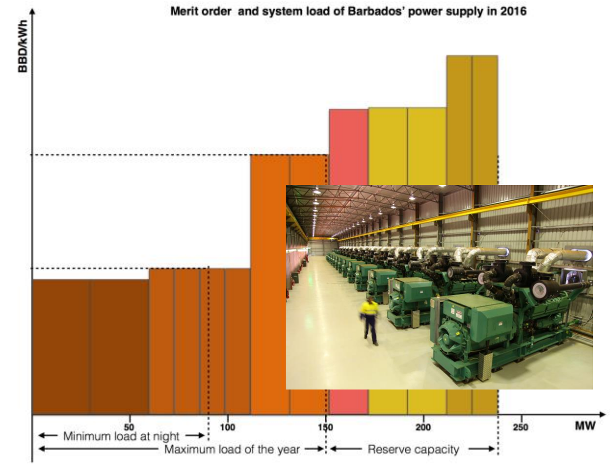
Data and calculations in the (liquid) biomass module:

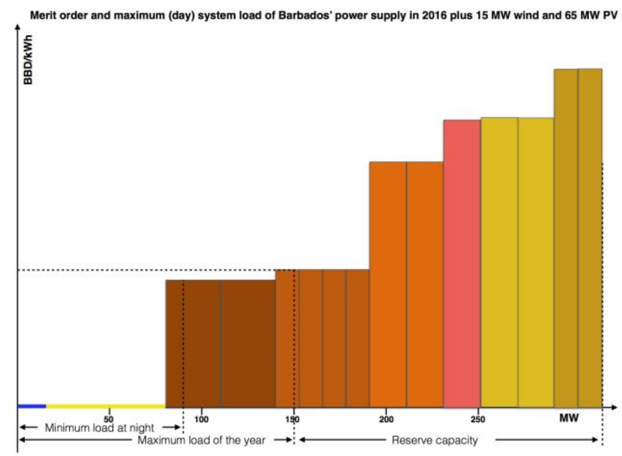
- System efficiency data
- Cost of electricity from liquid biomass (investment and operation)
- Take investment as given by conversion of existing conventional diesel generators and turbines
- Result: Hourly biomass production per MW installed

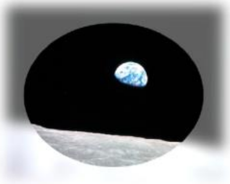
Basic modules of the model: Conventional power module

Data and calculations of the module:

- Capacities and fuel of each unit
- Fuel costs for different conventional units
- O&M costs for different conventional units
- Results:
  - Variable costs per MWh for every conventional unit
  - Time required for cold start
  - Merit order of conventional modules







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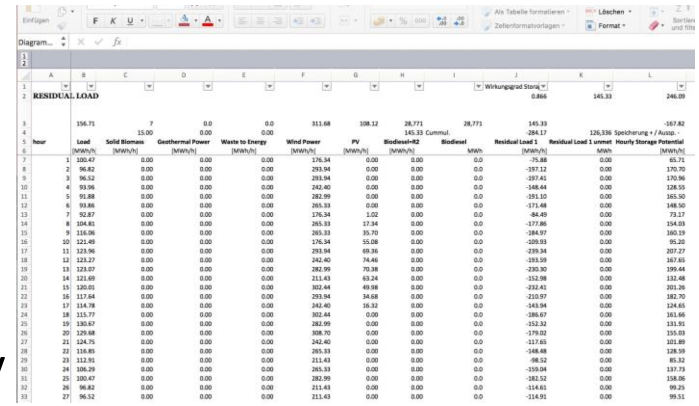
Basic modules of the model: Dispatch module

- Calculate wind and PV production for every hour
- Subtract from load to calculate residual load
- Take difference from storage or add to storage, if production is higher than demand
- If taking from storage take care of storage efficiency
- Keep track of filling level of storage
- If storage is full and you are overproducing, keep track of the power which is overproduced
- If storage is empty use biomass to supply the residual load, as biomass is available
- If there is no more biomass use conventional units to cover the remaining load
- Keep track of all production and costs for the entire year



									Wirkungsgrad Stora		
RESIDUAL LOAD									0.866	145.33	246.09
	156.71	7	0.0	0.0	311.68	108.12	28,771	28,771	145.33		-167.82
		15.00	0.00	0.00			145.33	Cummul.	-284.17	126,336	Speicherung + / Aussp. -
hour	Load	Solid Biomass	Geothermal Power	Waste to Energy	Wind Power	PV	Biodiesel=R2	Biodiesel	Residual Load 1	Residual Load 1 unmet	Hourly Storage Potential
	[MWh/h]	[MWh/h]	[MWh/h]	[MWh/h]	[MWh/h]	[MWh/h]	[MWh/h]	MWh	[MWh/h]	MWh	[MWh/h]
1	100.47	0.00	0.00	0.00	176.34	0.00	0.00	0.0	-75.88	0.00	65.71
2	96.82	0.00	0.00	0.00	293.94	0.00	0.00	0.0	-197.12	0.00	170.70
3	96.52	0.00	0.00	0.00	293.94	0.00	0.00	0.0	-197.41	0.00	170.96
4	93.96	0.00	0.00	0.00	242.40	0.00	0.00	0.0	-148.44	0.00	128.55
5	91.88	0.00	0.00	0.00	282.99	0.00	0.00	0.0	-191.10	0.00	165.50
6	93.86	0.00	0.00	0.00	265.33	0.00	0.00	0.0	-171.48	0.00	148.50
7	92.87	0.00	0.00	0.00	176.34	1.02	0.00	0.0	-84.49	0.00	73.17
8	104.81	0.00	0.00	0.00	265.33	17.34	0.00	0.0	-177.86	0.00	154.03
9	116.06	0.00	0.00	0.00	265.33	35.70	0.00	0.0	-184.97	0.00	160.19
10	121.49	0.00	0.00	0.00	176.34	55.08	0.00	0.0	-109.93	0.00	95.20
11	123.96	0.00	0.00	0.00	293.94	69.36	0.00	0.0	-239.34	0.00	207.27
12	123.27	0.00	0.00	0.00	242.40	74.46	0.00	0.0	-193.59	0.00	167.65
13	123.07	0.00	0.00	0.00	282.99	70.38	0.00	0.0	-230.30	0.00	199.44
14	121.69	0.00	0.00	0.00	211.43	63.24	0.00	0.0	-152.98	0.00	132.48
15	120.01	0.00	0.00	0.00	302.44	49.98	0.00	0.0	-232.41	0.00	201.26
16	117.64	0.00	0.00	0.00	293.94	34.68	0.00	0.0	-210.97	0.00	182.70
17	114.78	0.00	0.00	0.00	242.40	16.32	0.00	0.0	-143.94	0.00	124.65
18	115.77	0.00	0.00	0.00	302.44	0.00	0.00	0.0	-186.67	0.00	161.66
19	130.67	0.00	0.00	0.00	282.99	0.00	0.00	0.0	-152.32	0.00	131.91
20	129.68	0.00	0.00	0.00	308.70	0.00	0.00	0.0	-179.02	0.00	155.03
21	124.75	0.00	0.00	0.00	242.40	0.00	0.00	0.0	-117.65	0.00	101.89
22	116.85	0.00	0.00	0.00	265.33	0.00	0.00	0.0	-148.48	0.00	128.59
23	112.91	0.00	0.00	0.00	211.43	0.00	0.00	0.0	-98.52	0.00	85.32
24	106.29	0.00	0.00	0.00	265.33	0.00	0.00	0.0	-159.04	0.00	137.73
25	100.47	0.00	0.00	0.00	282.99	0.00	0.00	0.0	-182.52	0.00	158.06
26	96.82	0.00	0.00	0.00	211.43	0.00	0.00	0.0	-114.61	0.00	99.25
27	96.52	0.00	0.00	0.00	211.43	0.00	0.00	0.0	-114.91	0.00	99.51

Basic model structure (hourly calculation)

Hour	Load								
1	**Hourly load curve**								
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
..									
....									
8760									

Basic model structure (hourly calculation)

Hour	Load	PV							
	Hourly load curve	**-**							
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
..									
....									
8760									

Basic model structure (hourly calculation)

Hour	Load	PV	Wind						
	Hourly load curve	**-**	**-**						
1									
2									
3									
4									
5									
6									
7									
8									
..									
....									
8760									

Basic model structure (hourly calculation)

Hour	Load	PV	Wind	Solid Biomass					
	Hourly load curve	**-**	**-**	**-**					
1									
2									
3									
4									
5									
6									
7									
8									
..									
....									
8760									

Basic model structure (hourly calculation)

Hour	Load	PV	Wind	Solid Biomass	Residual Load 1 (R1)				
	Hourly load curve	**-**	**-**	**-**	**=**				
1									
2									
3									
4									
5									
6									
7									
8									
..									
....									
8760									

Basic model structure (hourly calculation)

Hour	Load	PV	Wind	Solid Biomass	Residual Load 1 (R1)	Storage t-1			
	Hourly load curve	**-**	**-**	**-**	**=**	**>/< R1**			
1									
2									
3									
4									
5									
6									
7									
8									
..									
....									
8760									

Basic model structure (hourly calculation)

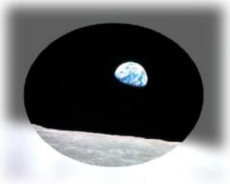
Hour	Load	PV	Wind	Solid Biomass	Residual Load 1 (R1)	Storage t-1	Storage t		
	Hourly load curve	**-**	**-**	**-**	**=**	**>/< R1**	**S_{t-1} +/- R1**		
1									
2									
3									
4									
5									
6									
7									
8									
..									
....									
8760									

Basic model structure (hourly calculation)

Hour	Load	PV	Wind	Solid Biomass	Residual Load 1 (R1)	Storage t-1	Storage t	Residual Load 2 (R2)	
	Hourly load curve	**-**	**-**	**-**	**=**	**>/< R1**	**S_{t-1} +/- R1**	**R2 = R1 +/- S_t**	
1									
2									
3									
4									
5									
6									
7									
8									
..									
....									
8760									

Basic model structure (hourly calculation)

Hour	Load	PV	Wind	Solid Biomass	Residual Load 1 (R1)	Storage t-1	Storage t	Residual Load 2 (R2)	Back-up
	Hourly load curve	**-**	**-**	**-**	**=**	**>/< R1**	S_{t-1} **+/- R1**	**R2 = R1 +/-** S_t	**= R2**
1									
2									
3									
4									
5									
6									
7									
8									
..									
....									
8760									



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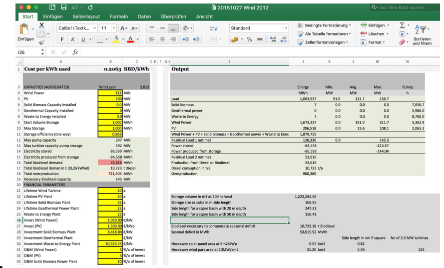
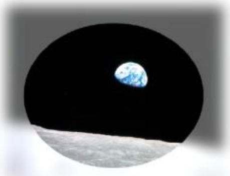
Basic modules of the model: Results module



Give aggregated results for the entire year:

- production from each resource (in GWh)
- used maximum capacities for wind, PV, biomass, storage (pumps, generators, volume), conventional generators (in MW (MWh for storage volume)
- total production (in GWh)
- total supply (in GWh)
- costs for each resource (in million €)
- total cost for all production (in million €)
- average cost per kWh produced (in €/kWh)
- average cost per kWh supplied to final demand (in €/kWh)



Basic modules of the model: Results module

20151027 Wind 2012

	A	B	C
1	**Cost per kWh used**	**0.2063**	**BBD/kWh**
3	CAPACITIES (AGGREGATED)	Wind year	2,012
4	Wind Power	312	MW
5	PV	100	MW
6	Solid Biomass Capacity installed	0.0	MW
7	Geothermal Capacity installed	0	MW
8	Waste to Energy installed	0.0	MW
9	Start Volume Storage	1,000	MWh
10	Max Storage	1,000	MWh
11	Storage efficiency (one way)	0.866	
12	Max pump capacity	247	MW
13	Max turbine capacity pump storage	192	MW
14	Electricity stored	86,599	MWh
15	Electricity produced from storage	-84,558	MWh
16	Total biodiesel demand	53,616	MWh
17	Total biodiesel deman in t ((0,2l/kWhel)	10,723	t Diesel
18	Total overproduction	721,506	MWh
19	Necessary Biodiesel capacity	145	MW
20	FINANCIAL PARAMETERS		
21	Lifetime Wind Turbine	20	a
22	Lifetime PV Plant	20	a
23	Lifetime Solid Biomass Plant	25	a
24	Lifetime Geothermal Power Plant	25	a
25	Waste to Energy Plant	25	a
26	Invest (Wind Power)	1,050.00	€/kW
27	Invest (PV)	1,500.00	€/kWp
28	Investment Solid Biomass Plant	8,418.84	€/kW
29	Investment Geothermal Plant		€/kW
30	Investment Waste to Energy Plant	10,523.55	€/kW
31	O&M (Wind Power)	5	%/a of invest
32	O&M (PV)	5	%/a of invest
33	O&M Solid Biomass Power Plant	10	%/a of invest

Output

	Energy	Min.	Avg.	Max.	FLHeq
	MWh	MW	MW	MW	h
Load	1,063,937	91.9	122.7	156.7	
Solid biomass	7	0.0	0.0	0.0	7,056.7
Geothermal power	0	0.0	0.0	0.0	5,986.0
Waste to Energy	7	0.0	0.0	0.0	8,760.0
Wind Power	1,673,227	0.0	191.0	311.7	5,362.9
PV	206,518	0.0	23.6	108.1	2,065.2
Wind Power + PV + Solid biomass + Geothermal power + Waste to Ener	1,879,759				
Residual Load 1 not met	126,336	0.0		145.3	
Power stored	-84,558			-213.57	
Power produced from storage	-86,599			-144.04	
Residual Load 2 not met	53,616				
Production from Diesel or Biodiesel	53,616				
Diesel consuption in t/a	10,723	t/a			
Overproduction	900,380				

Storage volume in m3 at 300 m head	1,223,241.59				
Storage size as cube in m side length	106.95				
Side length for a sqare basin with 20 m depth	247.31				
Side length for a sqare basin with 50 m depth	156.41				
Biodiesel necessary to compensate seasonal deficit	10,723.18	t Biodiesel			
Sesonal deficit in MWh	53,615.92	MWh			
			Side length in km if square		No of 2.5 MW turbines
Necessary solar panel area at 8m2/kWp	0.67	km2	0.82		
Necessary wind park area at 10MW/km2	31.20	km2	5.59		125

Model output for Barbados
Summary of results

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

Panel for quick change and response

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	
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
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Power generation capacity for Waste to Energy	0.0	MW
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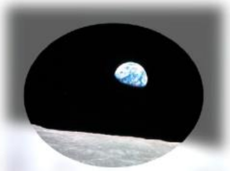
Syngas storage volume reqired	0.0	MWh gas
Biogas storage volume required at ambient pressure	0.0	
Syngasgas storage volume required at ambient pressure	0.0	m3
Necessary Biodiesel capacity	143.8	MW
Total biodiesel demand	24 747	MWh
Total biodiesel deman in t ((0,2l/kWhel)	4 949	t Diesel
Total overproduction power	487 624	MWh
Total overproduction gas	0	MWh gas

Model output for Barbados
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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Basic modules of the model: Graphics module

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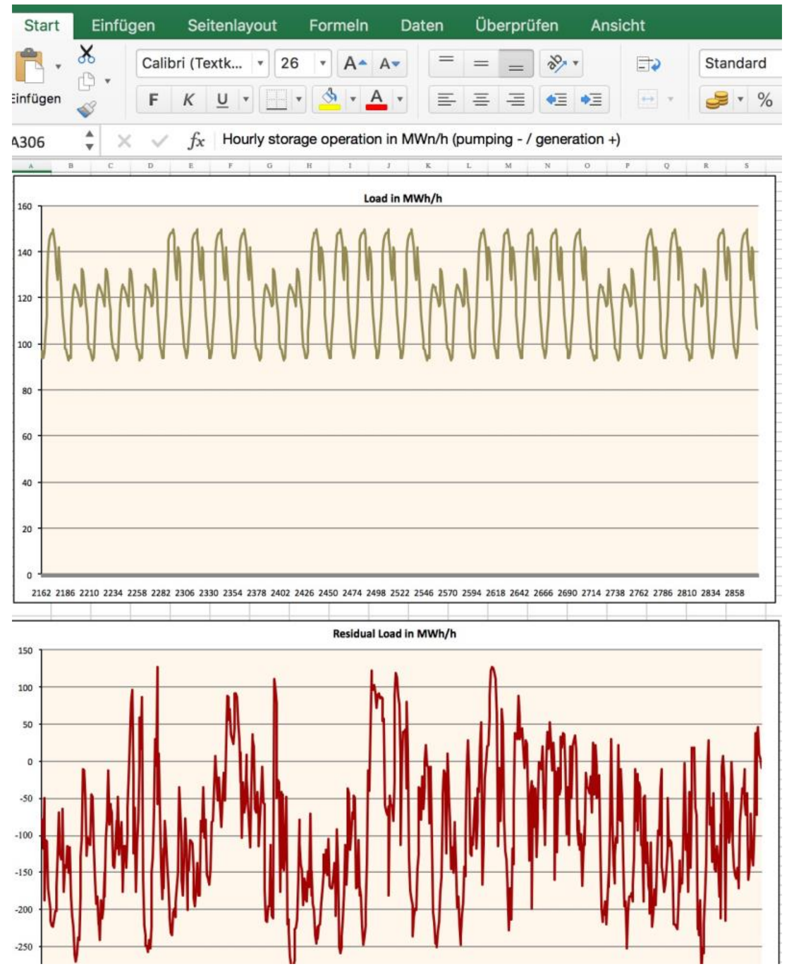
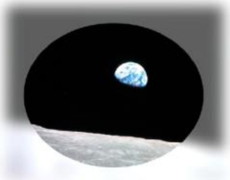
Graphs of the model results:

- demand
- wind power production
- PV production
- storage operation
- biomass energy production
- conventional power production
- excess energy production
- daily graphs
- monthly graphs
- annual graphs





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Tasks till Thursday

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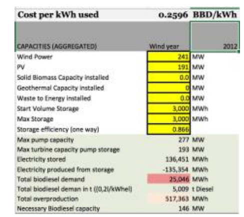
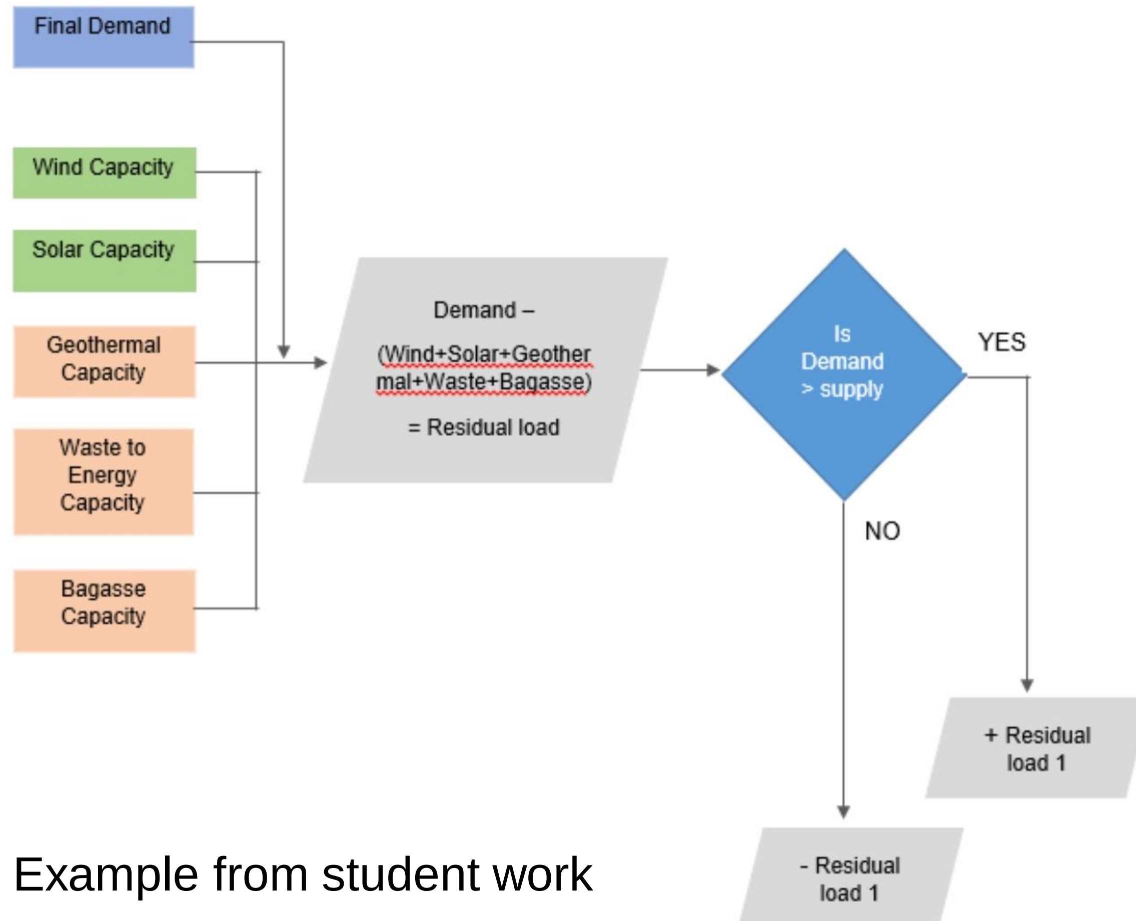
1. We form two groups
2. Every group gets a copy of the model for Barbados
3. Task A: Use the model to test the impact of varying the model inputs for (try to keep biodiesel at 5,000t/a) and note the results:
    1. Wind capacity (-100 MW))
    2. PV capacity (-150 MW)
    3. Storage capacity (500 MWh)
    4. What happens to the cost per kWh? (Keep biodiesel to 5000 t/a
    5. Try to find the lowest cost combination of wind, PV and storage capacity (with no more than 5,000 t/a of biodiesel)
    6. What happens to the overproduction (in each case)?
    7. Try to vary other parameters (investment costs (-10%), interest rate (10%), height of wind turbine (120m), roughness (0.1)



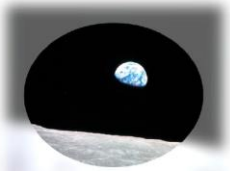
Cost per kWh used	0.2596	BBD/kWh
CAPACITIES (AGGREGATED)	Wind year	2012
Wind Power	241	MW
PV	191	MW
Solid Biomass Capacity installed	0.0	MW
Geothermal Capacity installed	0	MW
Waste to Energy installed	0.0	MW
Start Volume Storage	3,000	MWh
Max Storage	3,000	MWh
Storage efficiency (one way)	0.866	
Max pump capacity	277	MW
Max turbine capacity pump storage	193	MW
Electricity stored	136,451	MWh
Electricity produced from storage	-135,354	MWh
Total biodiesel demand	25,046	MWh
Total biodiesel deman in t ((0,2l/kWhel)	5,009	t Diesel
Total overproduction	517,363	MWh
Necessary Biodiesel capacity	146	MW

Tasks till Thursday

4. Task B: Develop your own logical structure of how your group wants to structure your spreadsheet model



Example from student work



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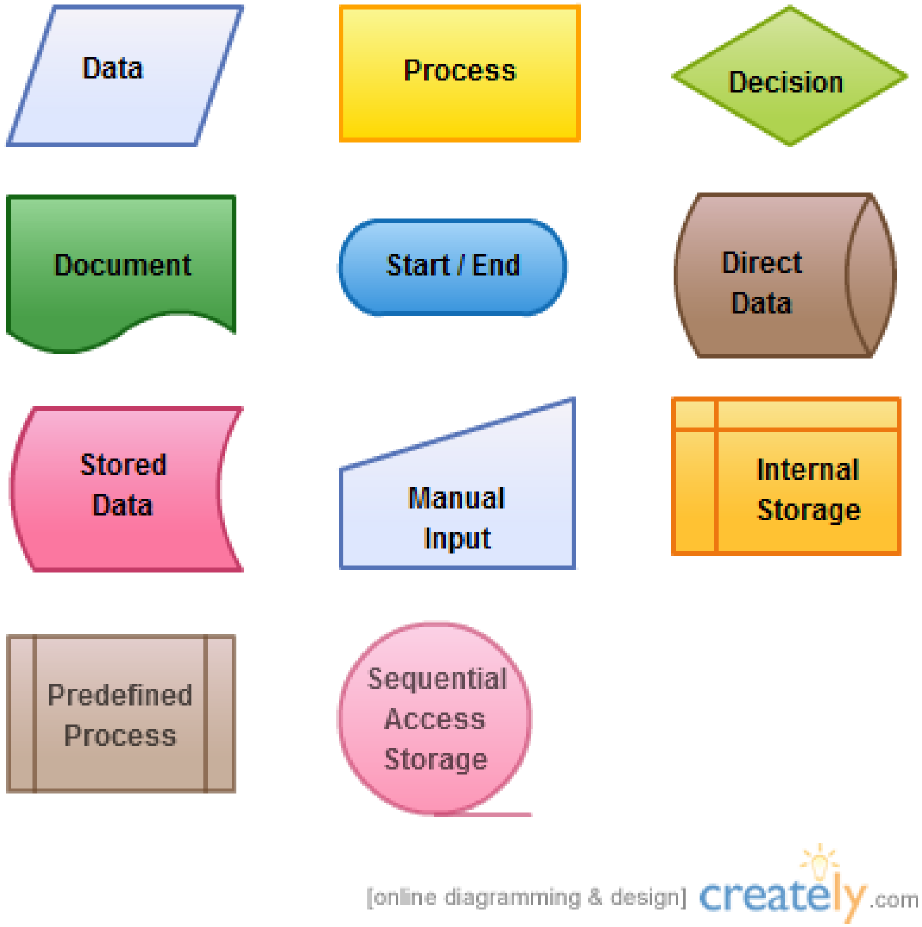
Basics of logical flow charting
Main symbols used

Basic flow chart symbols:

- Start/End
- Data input
- Manual input
- Direct data
- Stored data
- Process
- Decision
- Internal storage



Basics of logical flow charting:
Example flow chart

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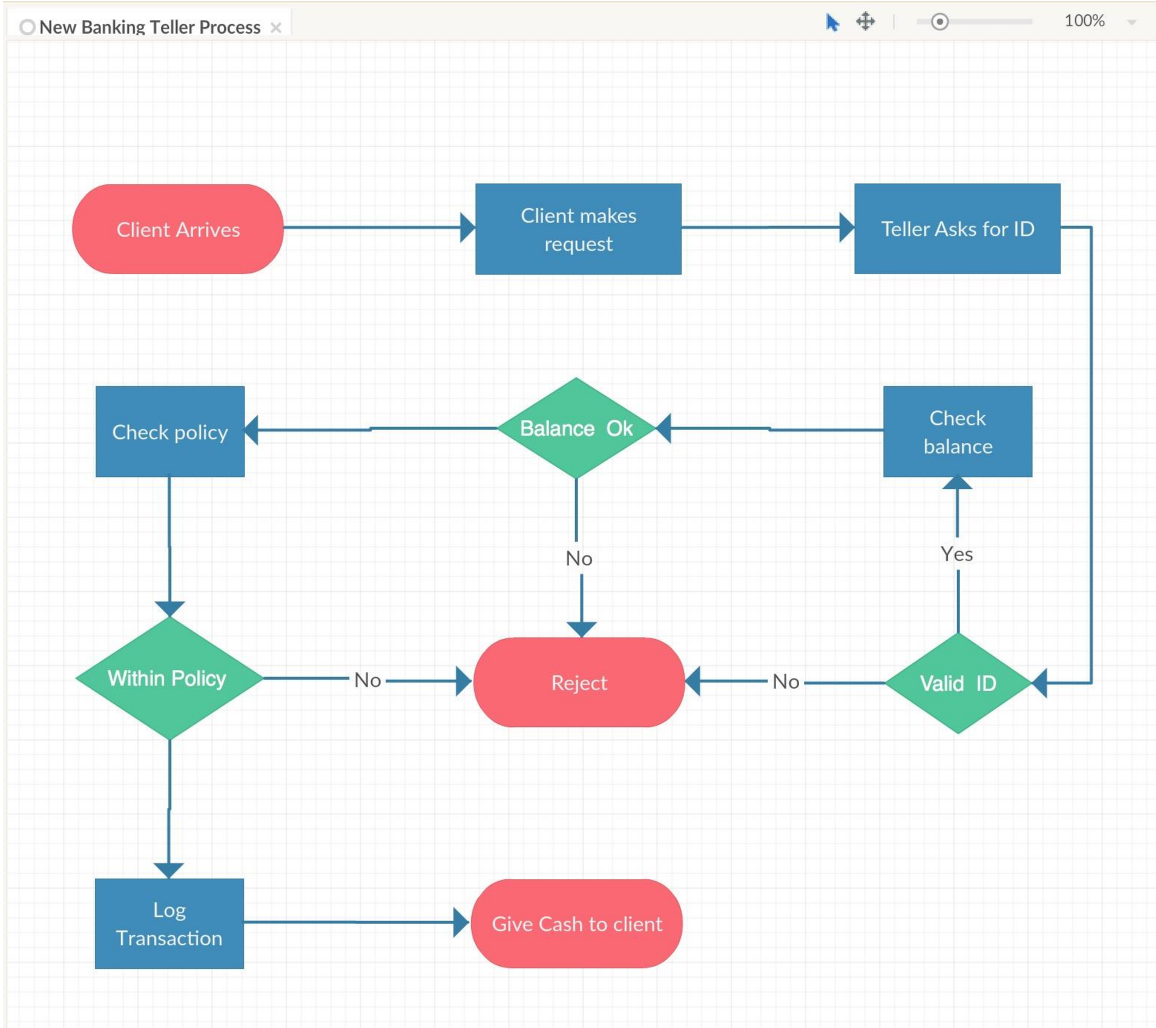
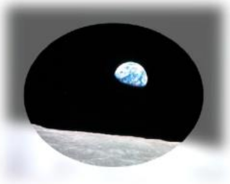
Simple example:

Banking Teller Process

(Can we give money to this client?)





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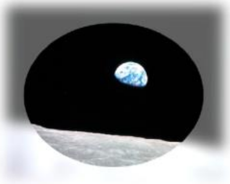
Task C: **until the next training session**

Task C:

Develop **your own** spread sheet model!

(until the next training session)

You may use the hourly data (wind, PV, load) from the model you were given.



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Time for questions ….