Part 4: Renewable Electricity Output and Integration Modelling

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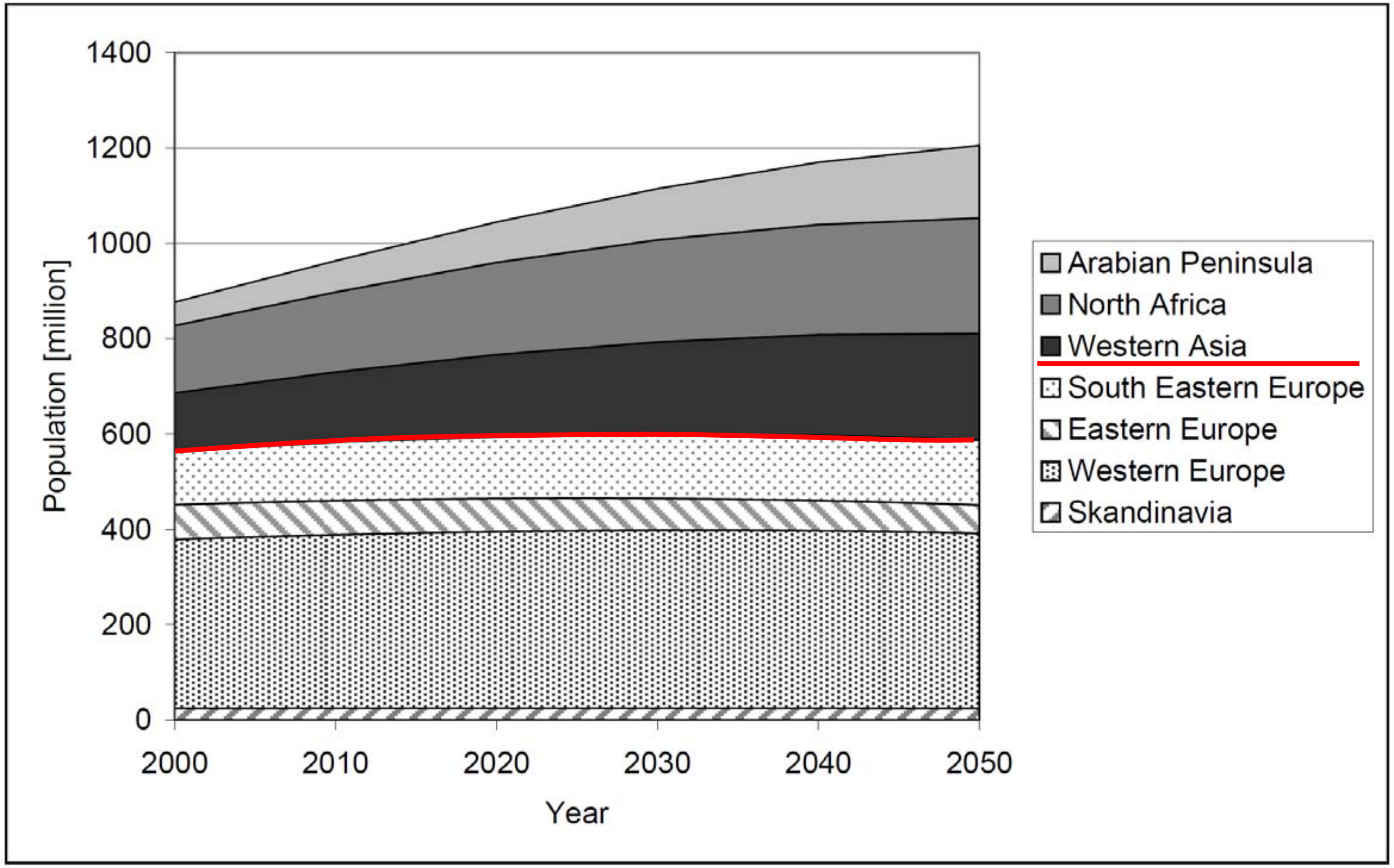
Demand Side Modelling

Mounting an Electricity Demand Scenario

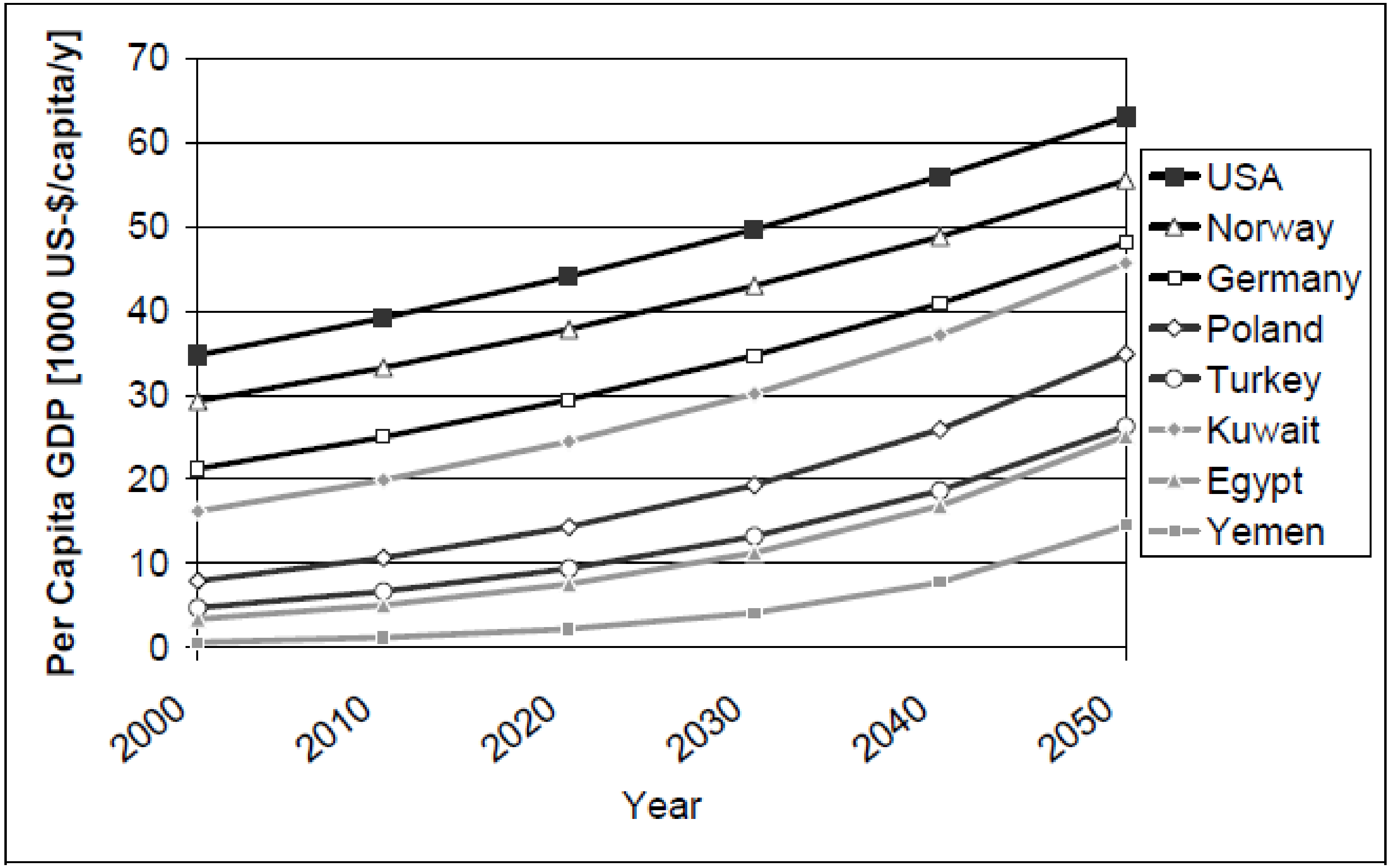
1. Present Annual Demand and Peak Load from National Power Statistics
2. Defining and Quantifying Electricity Demand Drivers
3. Future Annual Demand and Peak Load Perspectives
4. Required Security Margin for Power Capacity

1st Driver for Power Demand: Population



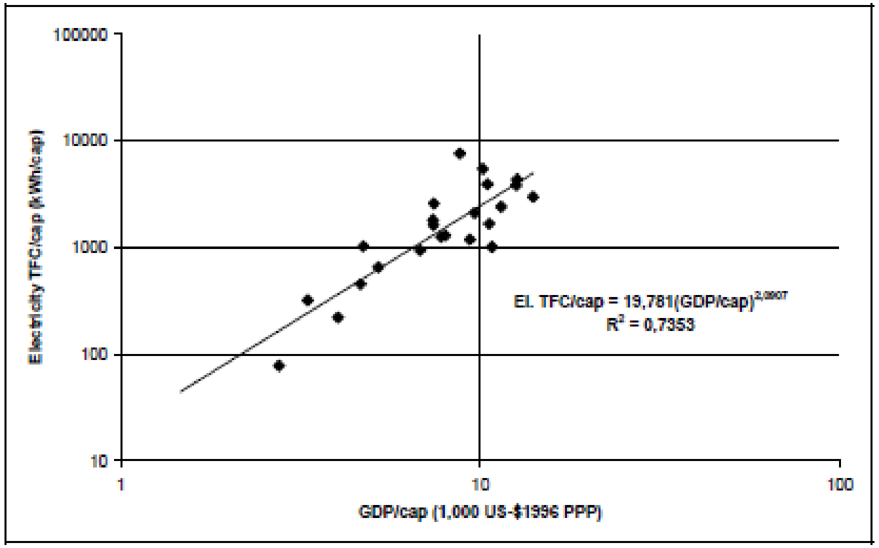
from United Nations World Population Prospects

2nd Driver for Power Demand: Economic Growth

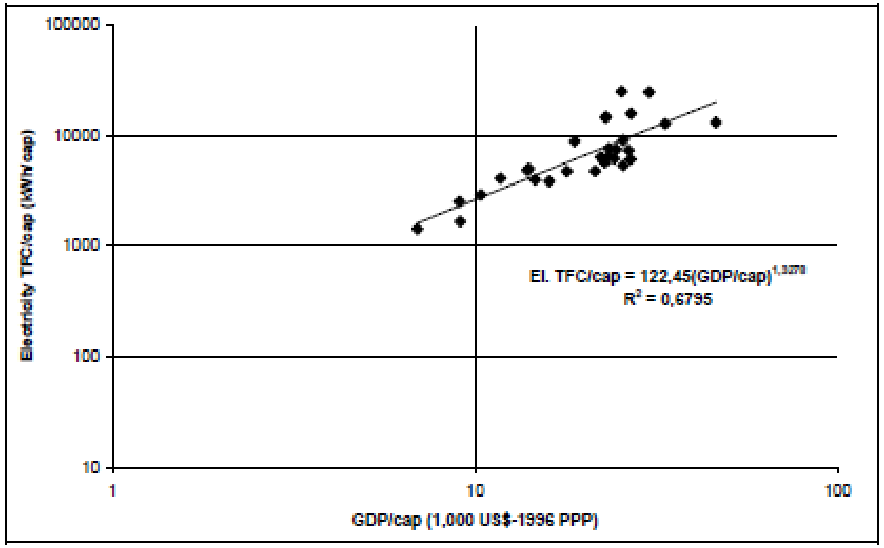


from own estimates or other outlook studies

3rd Driver for Power Demand: Efficiency Gains



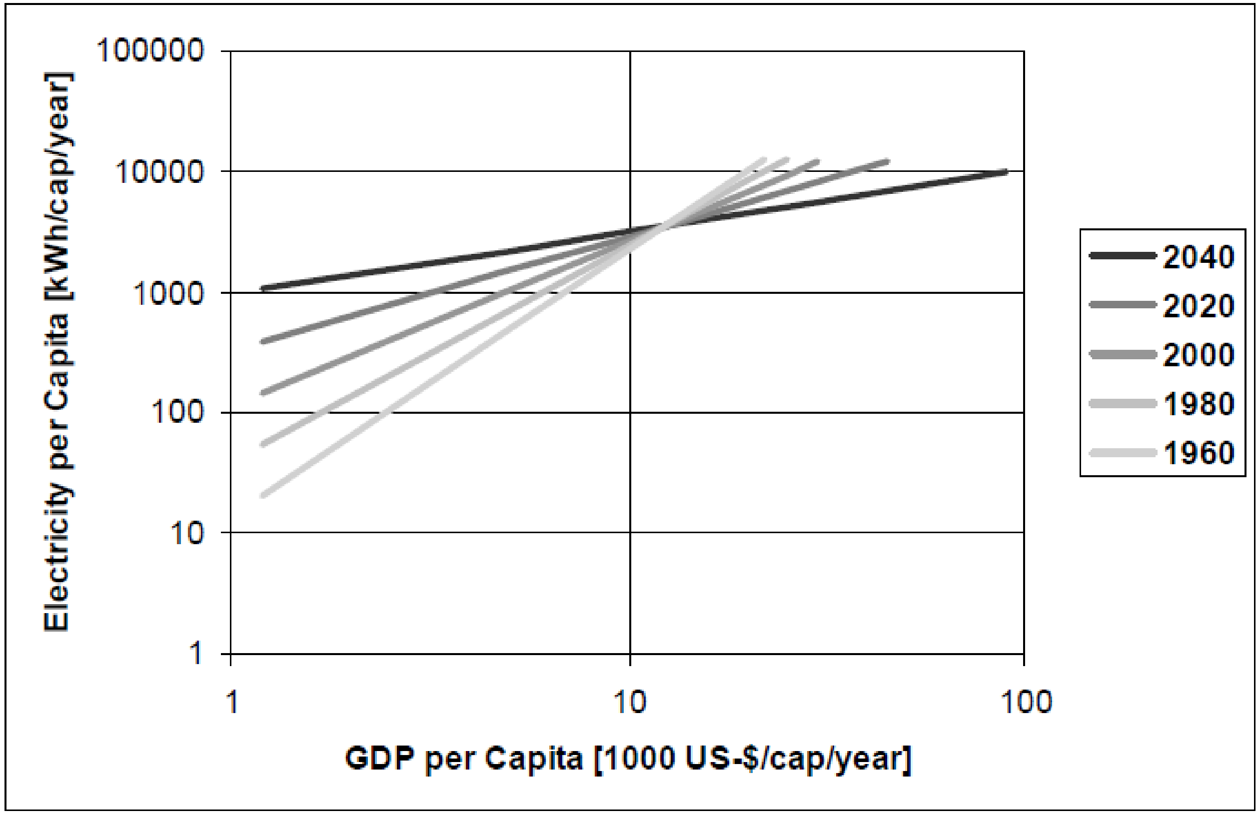
a) In the year 1960



b) In the year 2000

Figure 4: Examples for correlation between total final consumption per capita and GDP per capita. Data sources: (Heston et al. 2002), (IEA 2003-1,2), (Statistisches Bundesamt 2003)

3rd Driver for Power Demand: Efficiency Gains



empirical uncoupling of power demand and gross domestic product (GDP)

$$\hat{y}_{i,t} = a_t \cdot x_{i,t}^{\,b_t}$$

t = time variable
i = country
x = GDP per capita
y = electricity per capita

$$a(t) = 13.65 \cdot \exp(0{,}0531 \cdot (t - t_o))$$

$$b(t) = 2.2131 - 0.0212 \cdot (t - t_o)$$

Electricity Demand Scenario

$$\tilde{y}(t) = \hat{y}(t) \cdot (1 + \delta(t)) + \varphi(t)$$ correction function

$$\delta(t) = \delta(t_E) \cdot \varepsilon(t) + \delta(t_S) \cdot (1 - \varepsilon(t))$$ electricity distribution losses

$$\varphi(t) = \varphi(t_E) \cdot \varepsilon(t) + \varphi(t_S) \cdot (1 - \varepsilon(t))$$ change of demand pattern

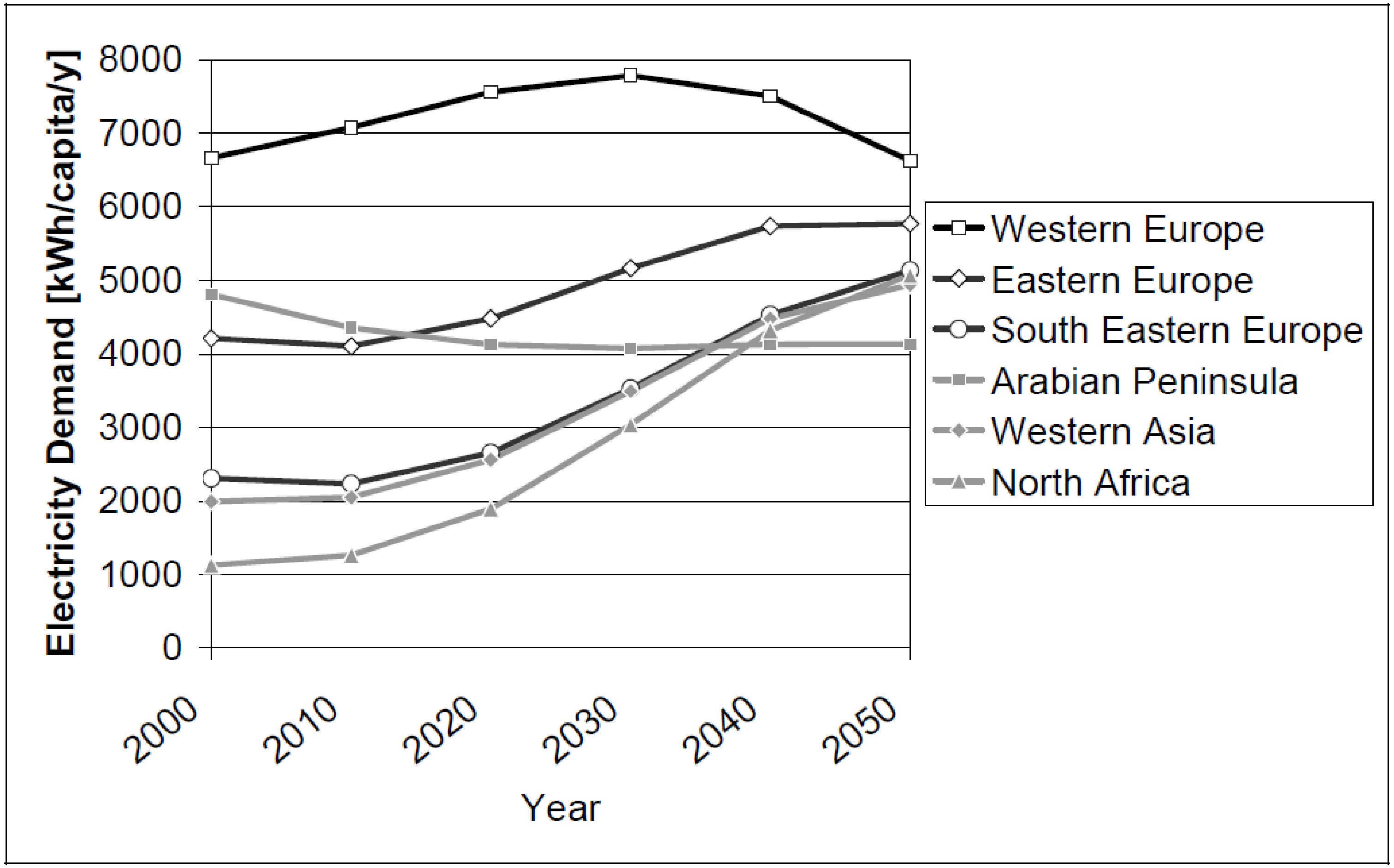
$$\varepsilon = \frac{t - t_S}{t_E - t_S} \qquad 2001 \leq t \leq 2050$$ weighting factor

$$y(t) = y(t_S) \cdot (1 - \varepsilon(t)) + \tilde{y}(t) \cdot \varepsilon(t)$$ demand function

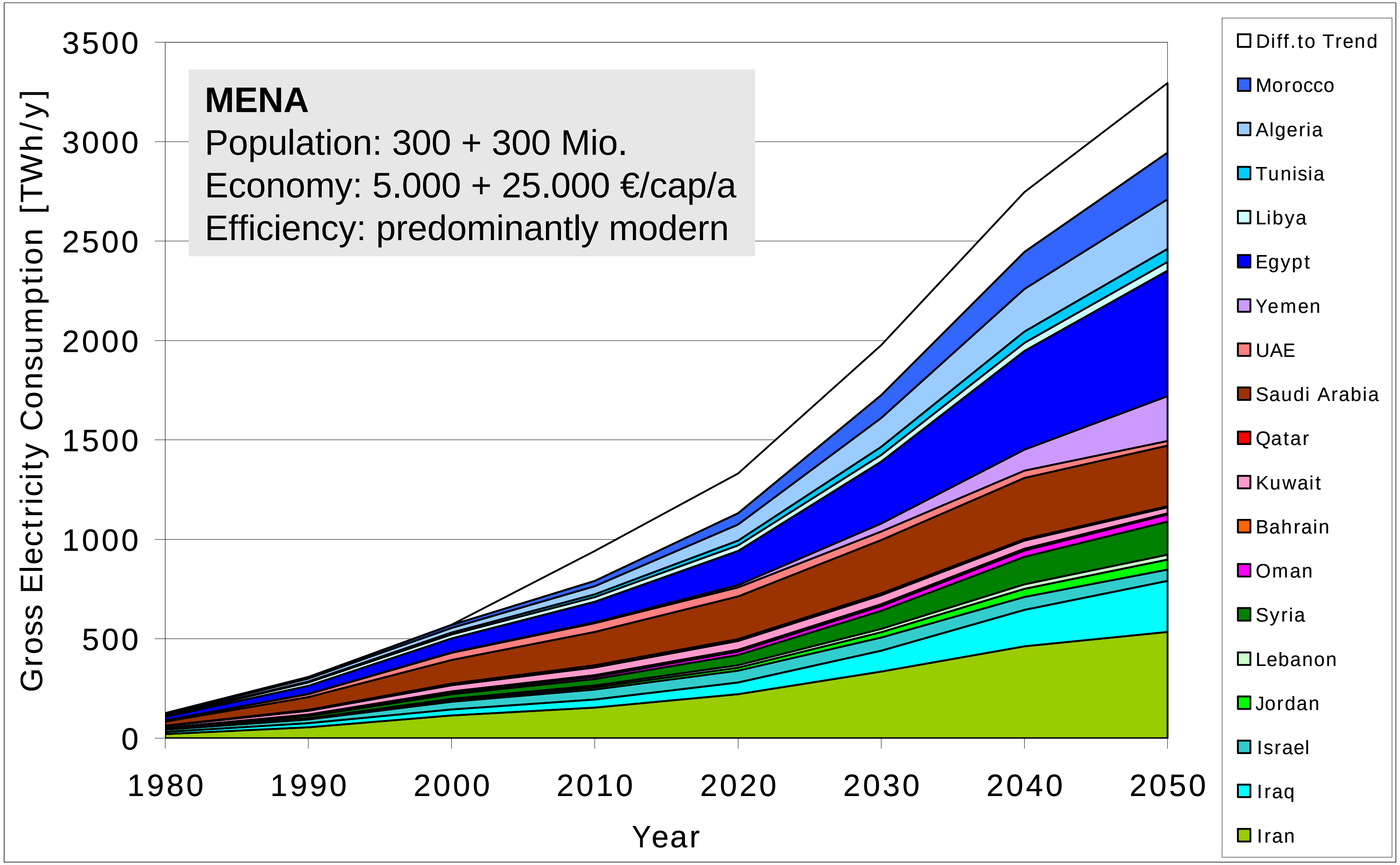
t_S = start time
t_E = end time

use for own estimates or use other outlook studies

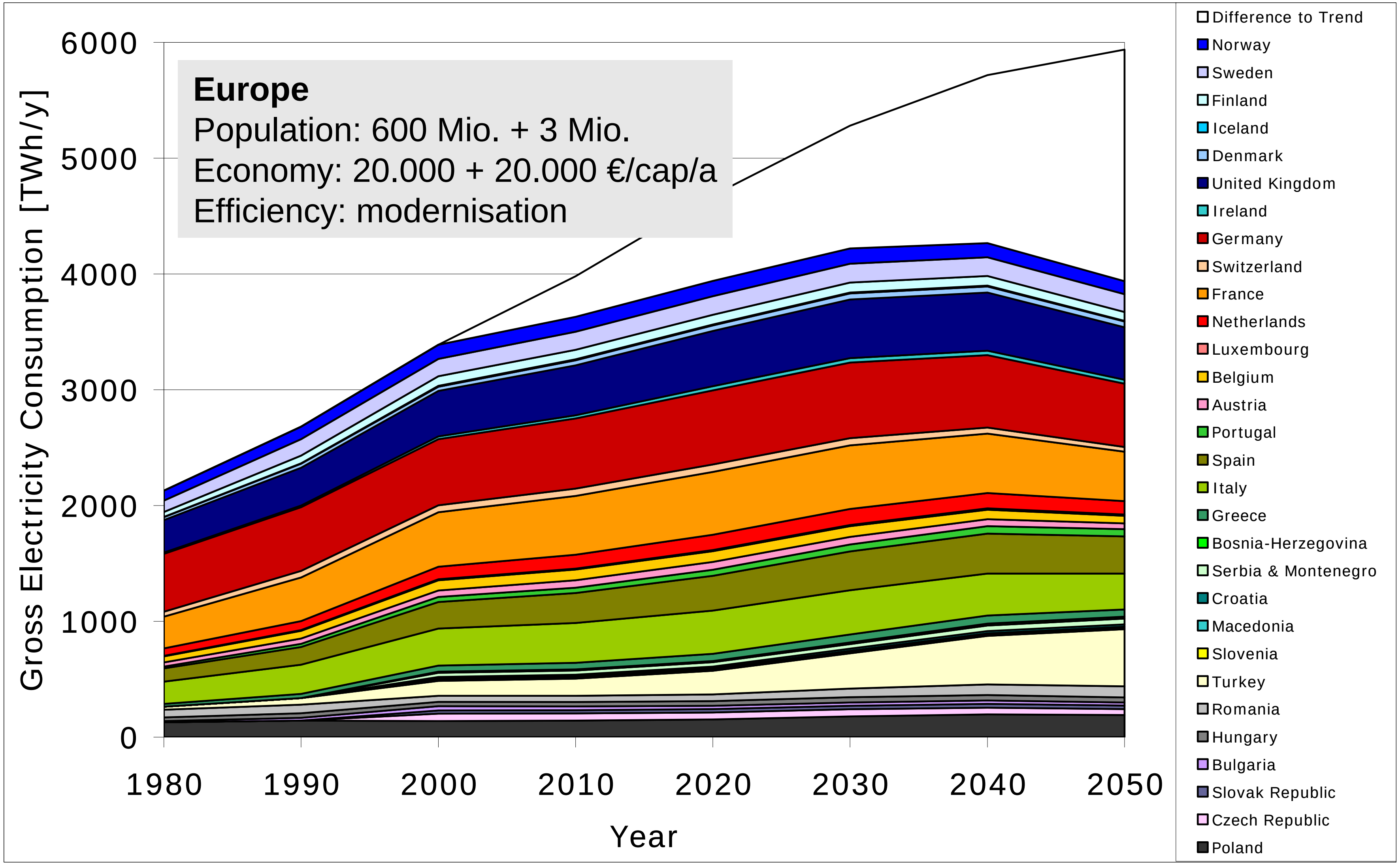
Per Capita Electricity Demand Scenario



Annual Electricity Demand Scenario MENA



Annual Electricity Demand Scenario Europe



Demand Scenario Assumptions

Peak load assumed to grow proportional to consumption.
Minimum firm capacity reserve kept constant 25% over peak load.
Time pattern of load assumed to stay constant.

	Peak Load [GW]	Electricity [TWh/y]	Full Load [h/y]
Spain	34,7	228,2	6576
Germany	83,4	571,5	6853
France	75,3	471,1	6256
Italy	52,4	319,6	6100
Greece	8,6	53,8	6253
Slovakia	4,0	28,1	7114
Poland	21,0	138,8	6611
Sweden	27,0	150,1	5559
Turkey	19,6	128,4	6551

Start values 2000

➔ minimum availability of power = 125% of peak load

Supply Side Modelling

Portfolio of Supply Options:

- ✓ Coal, Lignite
- ✓ Oil, Gas
- ✓ Nuclear Fission

ideally stored primary energy

- ✓ Concentrating Solar Power (CSP)
- ✓ Geothermal Power (Hot Dry Rock)
- ✓ Biomass
- ✓ Hydropower

storable primary energy

- ✓ Wind Power
- ✓ Photovoltaic
- ✓ Wave / Tidal

fluctuating primary energy

Portfolio of Supply Options

	Unit Capacity	Capacity Credit *	Capacity Factor **	Resource	Applications	Comment
Wind Power	1 kW – 5 MW	0 – 30 %	15 – 50 %	kinetic energy of the wind	electricity	fluctuating, supply defined by resource
Photovoltaic	1 W – 5 MW	0 %	5 – 25 %	direct and diffuse irradiance on a tilted surface	electricity	fluctuating, supply defined by resource
Biomass	1 kW – 25 MW	50 - 90 %	40 – 60 %	biogas from the decomposition of organic residues, solid residues and wood	electricity and heat	seasonal fluctuations but good storability, power on demand
Geothermal (Hot Dry Rock)	25 – 50 MW	90 %	40 – 90 %	heat of hot dry rocks in several 1000 meters depth	electricity and heat	no fluctuations, power on demand
Hydropower	1 kW – 1000 MW	50 - 90 %	10 – 90 %	kinetic energy and pressure of water streams	electricity	seasonal fluctuation, good storability in dams, used also as pump storage for other sources
Solar Updraft	100 – 200 MW	10 to 70 % depending on storage	20 to 70 %	direct and diffuse irradiance on a horizontal surface	electricity	seasonal fluctuations, good storability, base load power
Concentrating Solar Thermal Power	10 kW – 200 MW	0 to 90 % depending on storage and hybridisation	20 to 90 %	direct irradiance on a surface tracking the sun	electricity and heat	fluctuations are compensated by thermal storage and (bio)fuel, power on demand
Gas Turbine	0.5 – 100 MW	90 %	10 – 90 %	natural gas, fuel oil	electricity and heat	power on demand
Steam Cycle	5 – 500 MW	90 %	40 – 90 %	coal, lignite, fuel oil, natural gas	electricity and heat	power on demand
Nuclear	> 500 MW	90 %	90 %	uranium	electricity and heat	base load power

Table 2: Some characteristics of contemporary power technologies. * Contribution to firm power and reserve capacity. ** Average annual utilisation.

Mounting an Electricity Supply Scenario

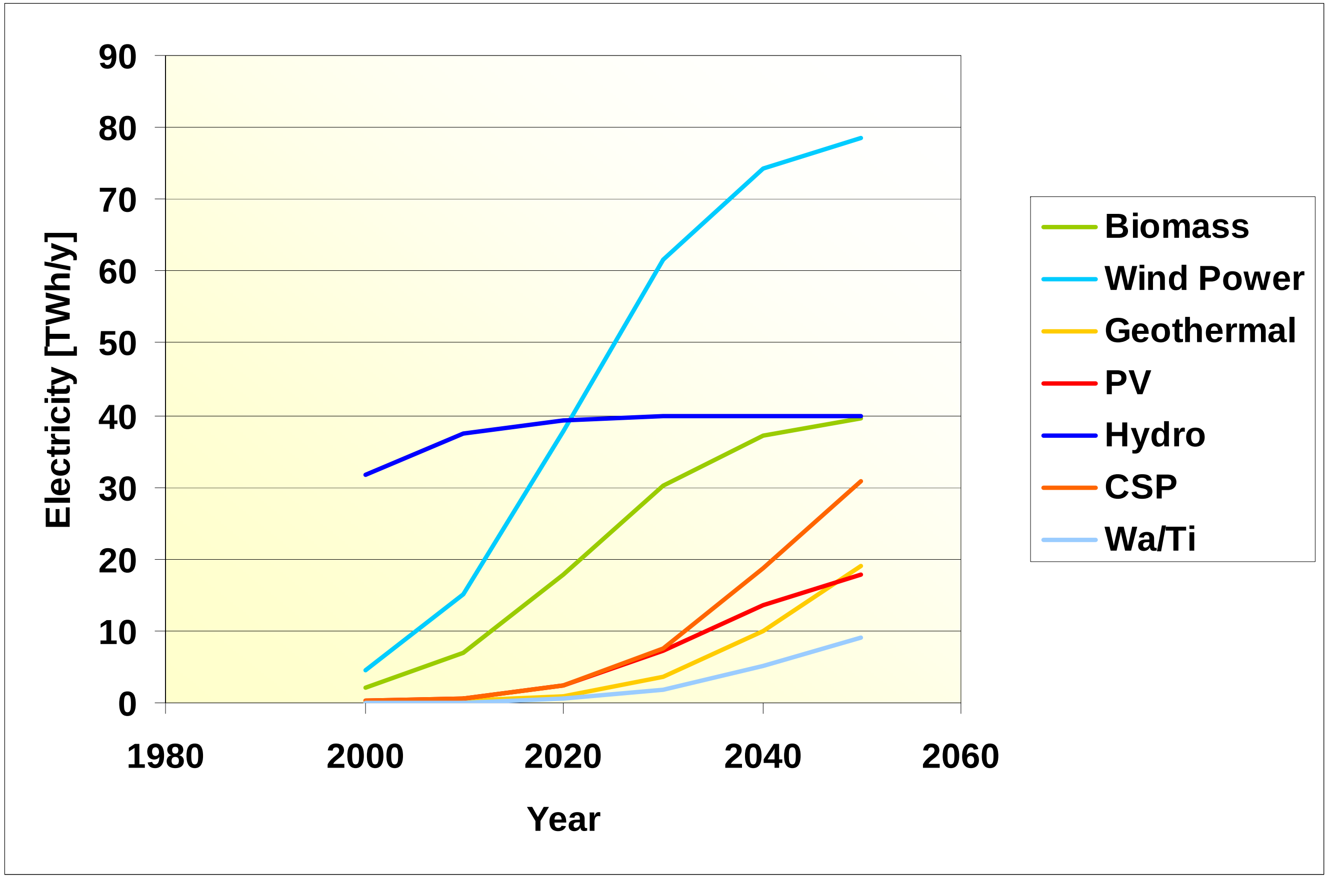
1. Integrated renewable shares cannot be larger than resource potentials
2. Technology growth rates must be achievable and sustainable
3. New capacity will equal demand minus existing capacity
4. Sustainability criteria must be satisfied
5. Annual electricity consumption must equal annual electricity generation
6. Firm capacity must equal 125% of peak load
7. Scenario results should match hourly power balance modeling

Growth Function:

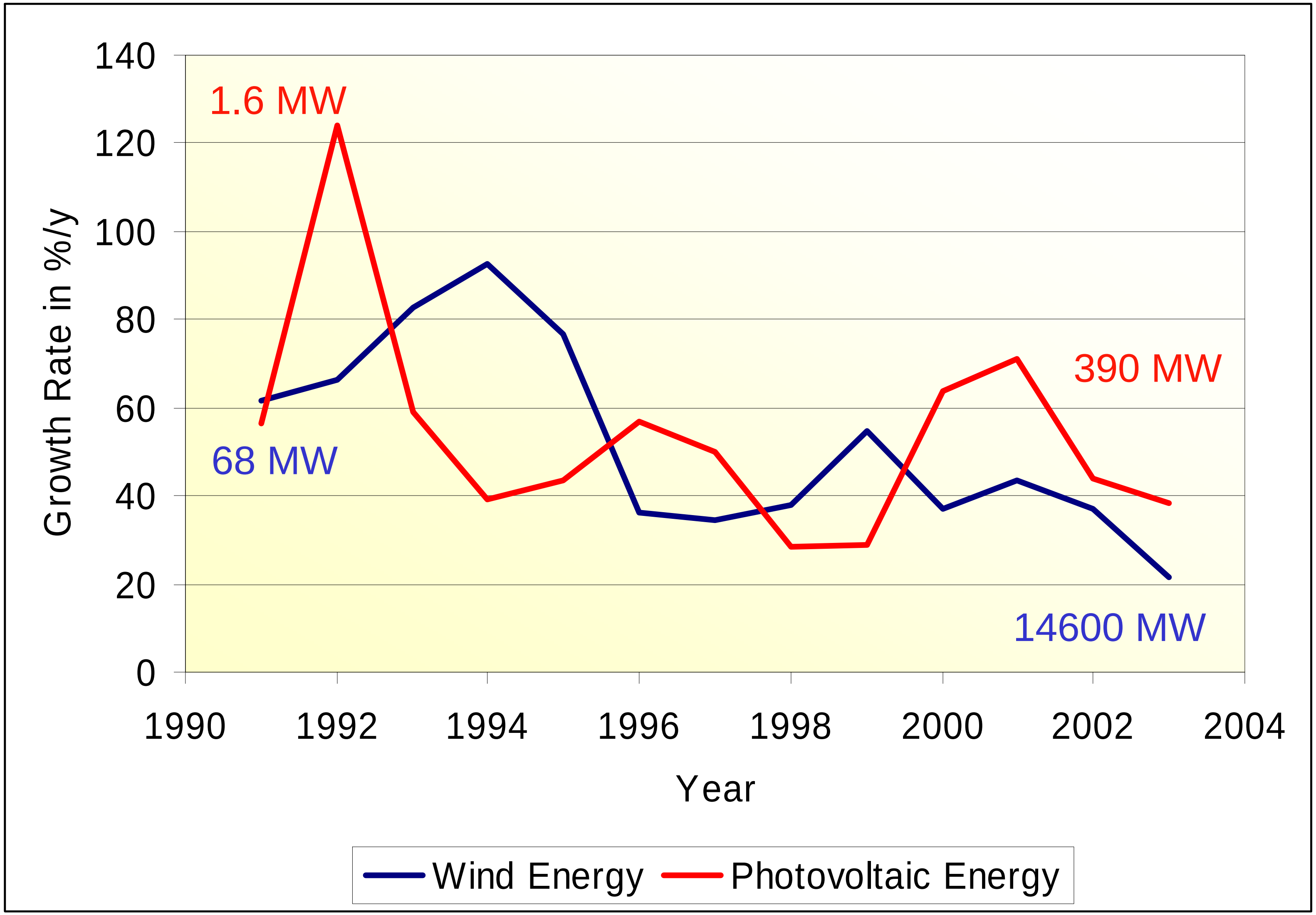
$$f(t) = \frac{G}{1 + e^{-k \cdot (t - t_0)} \cdot (\frac{G}{f(t_0)} - 1)}$$

G	potential
$f(t_0)$	start value
t	time
k	max. growth rate

potential G from resource mapping

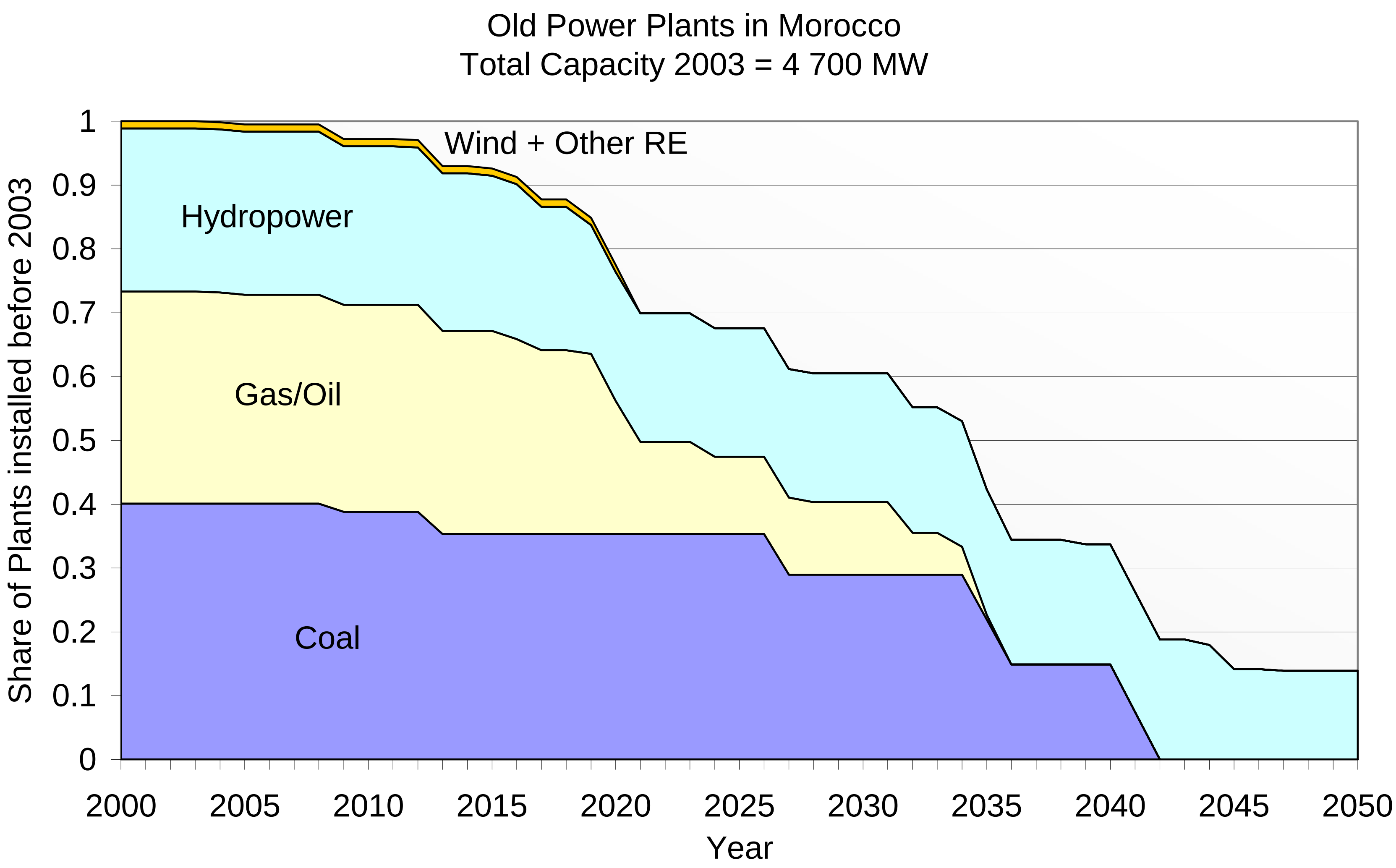


Growth Rates of PV and Wind Power in Germany



Source: Quaschning 2004

Life curve of power plants in Morocco installed before 2003



Criteria for Sustainable Electricity Supply Target:

✓ **Inexpensive**

low electricity cost
no long term subsidies

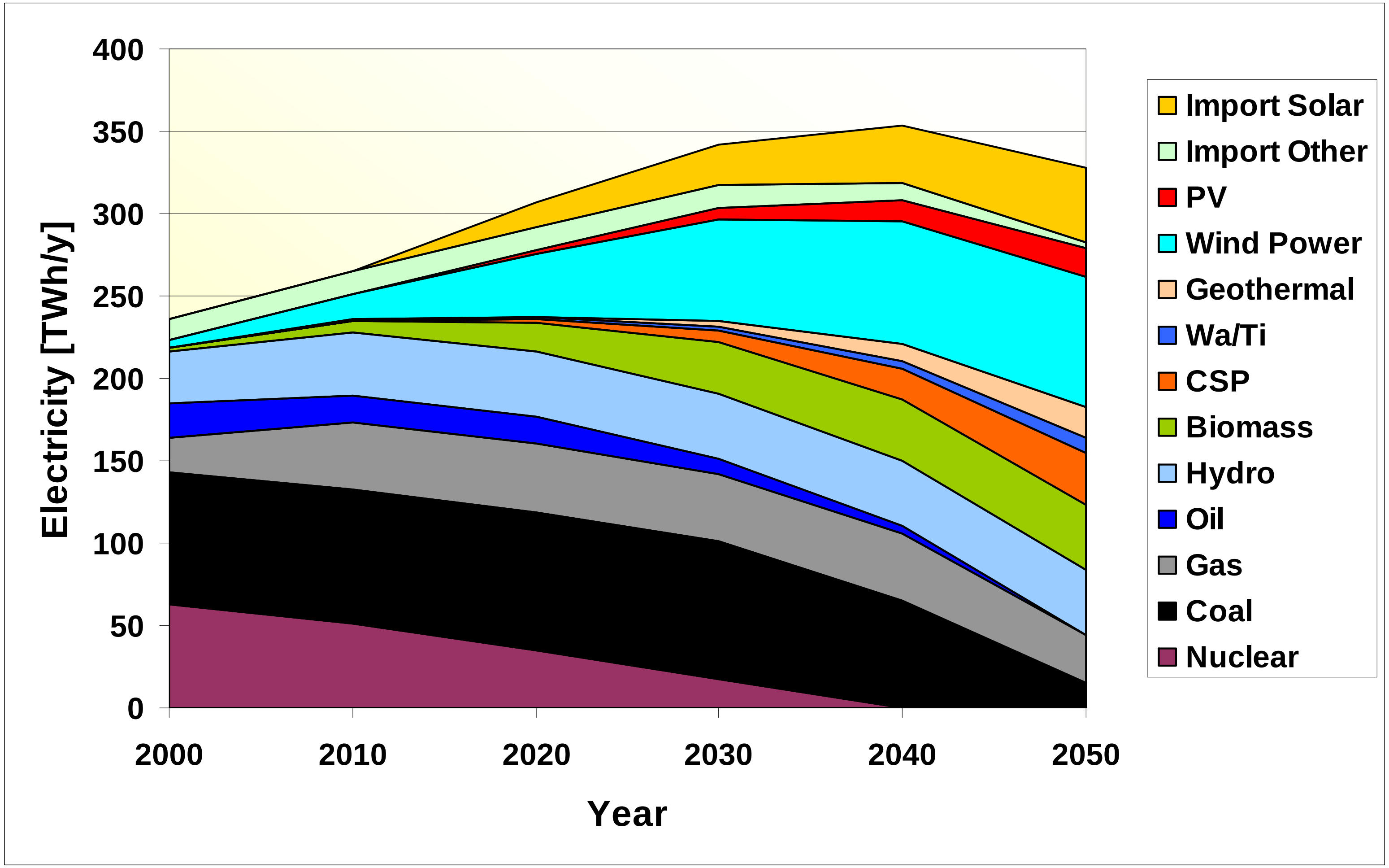
✓ **Secure**

diversified and redundant supply
power on demand
based on inexhaustible resources
available or at least visible technology
capacities expandable in time

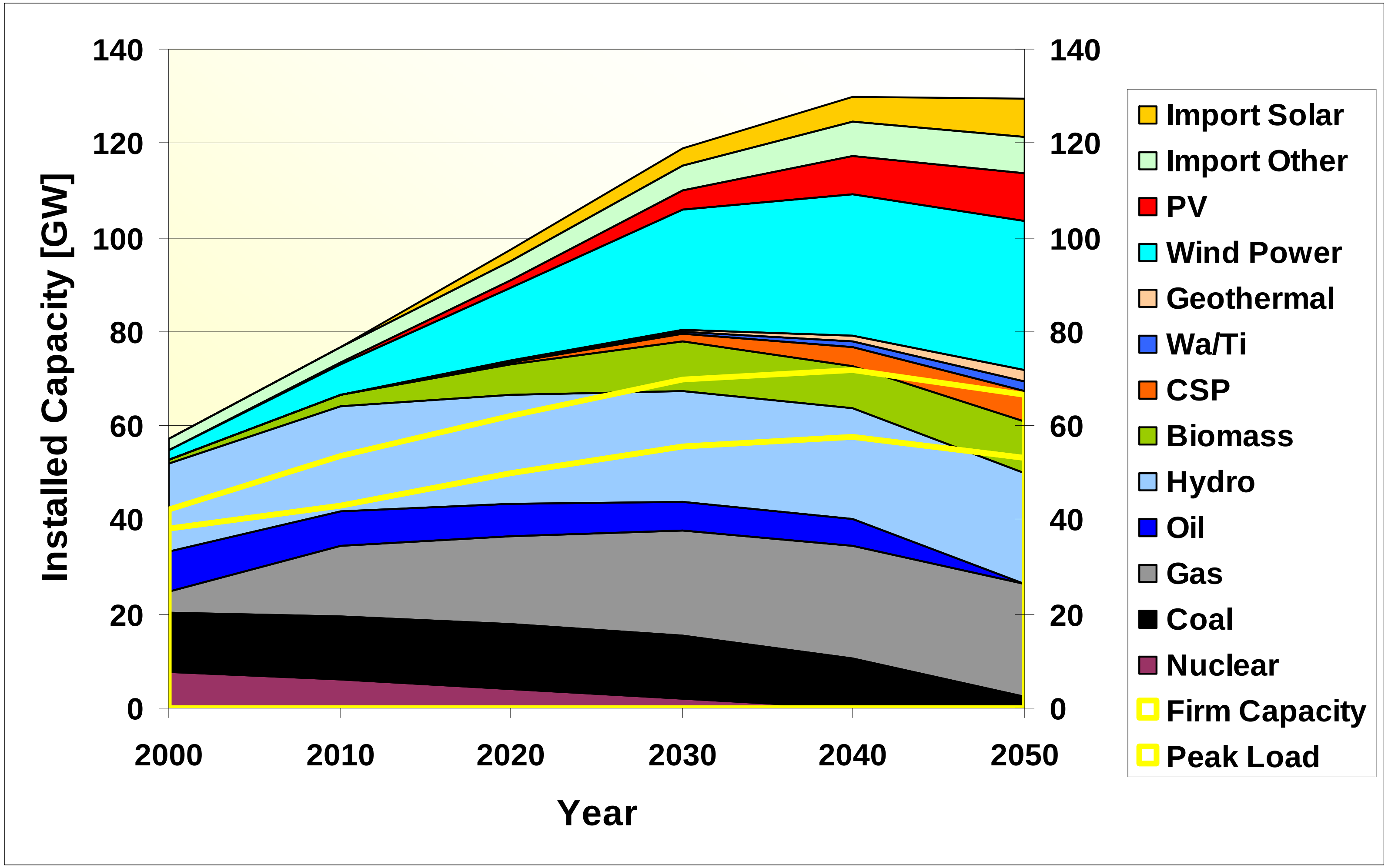
✓ **Compatible**

low pollution
climate protection
low risks for health and environment
fair access

Energy Balance: Supply = Demand



Power Balance: Firm Capacity = Peak Load x 125%



Electricity generation according to availability and needs

Electricity in TWh/a	2000	2010	2020	2030	2040	2050
Consumption	228,2	257,7	299,1	334,6	345,8	320,1
Wind	4,7	15,2	37,6	61,7	74,2	78,4
Photovoltaics	0,2	0,7	2,5	7,1	13,5	17,8
Geothermal	0,1	0,3	1,0	3,6	10,0	19,1
Biomass	2,1	7,0	17,8	30,3	37,1	39,5
CSP Plants	0,2	0,6	2,3	7,6	18,8	30,8
Wave / Tidal	0,0	0,1	0,5	1,9	5,0	9,2
Hydropower	31,8	37,5	39,3	39,8	40,0	40,0
Oil / Gas	41,6	57,4	57,7	50,6	44,9	29,2
Oil	20,6	16,5	16,5	9,4	3,8	0,0
Gas	**21,0**	40,9	41,2	41,2	41,2	29,2
Coal	**80,0**	**82,0**	**84,0**	**84,0**	**65,0**	**15,0**
Nuclear	**63,0**	**50,7**	**35,0**	**16,9**	**0,0**	**0,0**
Import Other	**12,3**	**14,0**	**14,0**	**14,0**	**10,0**	**4,0**
Import Solar	**0**	**0**	**15**	**25**	**35**	**45**

Capacity x Full Load Hours = Electricity Supply

Full load hours according to availability and needs

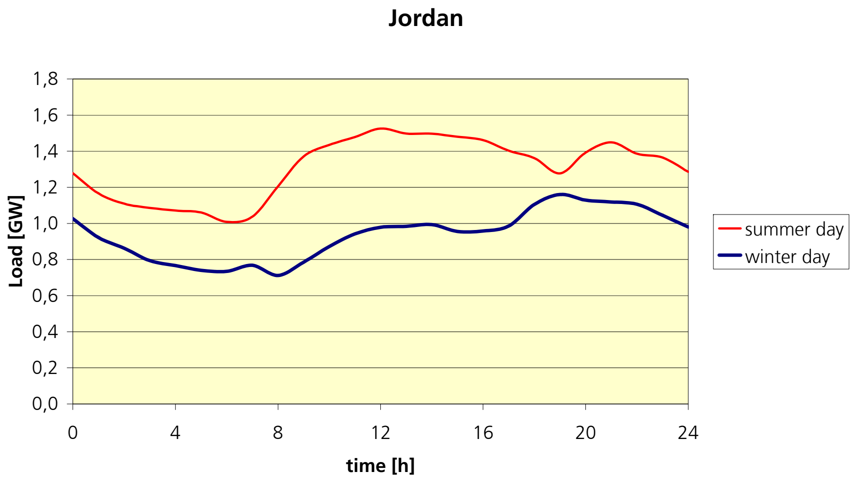
Full Load Hours h/a	2000	2010	2020	2030	2040	2050
Load	6005	6005	6005	6005	6005	6005
Wind	2325	2359	2393	2427	2460	2494
Photovoltaics	1353	1515	1677	1697	1707	1717
Geothermal	7500	7500	7500	7500	7500	7500
Biomass	2800	2800	2800	2800	4000	3500
CSP Plants	1900	3500	4500	5000	5000	5000
Wave / Tidal	4000	4000	4000	4000	4000	4000
Hydropower	1705	1705	1705	1705	1705	1705
Oil / Gas	3261	2533	2240	1787	1517	1225
Oil	2458	2185	2427	1537	686	686
Gas	4805	2707	2173	1856	1707	1225
Coal	6202	6202	6202	6202	6202	6202
Nuclear	8367	8367	8367	8367	8367	8367
Import Other (incl. Sol	4920	4667	3500	2800	1333	533
Import Solar HVDC)	0	0	6000	6250	7000	5625

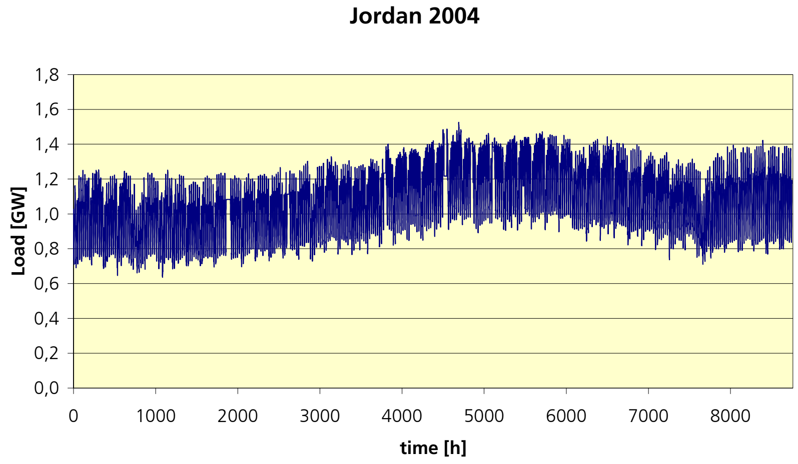
Installed capacity according to availability and needs

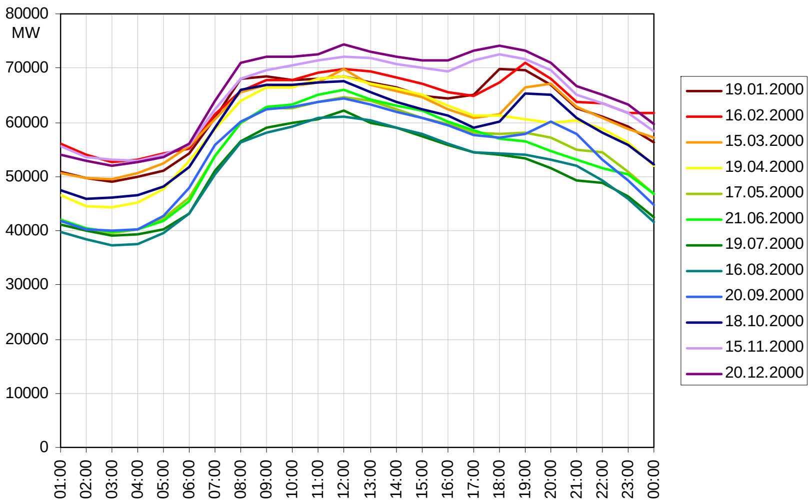
Capacity in GW	2000	2010	2020	2030	2040	2050
Peak Load	38,0	42,91	49,80	55,72	57,58	53,31
Wind	2,00	6,43	15,73	25,42	30,16	31,43
Photovoltaics	0,15	0,49	1,51	4,19	7,93	10,34
Geothermal	0,01	0,04	0,14	0,48	1,33	2,54
Biomass	0,75	2,48	6,36	10,82	9,28	11,28
CSP Plants	0,09	0,18	0,52	1,51	3,76	6,17
Wave / Tidal	0,01	0,04	0,14	0,46	1,26	2,29
Hydropower	18,65	21,97	23,05	23,35	23,43	23,45
Oil / Gas	12,77	22,67	25,75	28,30	29,63	23,87
Oil	8,4	7,56	6,80	6,12	5,51	0,00
Gas	4,4	15,11	18,94	22,18	24,11	23,87
Coal	12,9	13,22	13,55	13,55	10,48	2,42
Nuclear	7,5	6,06	4,18	2,02	0,00	0,00
Import Other	2,5	3,0	4,0	5,0	7,5	7,5
Import Solar	0,0	0,0	2,5	4,0	5,0	8,0

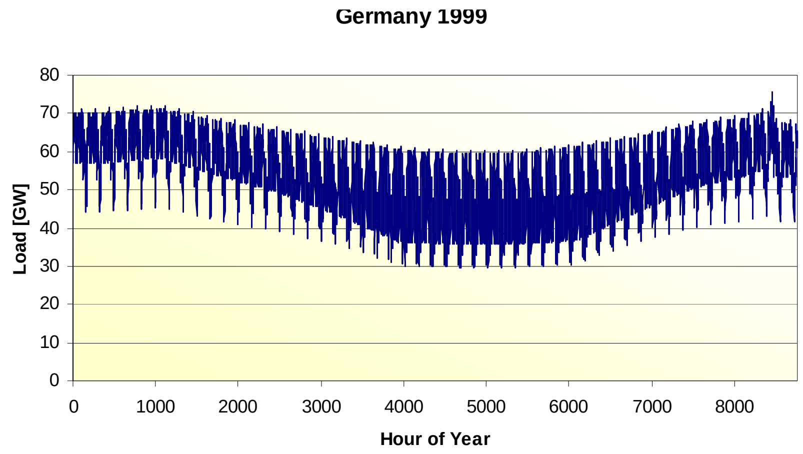
Hourly Time Series Modelling

National Daily and Annual Time Series of Demand

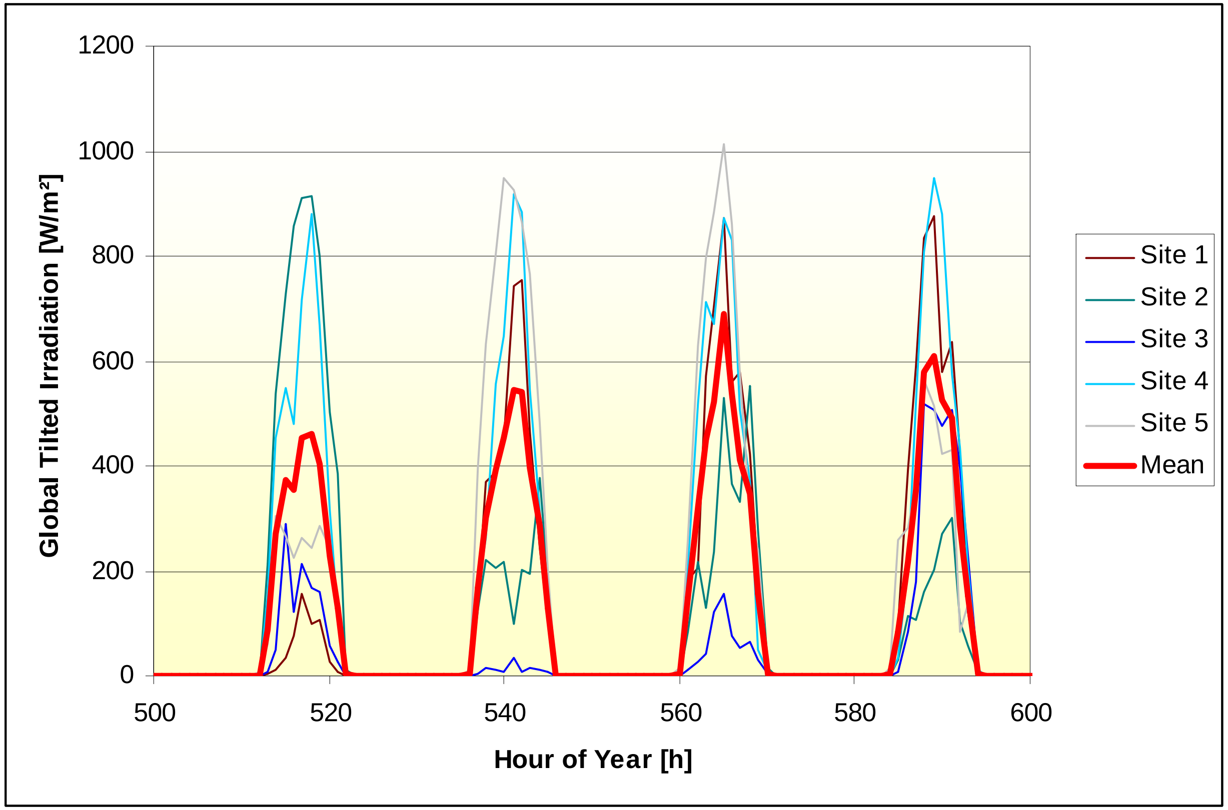






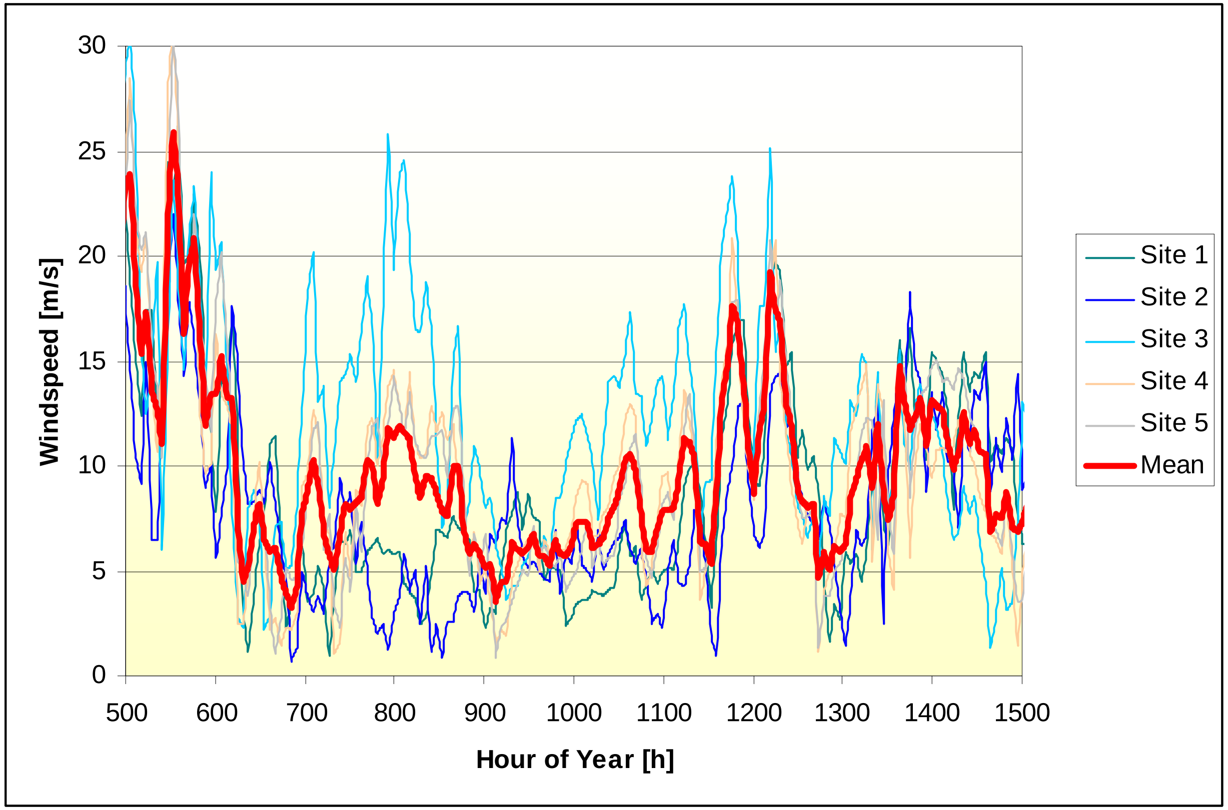


Photovoltaic Energy Resources



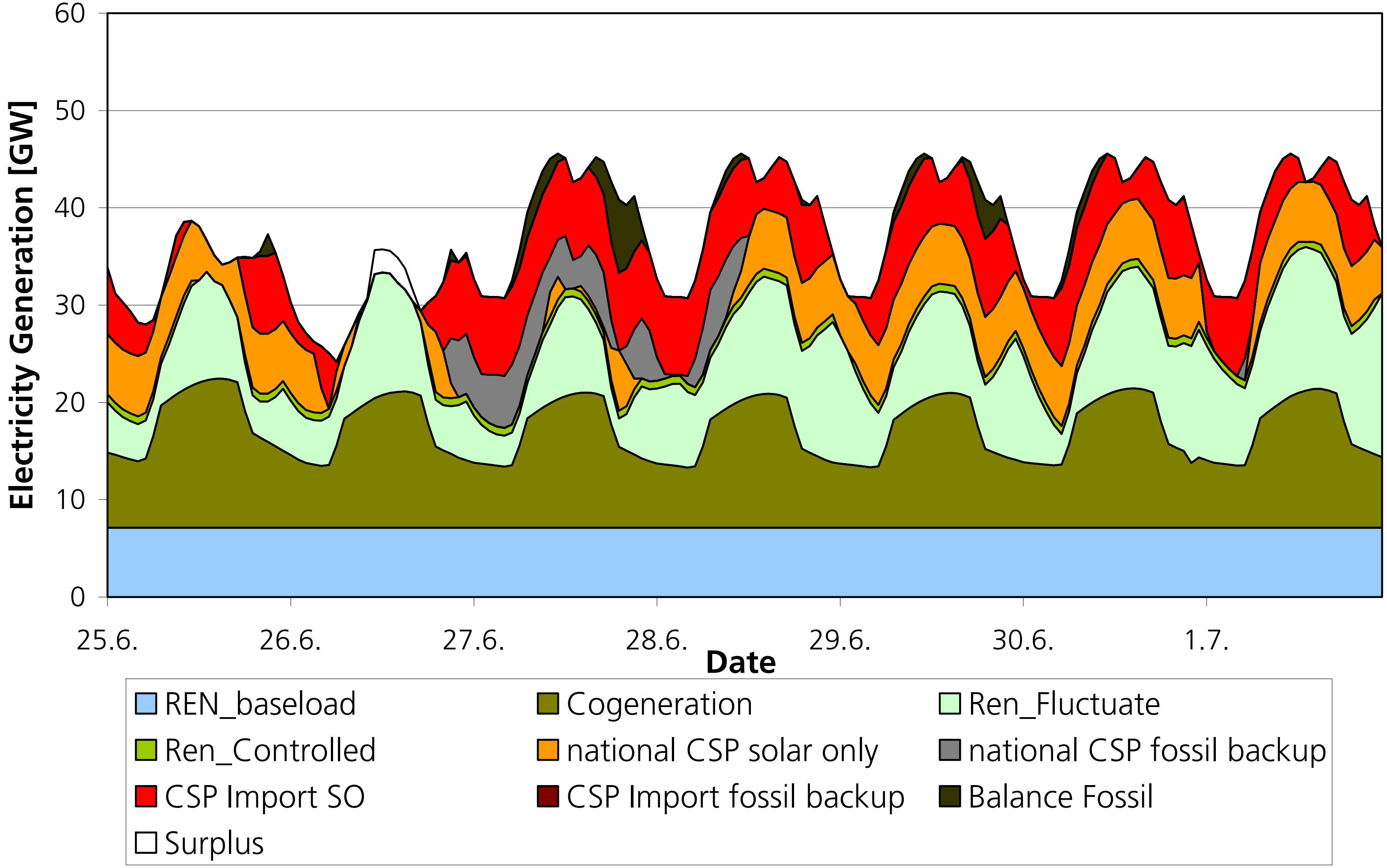
Example: GTI at 5 sites and mean value

Wind Energy Resources

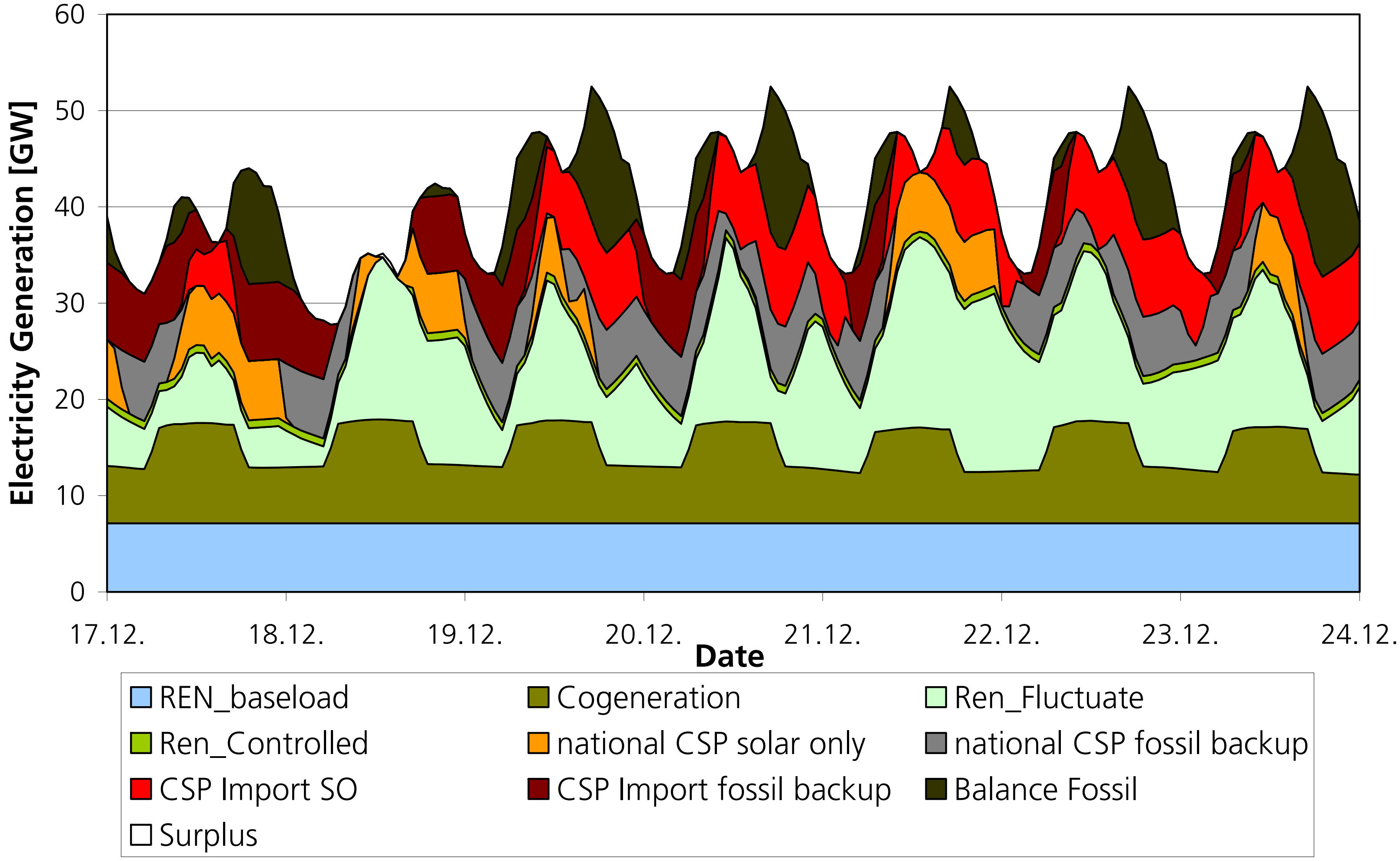


Example: Wind speed at 80 m for 5 sites and mean value

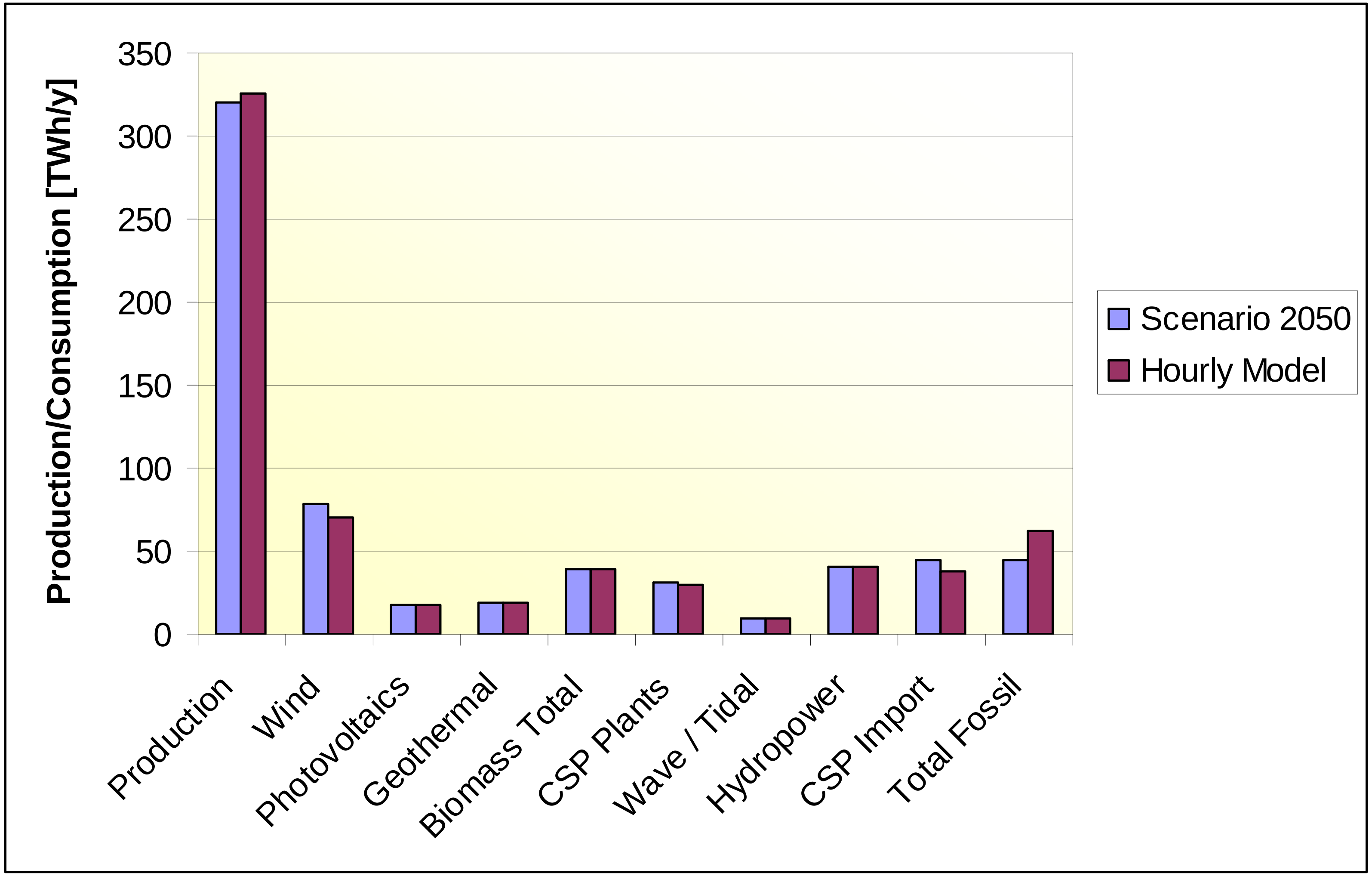
Hourly Model: Summer Week 2050



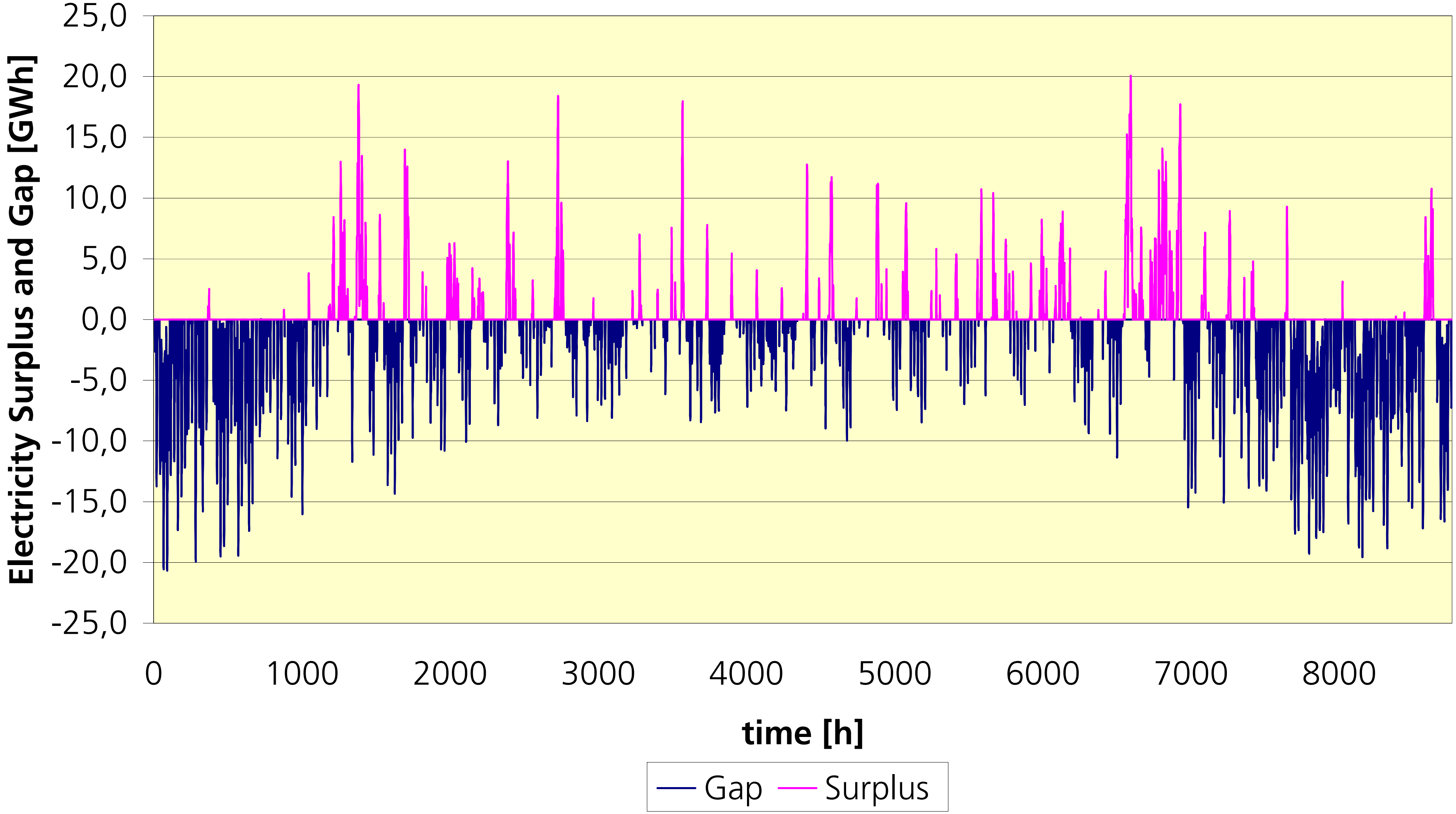
Hourly Model: Winter Week 2050



Scenario versus Hourly Model: Spain 2050



Surplus and Gap: Spain 2050



Conclusions

The Old Paradigm

Renewable sources of electricity are widely dispersed, fluctuating and unpredictable. Therefore, they will never be able to cover base load.

What has been overlooked

1. **Electric load is the statistic addition of widely dispersed, fluctuating and unpredictable consumers.**

2. **„Base load plants“ can only operate at constant power. There is no use in itself for plants restricted to that operation mode.**

The New Paradigm

A well balanced mix of renewable and conventional sources of electricity can cover base load, medium load and peak load demand.

Conventional base load plants will disappear while conventional peaking and balancing power plants will remain.