Integration of High Penetration of Solar and Wind Power in Power Systems: Experiences and Challenges
Lecture 6-7 + Tutorial 3

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Set-up of Lectures L6-L7 + T3

Lecture L6: Power system general balancing challenges at high share of variable renewable power production.

Lecture L7: Swedish/Nordic balancing challenges

Tutorial T3: Power System expansion planning, impact from assumptions

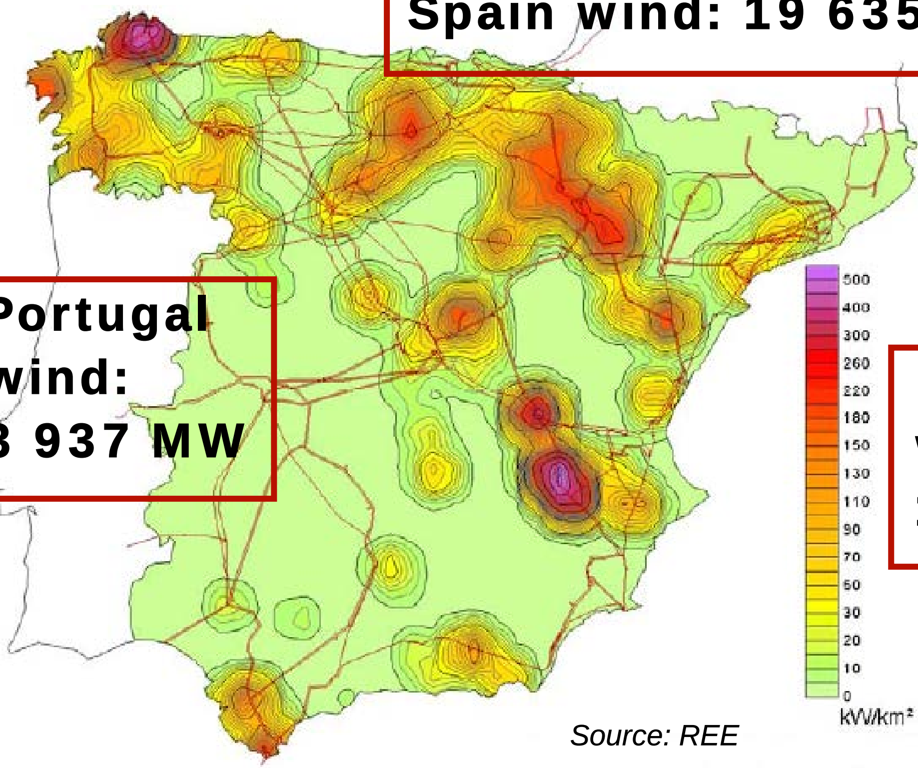
Aim of a power system

1. The consumers should get the required power (e.g. a 60 W bulb), when the push the on-button. This should work no matter there is an outage in a plant, wind is changing etc. = keep a **balance between total production and total consumption**.
2. The consumers must have a **realistic voltage**, e.g. around 230 V, in the outlet.
3. Point 1-2 should be obtained at a **realistic reliability.** This is **never** 100,000... percent,
4. Point 1-3 should be obtained in an **economic and sustainable** way.

Wind power and transmission capacity

Spain wind: 19 635 MW

Portugal wind: 3 937 MW



Source: REE

Irland wind: 1539 MW

	wind energy 2010
Sp	16 %
Po	17 %
Ir	13 %

	wind max share
Sp	54 %
Po	81 %
Ir	52 %

Portugal –Spain: 1200 MW
Spain – France: 1200 MW
Spain – Marocco: 650 MW

- Irland - Scottland: 450 MW
- Planned: +850 MW

Sweden 2014: 11,5 TWh (of 151) ➔ 8 %

Aim of a power grid

1. Use distant resources to balance a local load= keep a **balance between production and local consumption**.
2. The consumers must have a **realistic voltage**, e.g. around 230 V, in the outlet.
3. Use distant resources when there is a outage in local resource, i.e. keep a **realistic reliability.**
4. Point 1-3 should be obtained in an **economic and sustainable** way.

Questions for amounts of grids

Is it **economical** to have more grids for

1. more efficient balancing? Germany: **local batteries or Swedish hydro to balance their wind and solar ?**
2. a higher reliability? **More grids to use neighbours cheaper plants in high peak or keep own peak units? Can you rely on a neighbour?**
3. reduction in spillage? **More grids to use wind, hydro or solar ”surplus”?**

Renewable energy systems

- Energy is ”produced” where the resource is
- The energy has to be transported to consumption center
- The energy inflow varies, which requires storage and/or flexible system solutions

- This is valid for hydro power, **wind power**, solar power

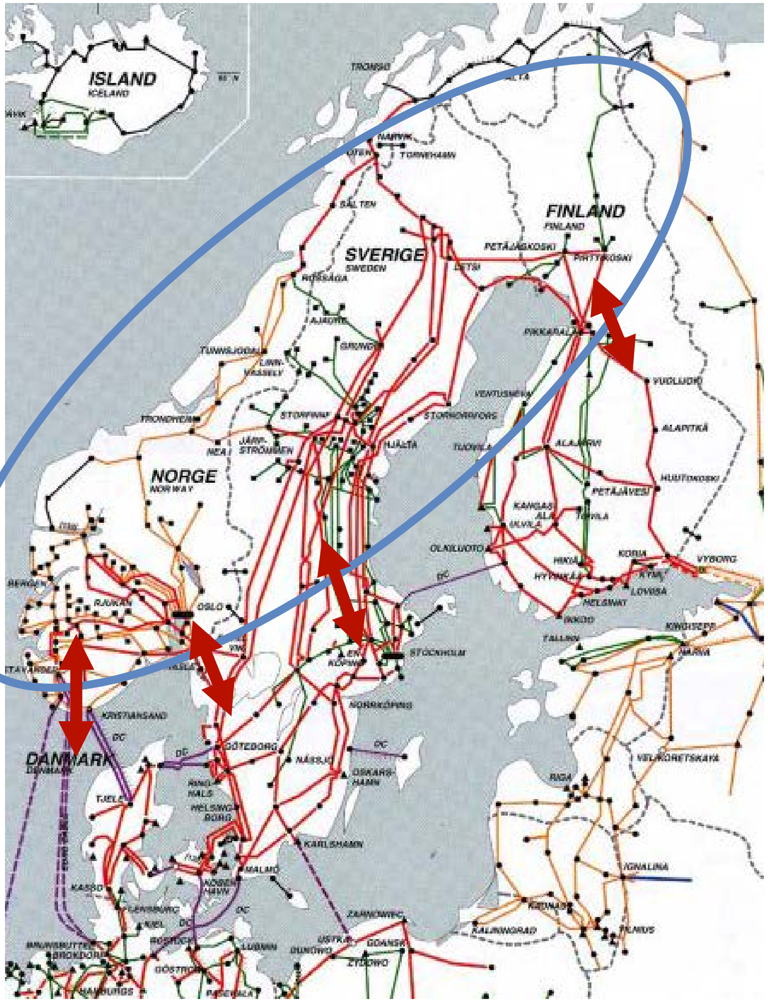
Example

Nordic hydro power (inflow) can vary 86 TWh between different years (Δ2001 to 1996)

Transport from NV to SE + continent

Energy balancing with thermal power in i Dk+F+Ge+Pl+NL+Ee

➔ **Sweden and our neighbors have had a need for cooperation since decades**



Three challenges in a power system with large amounts of solar and wind power

C1: Keep the **continuous balance**

C2: Handle situatiuations with **small** amounts of variable production.

C3: Handle situatiuations with **large** amounts of variable production.

Three challenges at large amount of variable renewables (solar/wind)

C1: Handling of the continuous balance.

- There must be a ramping capacity which is high enough
- Forecasts are uncertain so there must be enough online units to follow the net-load
- Larger interconnected areas reduces the overall variation, but requires enough grids.

Three challenges at large amount of variable renewables (solar/wind)

C2: Low wind and solar power production and high power consumption. This issue is called ”capacity adequacy issue”.

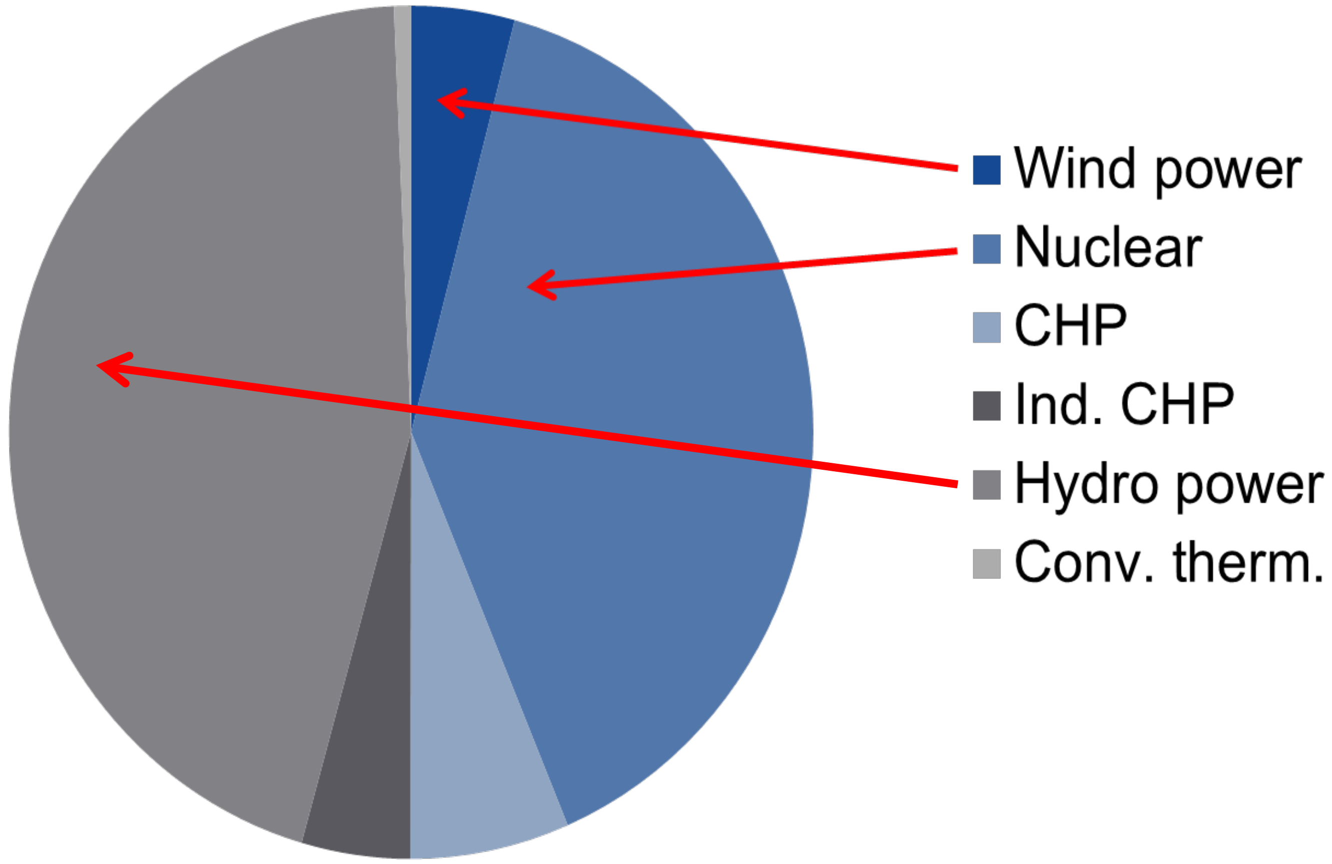
- There must be enough capacity (production, flexible demand and/or import) during these situations
- This may happen very rarely which is a challenge for the economy of these resources.
- More transmission reduces the need.

Three challenges at large amount of variable renewables (solar/wind)

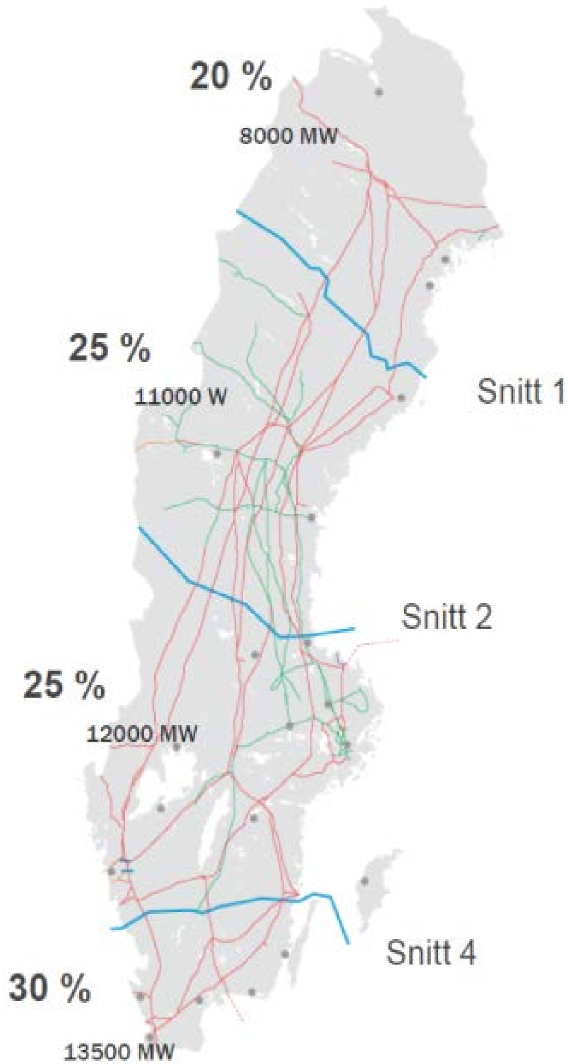
C3: High wind and solar power production + HVDC infeed and low power consumption.

- There must be enough inertia in the system in order to keep the frequency
- ”100 %” wind and solar **instant power supply**, means really high challenges concerning keeping voltage and frequency!
- There must be enough primary and secondary reserves in these situations.

Swedish power production year 201



Identified wind power projects in Sweden:



Identified wind power projects:

- **45000 MW (≈ 100 TWh/year)**

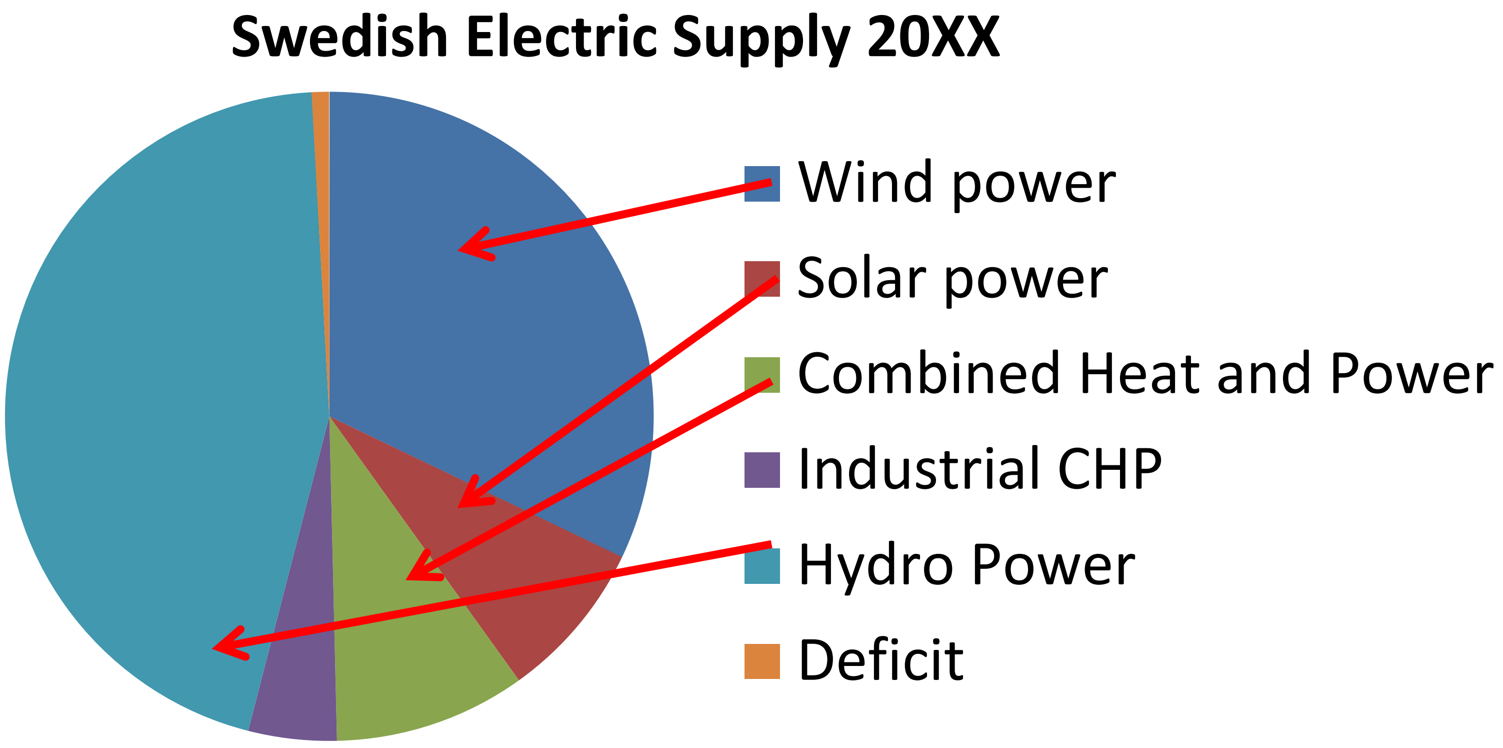
  today cons. ≈ 140 TWh/year :

Today capacities:

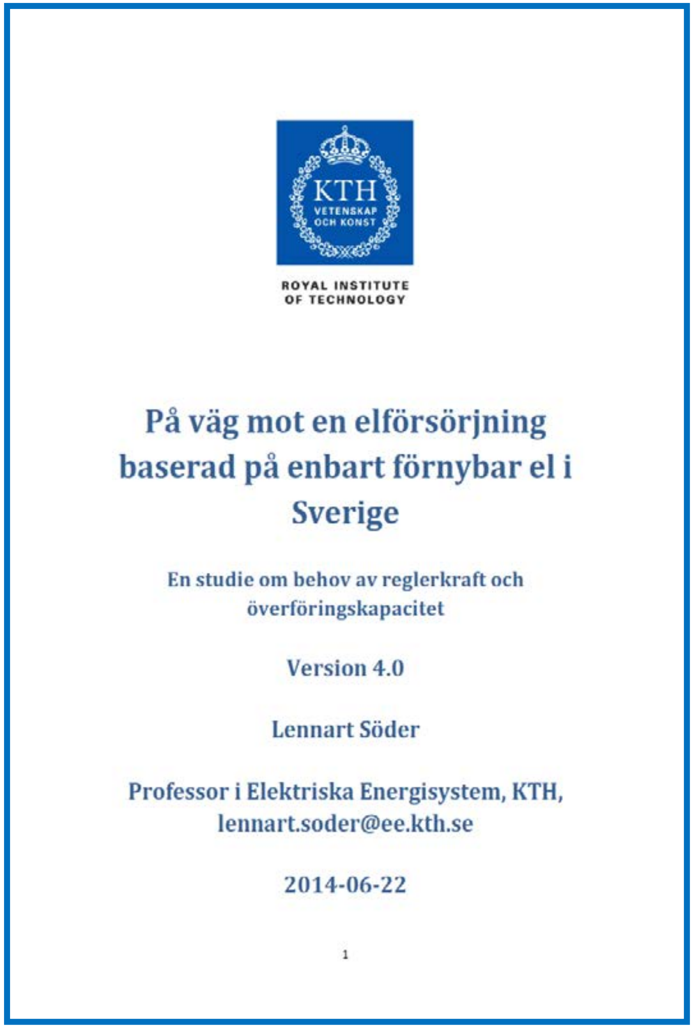
- **Hydro Power: 16000 MW (≈ 65 TWh)**
- **Nuclear power: 9000 MW (≈ 65 TWh)**
- **➔ total of 25000 MW**

Swedish Power production: Total 145,6 TWh

(same as 2011)



Report: Published 22 juni 2014


ROYAL INSTITUTE OF TECHNOLOGY

På väg mot en elförsörjning baserad på enbart förnybar el i Sverige

En studie om behov av reglerkraft och överföringskapacitet

Version 4.0

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2014-06-22

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Studies:

- Balancing from hour to hour in **”isolated” Sweden**!
- High wind+solar / low consumption
- Low wind+solar / high consumption
- Transmission constraints
- Can be downloaded from KTH:s home page
- **EXCEL-file for calculations**

http://kth.diva-portal.org/smash/record.jsf?searchId=1&pid=diva2:727697

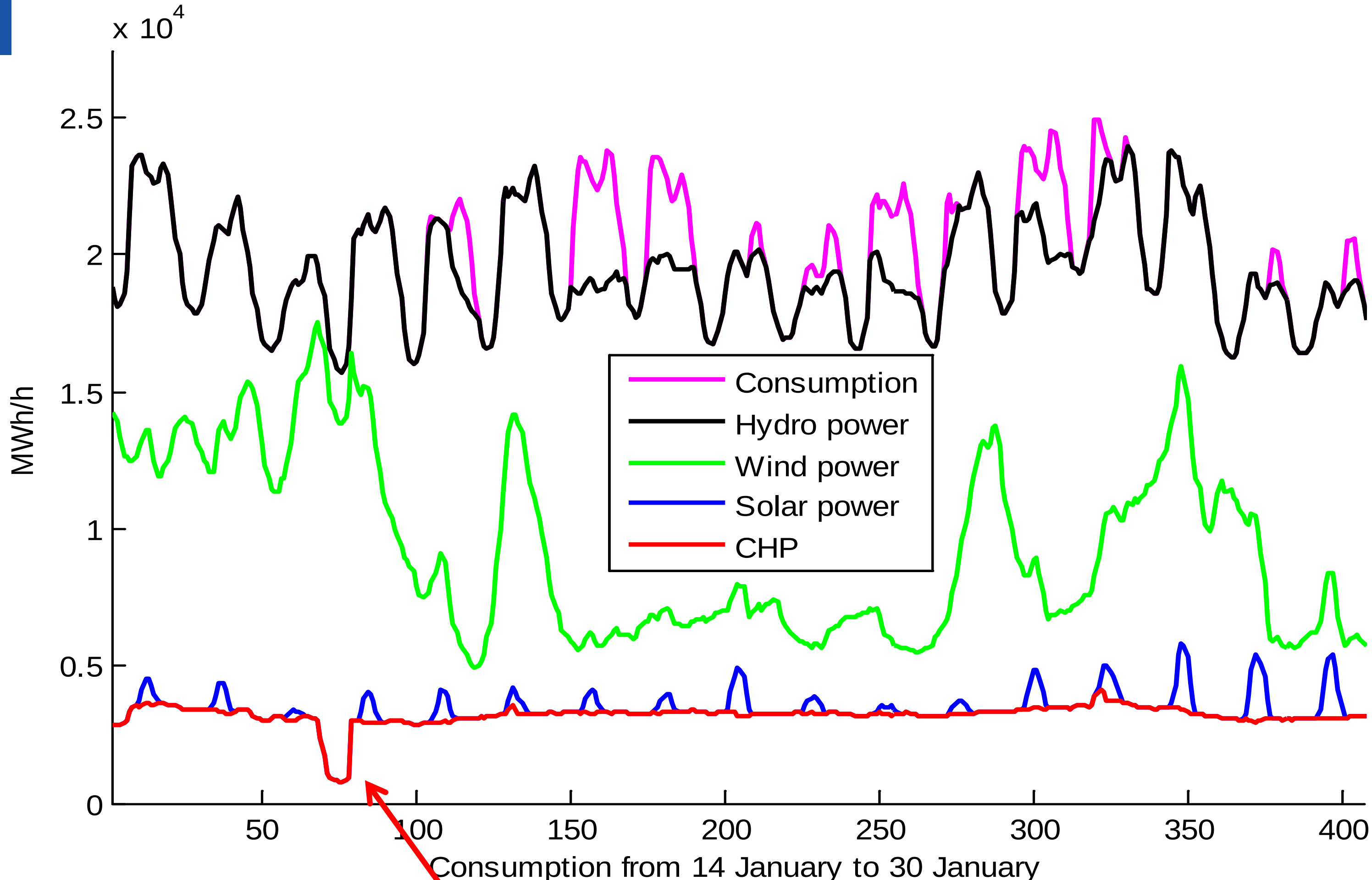
Current (2011) Swedish Power System

Source	TWh - 2011	Energy % - 2011	MW-capacity - 2011
Hydro	66,0	44,9	16197
Nuclear	58,0	39,5	9363
Wind	6,1	4,2	2899
Solar	0	0	0
CHP-Ind	6,4	4,4	1240
CHP-distr.	9,4	6,4	3551
Condens	1,01	0,7	3197
Total	**146,9**	**100**	**36447**

Studied Swedish Power System

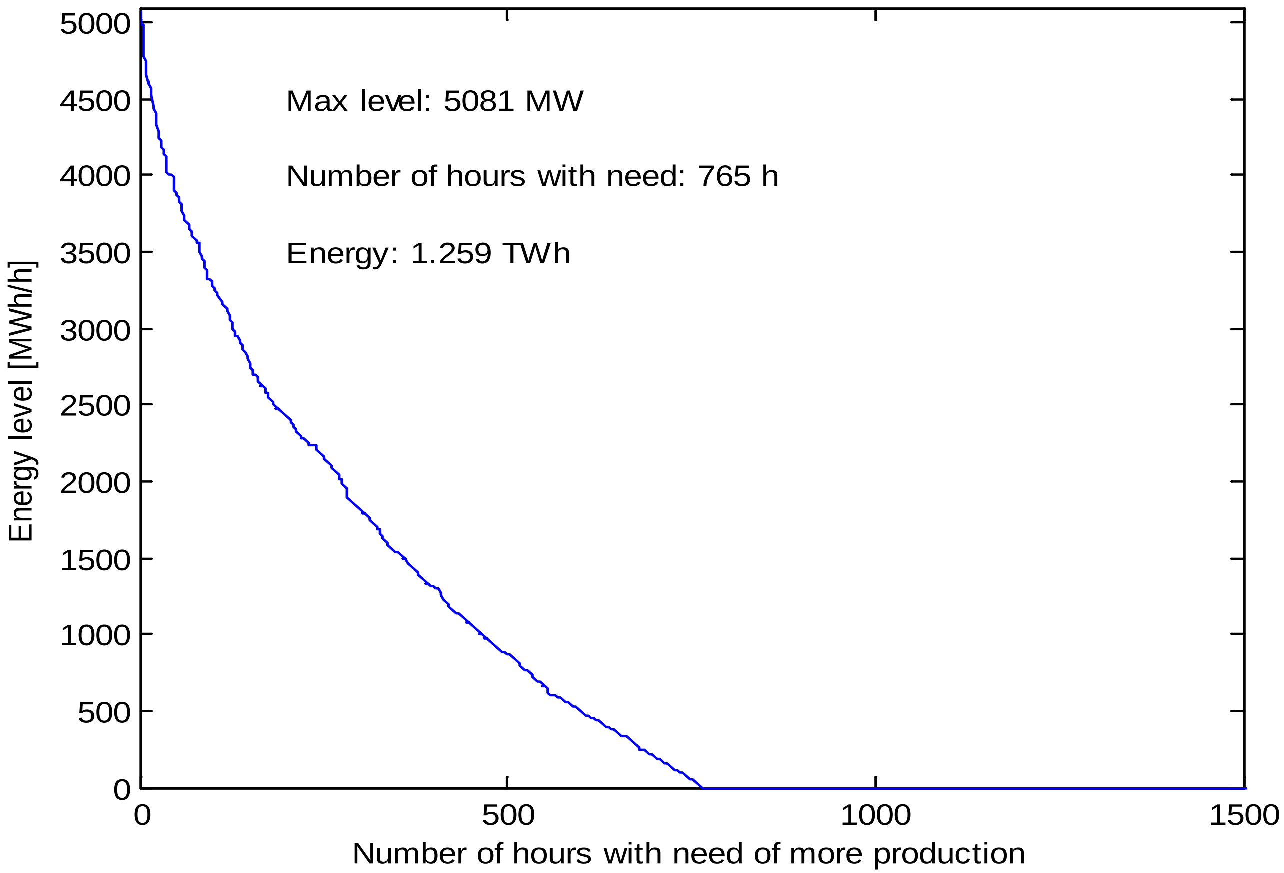
Source	TWh	Energy %	MW-max
Hydro	64,9	44,5	12951
Nuclear	0	0	0
Wind	46,7	32,1	15633
Solar	12,6	8,6	9849
CHP-Ind	6,4	4,4	1240
CHP-distr.	13,9	9,5	4126
Other	1,3	0,9	5081
Total	**139,9**	**100**	**48180**

Deficit situation



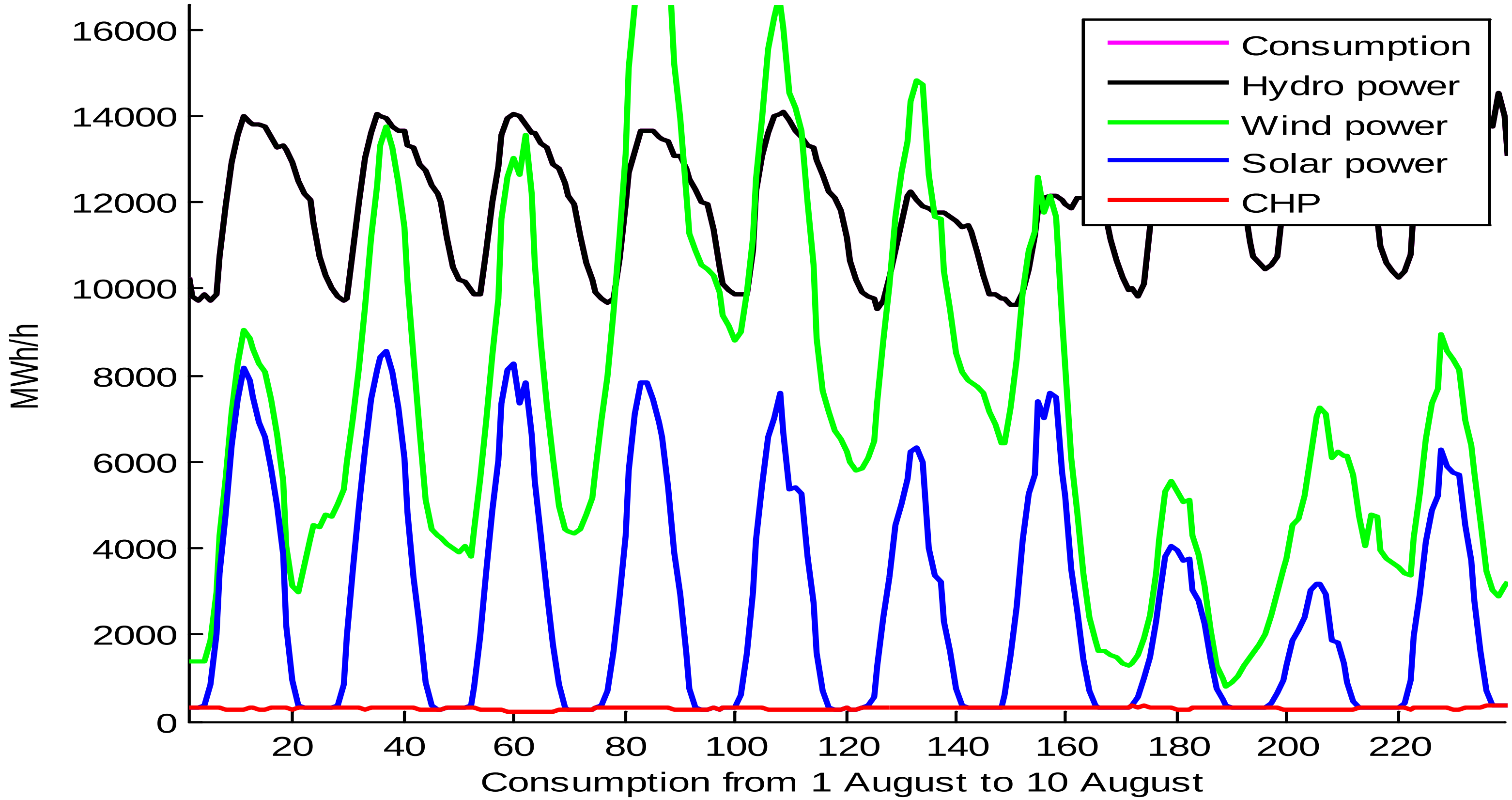
High wind ➔ decrease in CHP

Deficit situation (yearly basis)
Assumed need of OCGT



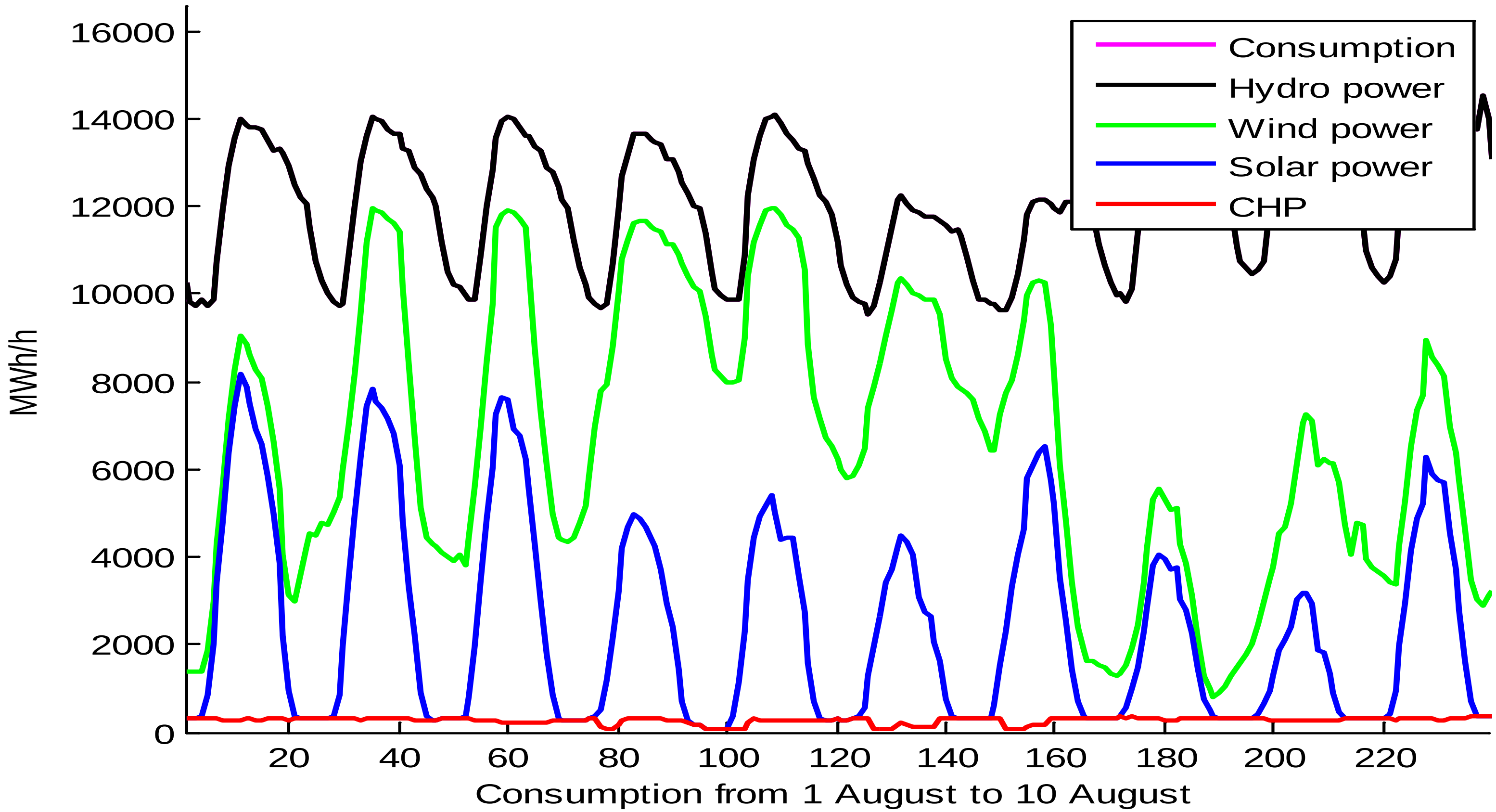
Cost for this: 2 öre/kWh = 0,2 Eurocent/kWh

Surplus situation (August)



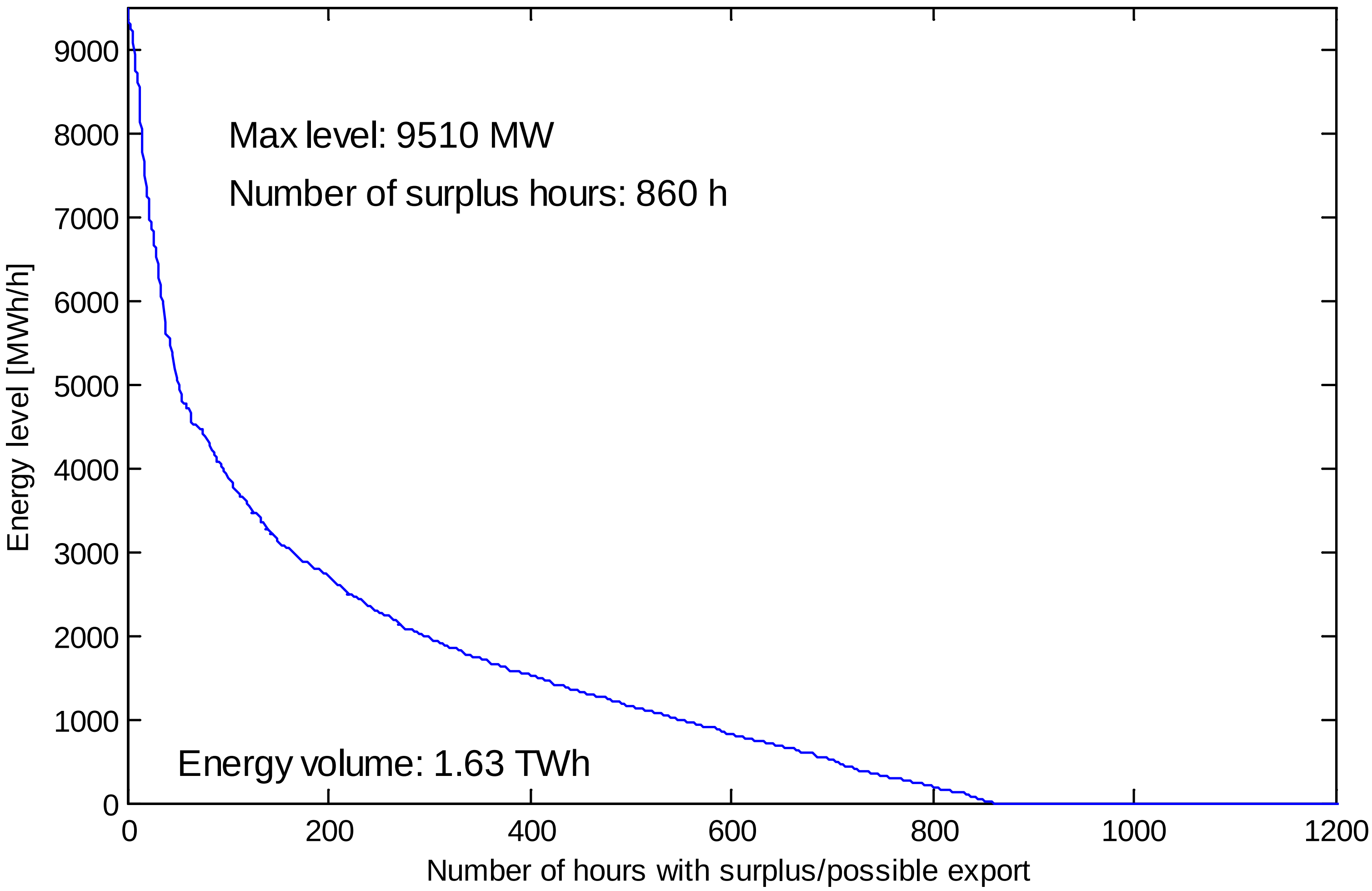
Not OK: 83% limit, min-hydro, min-CHP

Surplus situation (August)



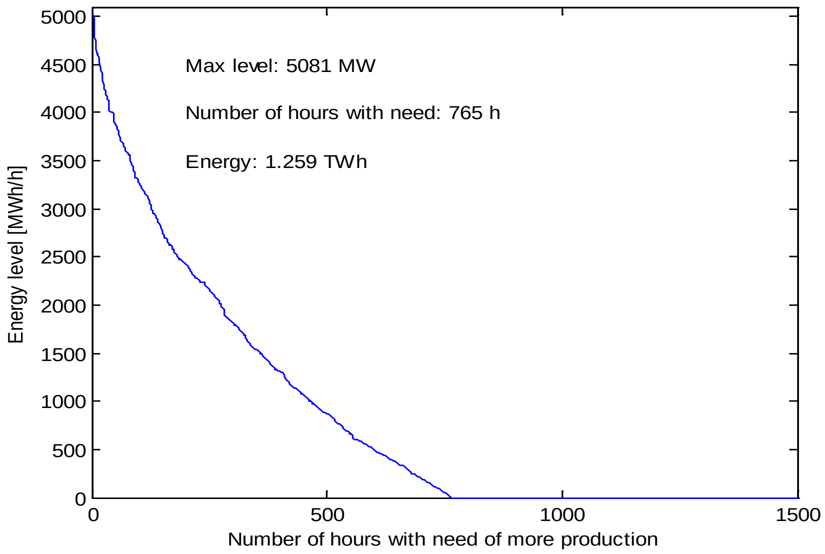
Now OK: 83% limit, min-hydro, min-CHP

Surplus during a year

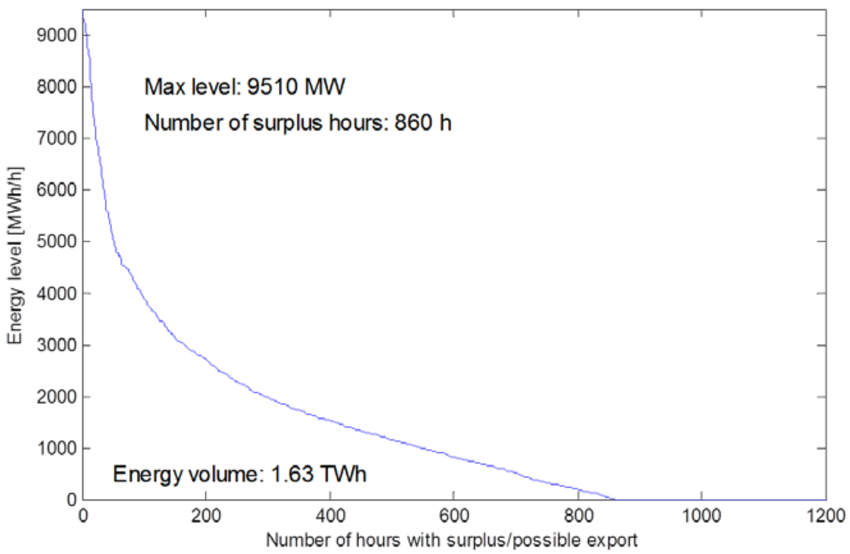


Variable renewable impact on transmission

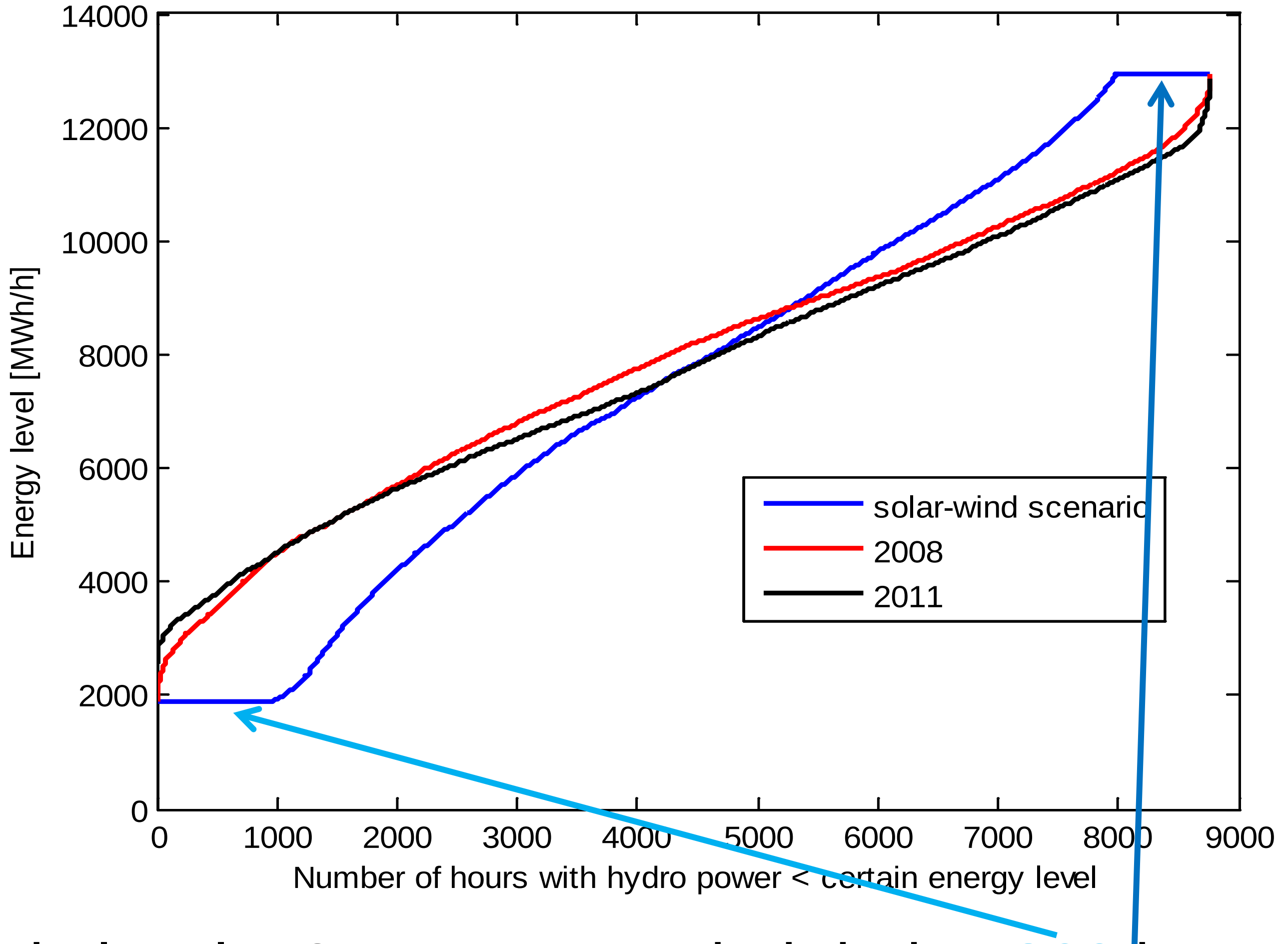
Need of extra capacity (import ?)



Surplus may be exported ?



Hydro power: Duration curves (test + 2008 + 2011)

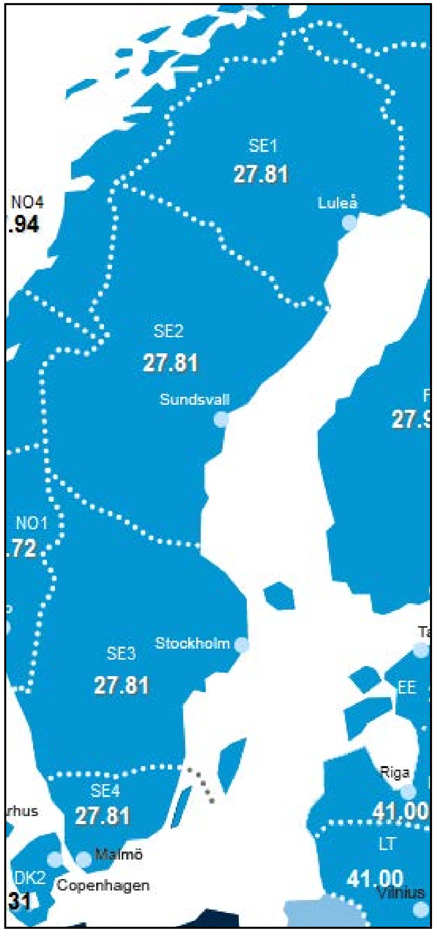


Min level: 1875 MW: Needed during **860** hours

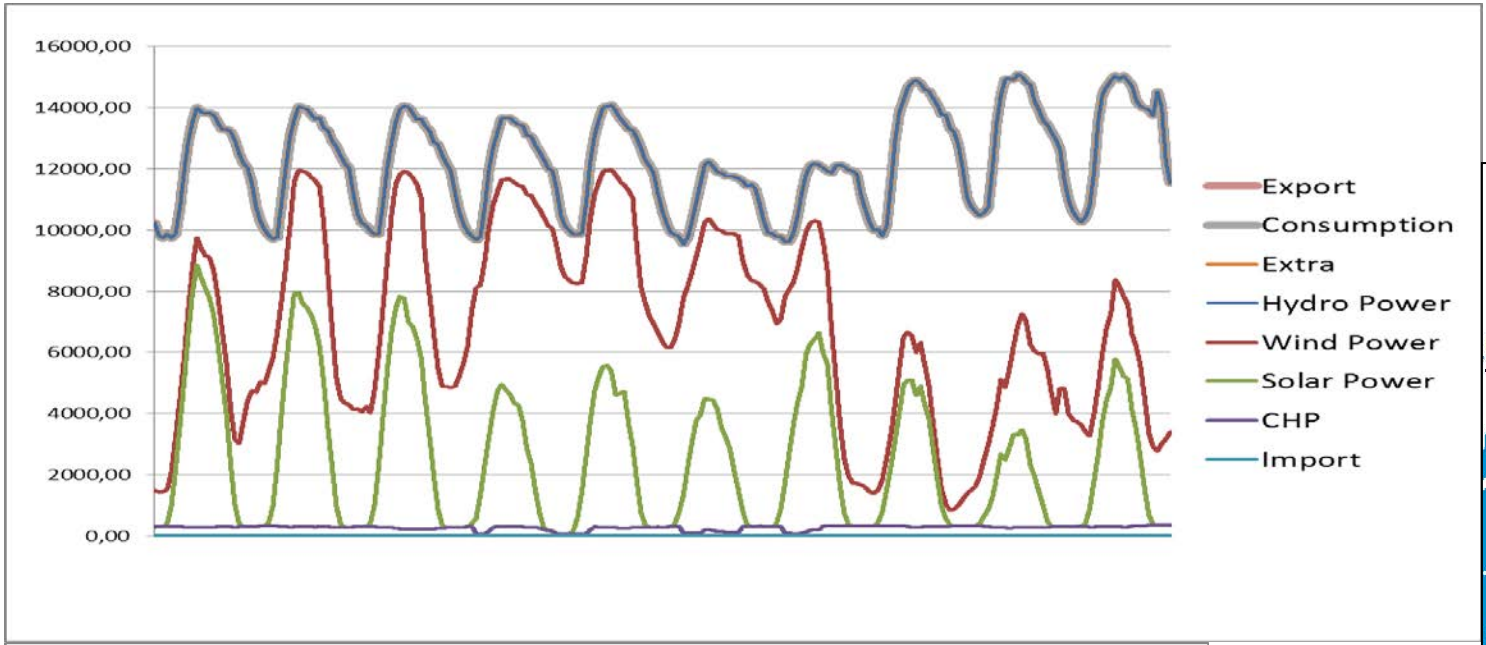
Max level: 12951 MW: Needed during **765** hours

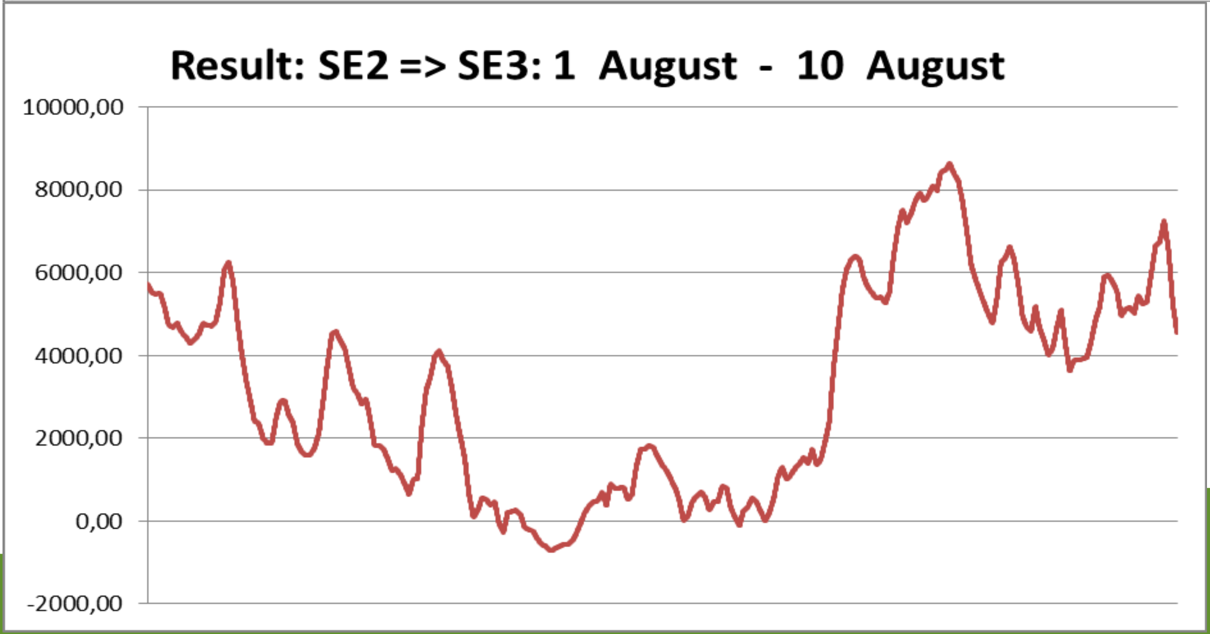
General <u>internal</u> transmission challenge

A. Voltage stability limits between areas
B. Q-control important
C. More transmission required, but low utilization time
D. Challenge to identify future transmission capacity with less nuclear
E. Detailed hydro simulation takes 10 minutes per week.

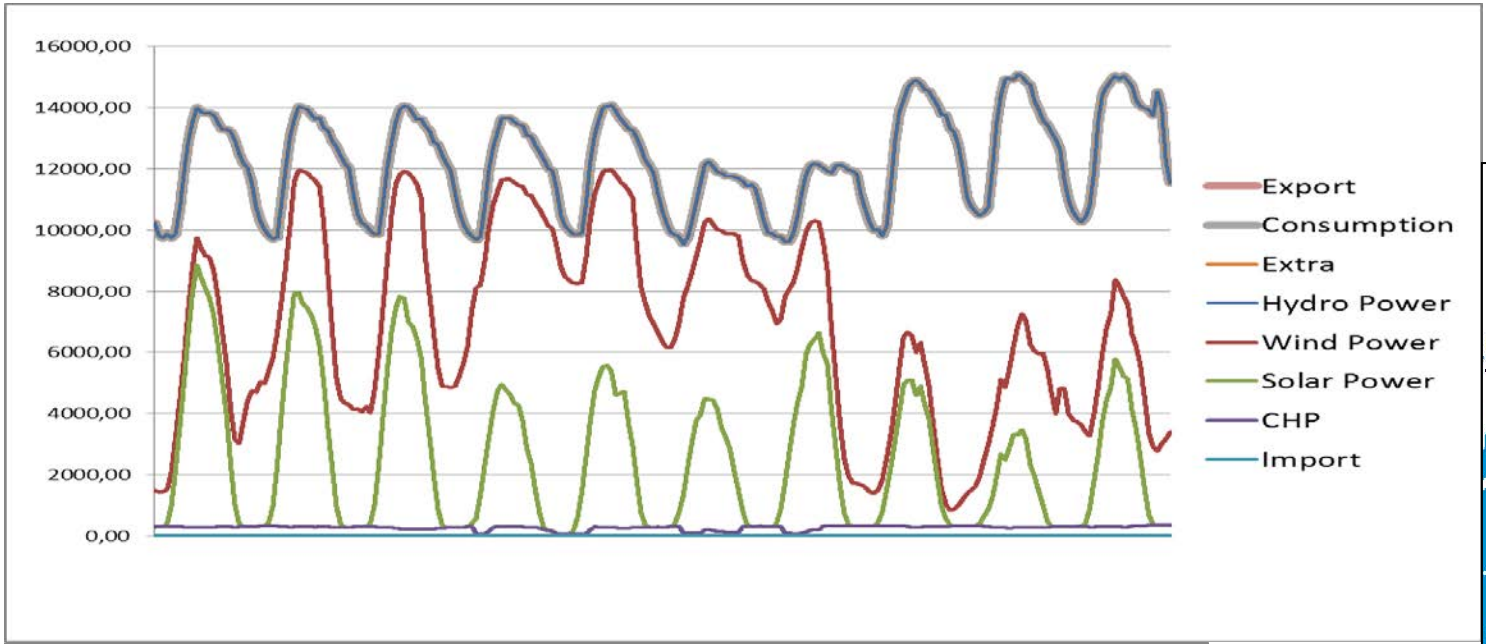


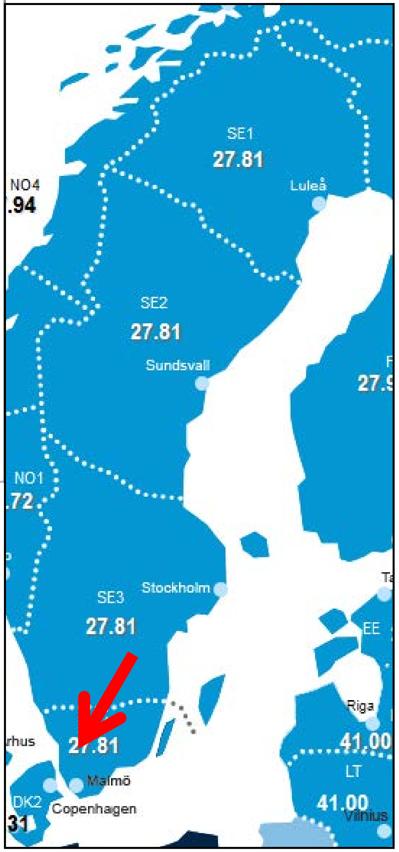
Surplus situation (August 1-10)

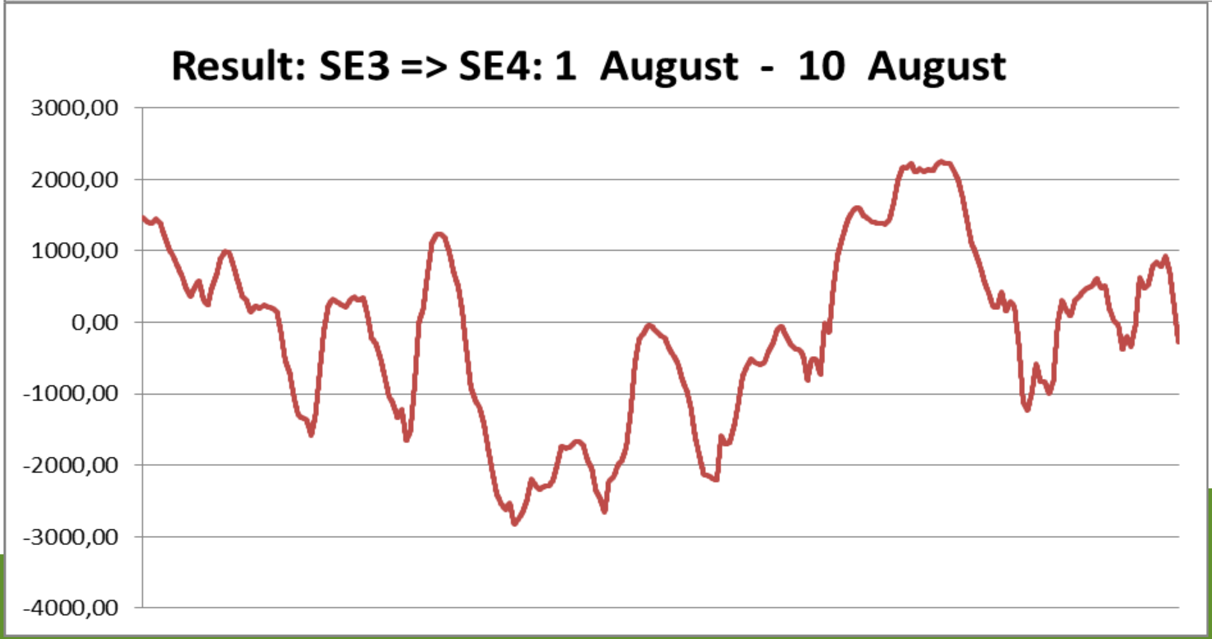




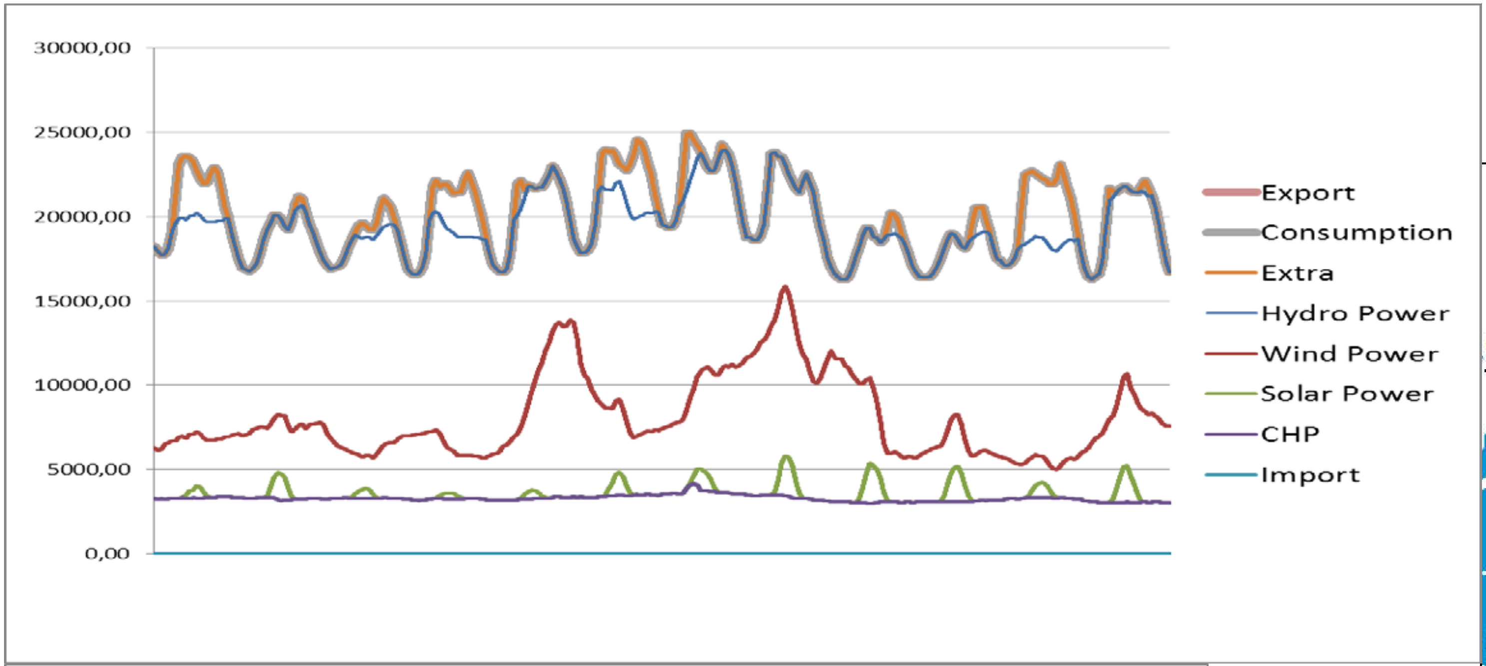
Surplus situation (August 1-10)

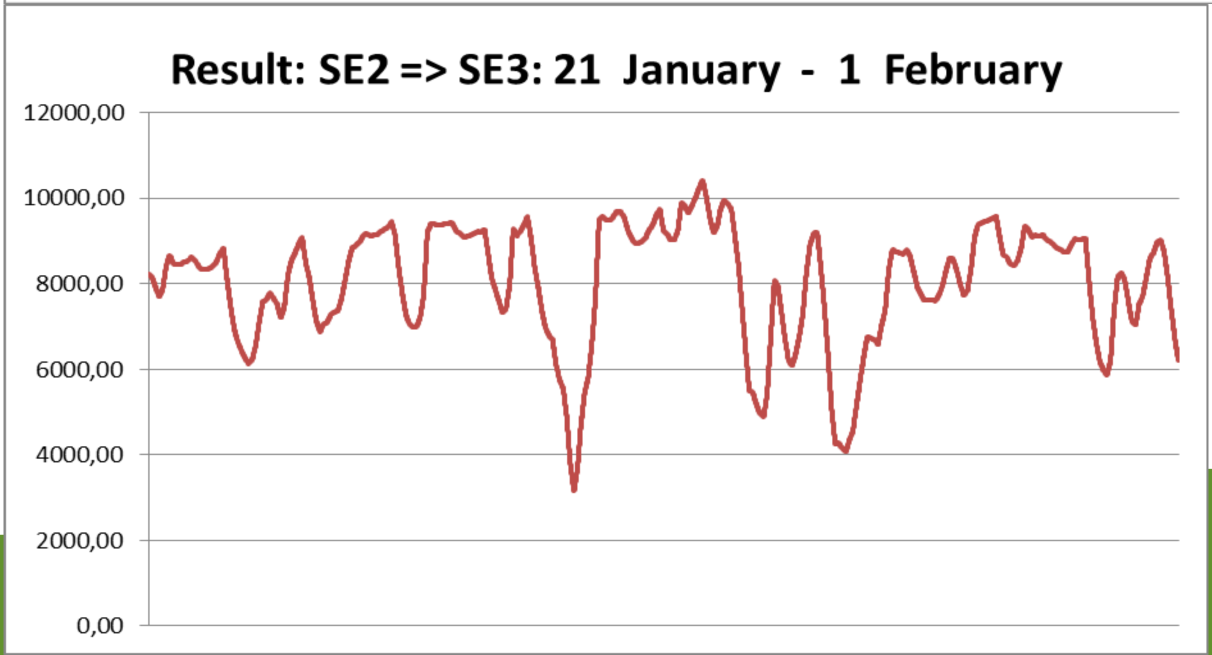




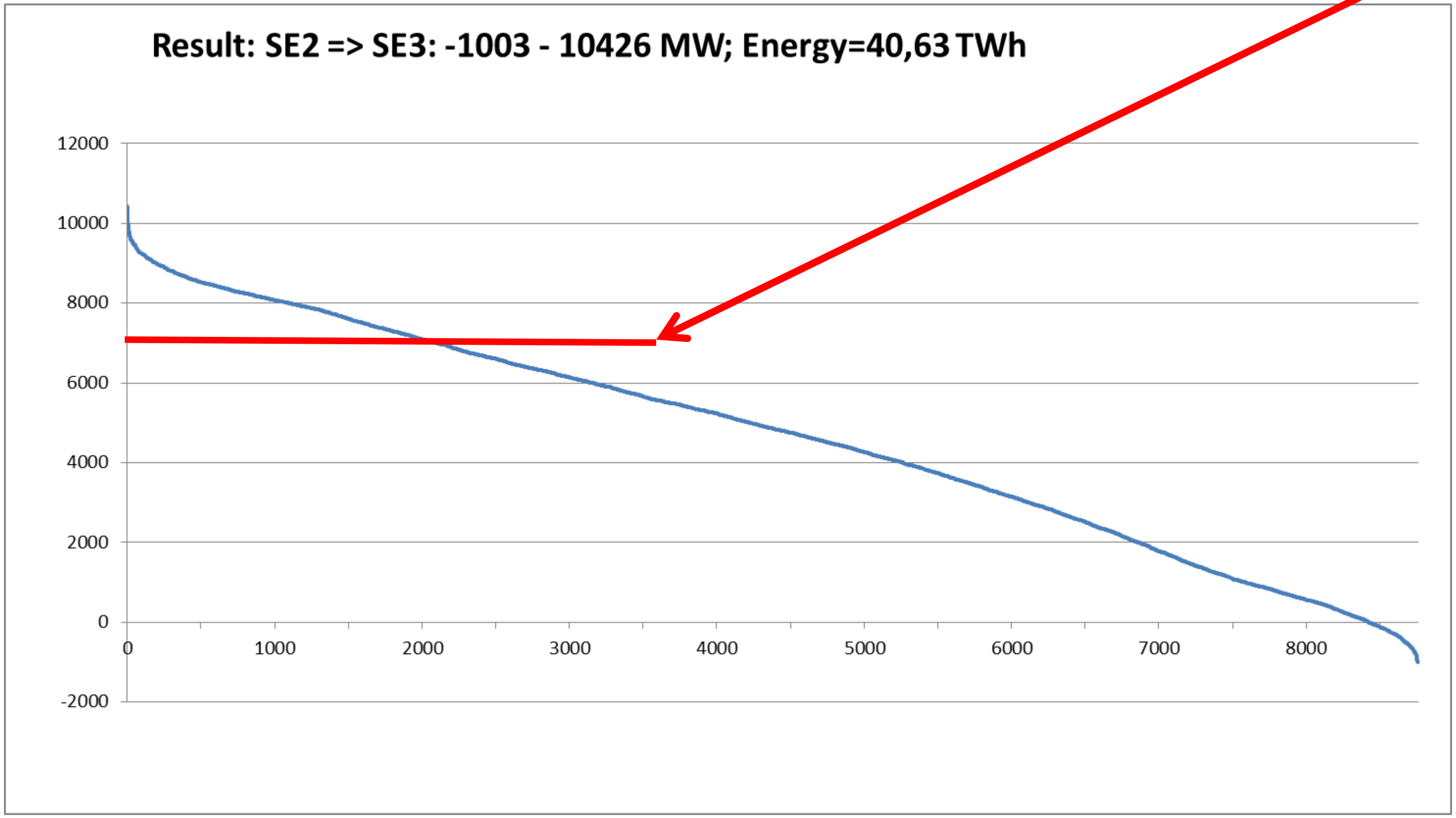


Transmission situation (Jan 21 – Feb 1)



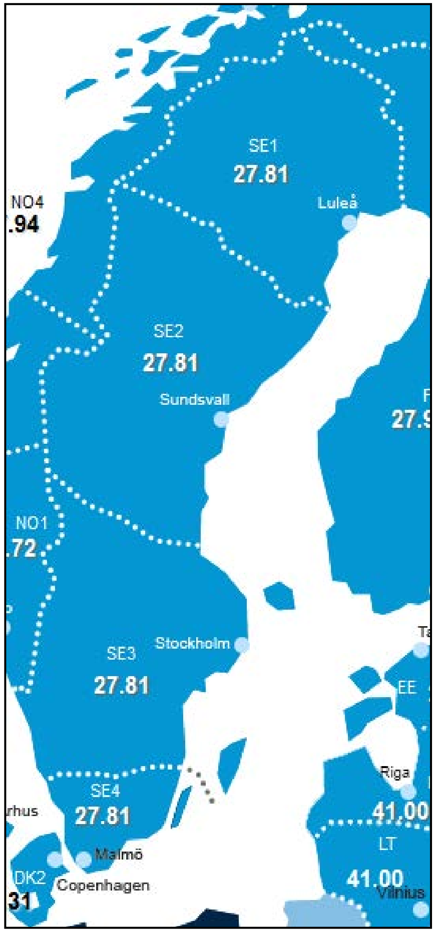


Transmission: Yearly duration : today ≈ 7000 MW



On transmission needs

A. Increase production in receiving end (= thermal, currently OCGT)
B. Capacity is available, small energy increase for first GW.
C. Since limit is voltage stability, SVC may be enough
D. Discussion on exchange of AC to DC
E. Optimization approach may be interesting



Three challenges in a power system with large amounts of solar and wind power

C1: Keep the **continuous balance**

C2: Handle situatiuations with **small** amounts of variable production.

C3: Handle situatiuations with **large** amounts of variable production.

Keep the balance in the power system

Different time steps:

1. Inertia (seconds)
2. Primary control (minutes)
3. Secondary control(quarter)
4. Tertiery control (quarter)
5. Intra-day-trade (hours)
6. Day-ahead-trade (day)
7. Weekly planning (week)
8. Yearly planning (year)

Security ↕ **Uncertianty**

Technology ↕ **Economy**

A synchronous power system

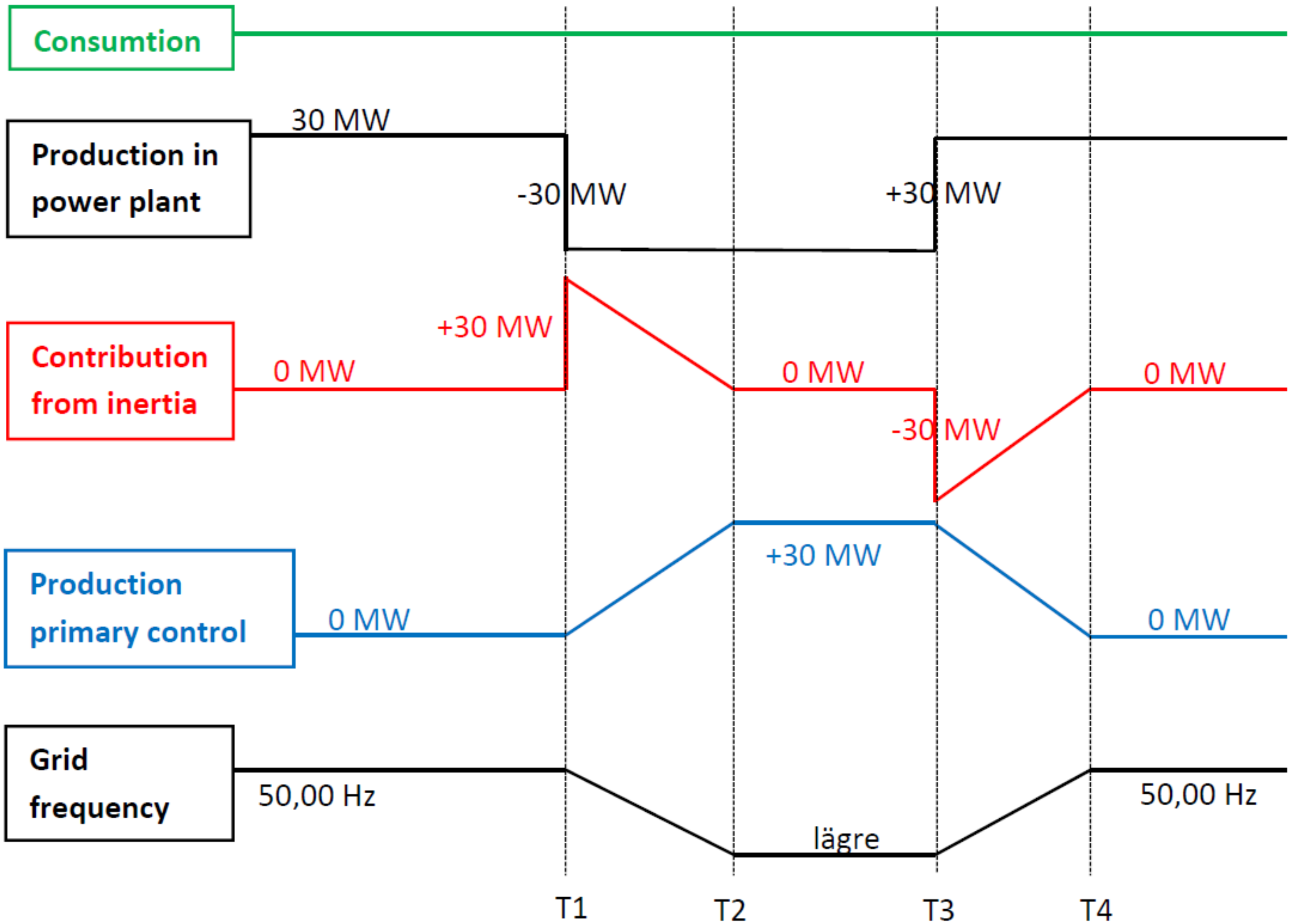
- A synchronous power system is a power system where all producers and consumers are connected to each other through transformers and AC transmission and distribution lines.
- Anything from a diesel generator set supplying a single load to a multi-national grid as the Nordel system (which connect Norway, Sweden, Finland and the eastern part of Denmark) can constitute a synchronous grid.
- An AC line has to have the same electric frequency at both ends of the line. If there were different frequencies at the ends then the voltage angle shift would increase until it reaches 180°, resulting in unacceptable large currents on the line. The same is valid for transformers. The conclusion is that in a synchronous grid the average electric frequency must be the same.

Power system challenge

Keep the balance:

- Production = consumption
- Electricity cannot be stored!
- Exactly when a bulb is lightned some generator will deliver the power
- Exactly when a power plant is stopped, the corresponding power will be delivered from another plant instead.

Keep the balance in a power system



The power system = a long bike

Keep active power balance

Bike

- Pedal forces = breaking forces
- Otherwise changed speed
- Break bike =>

Power System

- Total generation = total load
- Otherwise changed electric frequency
- Increase load => lo … ncy

Speed control

Bike

- Keep a constant speed
- Measure the speed (same on the whole bike)
- Reduced speed=> increase the force on the pedals.

Frequency control

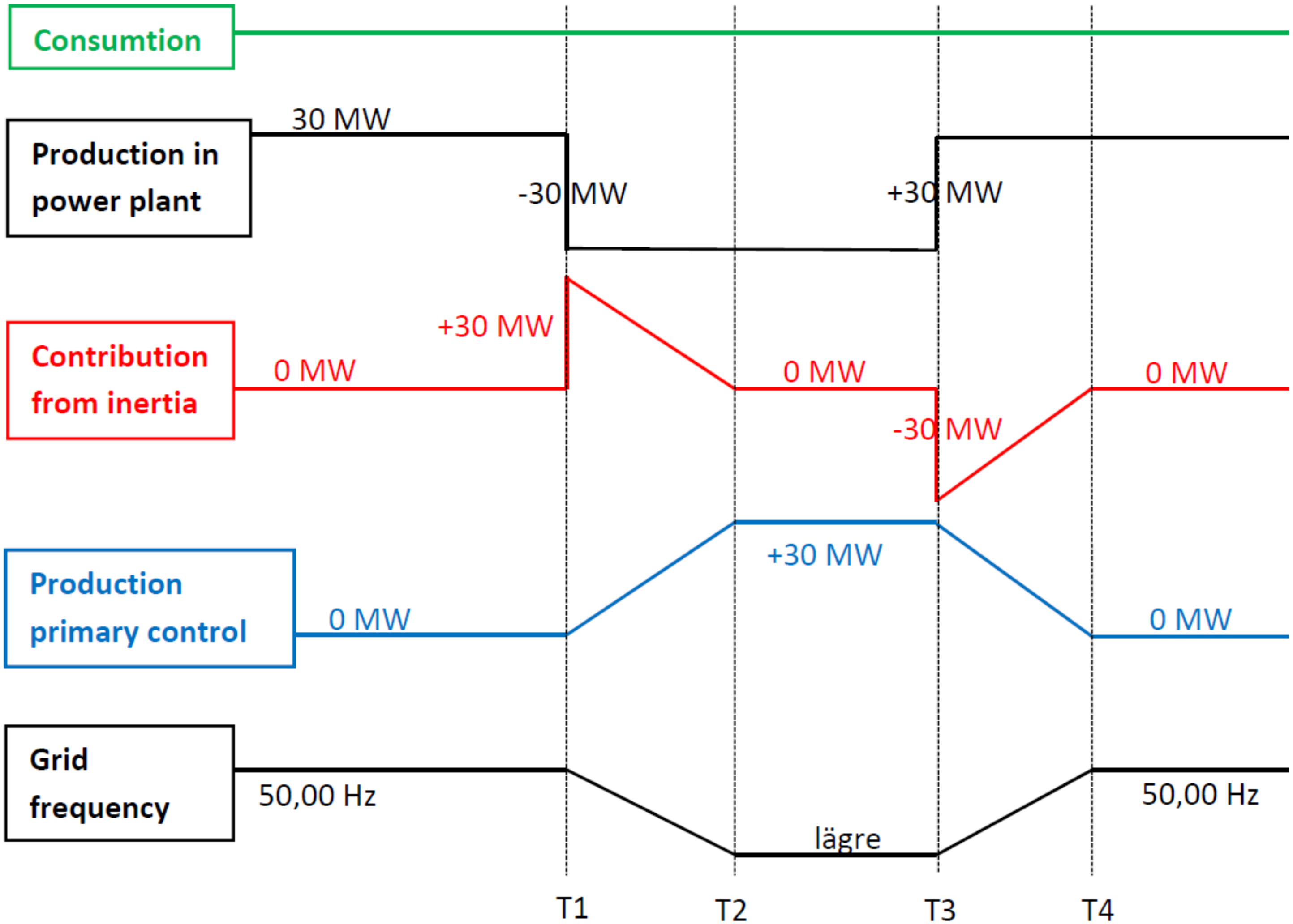
Bike

- Keep constant speed
- Measure speed (same on whole bike)
- Decreased speed

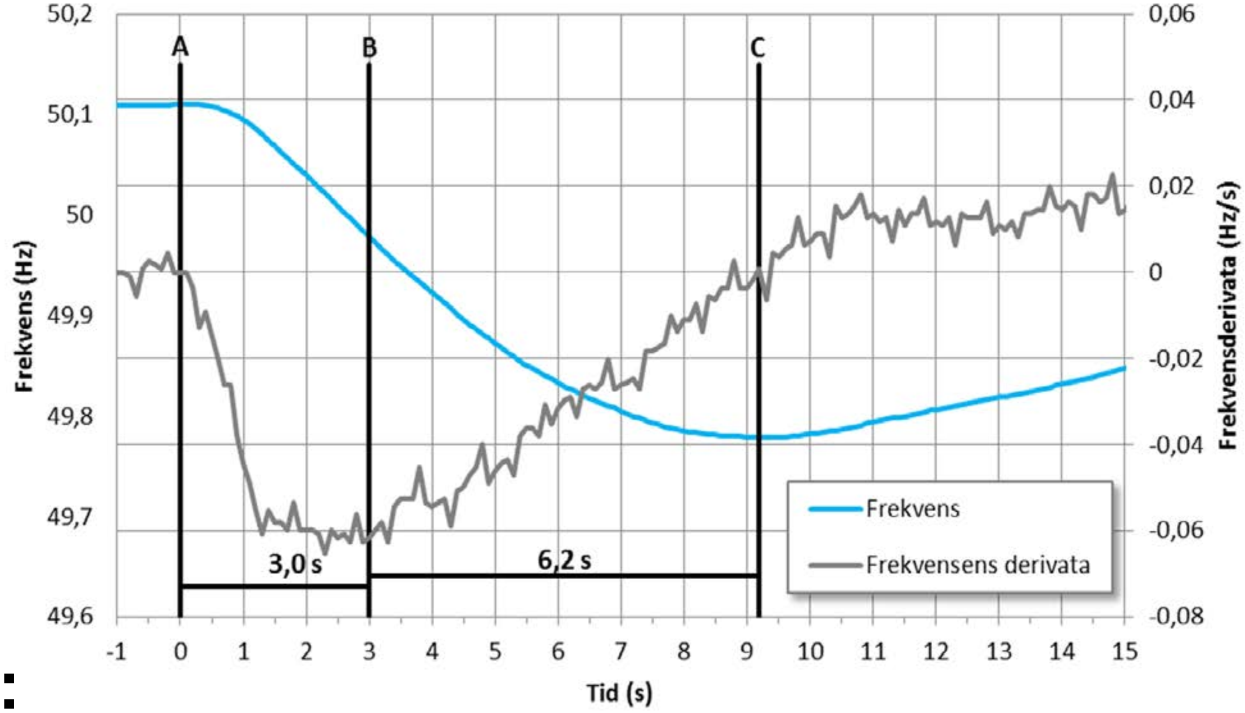
Power System

- Keep constant frequency
- Measure frequency (same in whole system)
- De… quency => … ge…

Keep the balance in a power system



Real initial phase of a power system outage



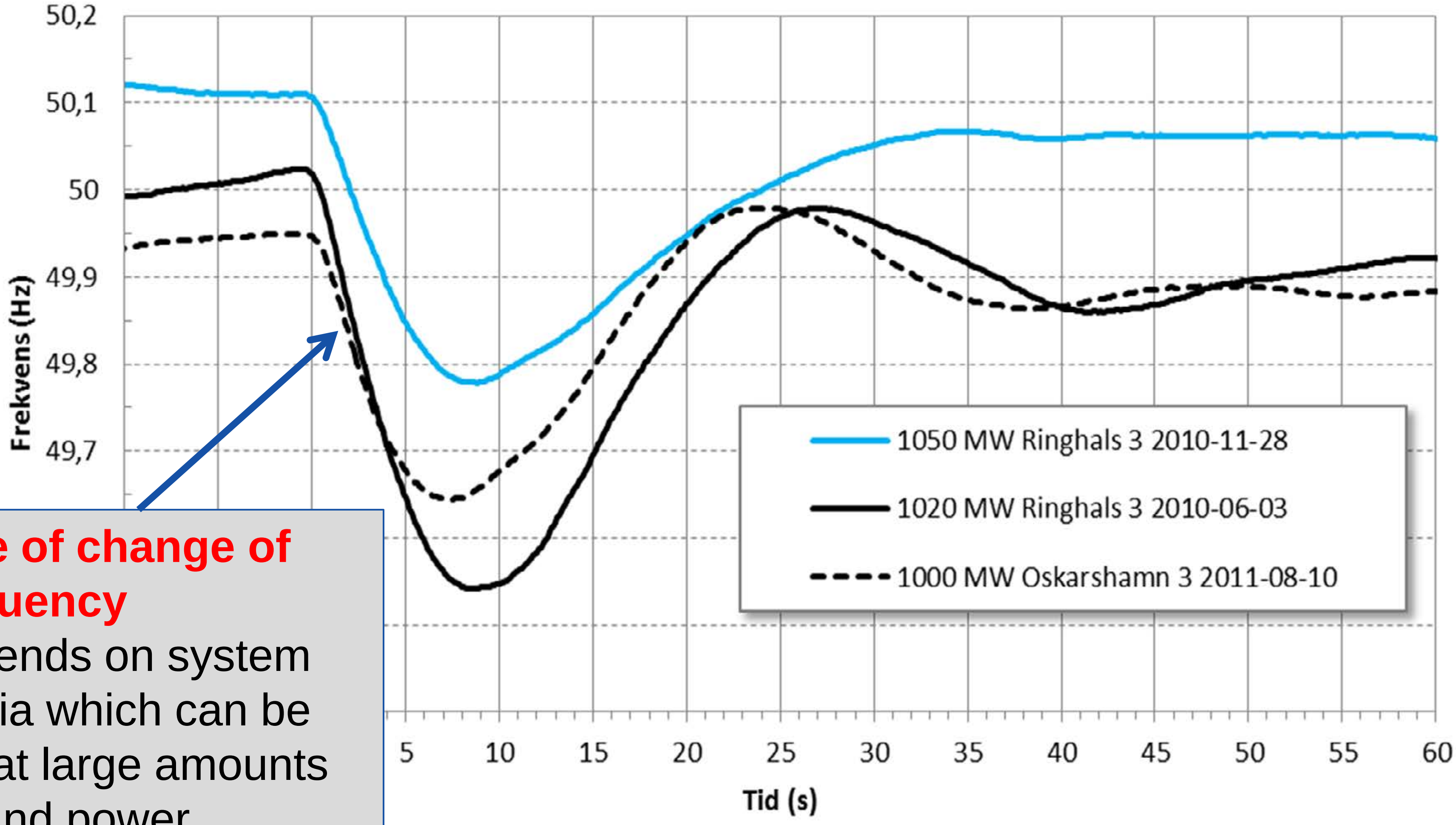
Time steps:

A. Disconnection of Swedish 1050 MW nuclear station

B. Primary control starts

C. Primary control has increased with 1050 MW

Frequency drop after 3 real outages in Sweden



Rate of change of frequency

Depends on system inertia which can be low at large amounts of wind power

Keep the balance in the power system

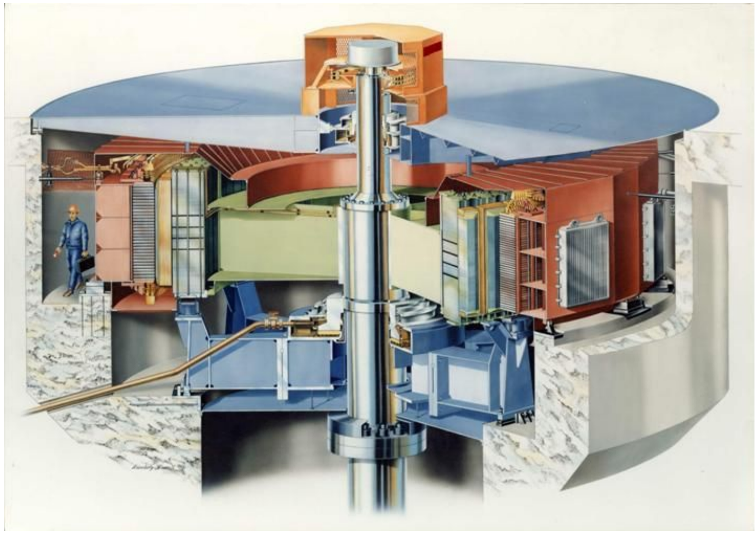
Different time steps:

1. Inertia (seconds)
2. Primary control (minutes)
3. Secondary control(quarter)
4. Tertiery control (quarter)
5. Intra-day-trade (hours)
6. Day-ahead-trade (day)
7. Weekly planning (week)
8. Yearly planning (year)

Security ↕ Uncertianty

Technology ↕ Economy

1. Inertia:
- In other power plants
- Technically possible in wind power plants



Contribution:

- E.g. hydro power stations (larger) use synchronous machines which are directly connected to the grid. This means an important contribution to the needed inertia.

Challenges:

- More slimmed constructions may reduce the inertia contribution.
- A challenge in power systems with, e.g. large amounts of solar power, wind power or HVDC infeed, which do not contribute with inertia.

Three challenges at large amount of variable renewables (solar/wind)

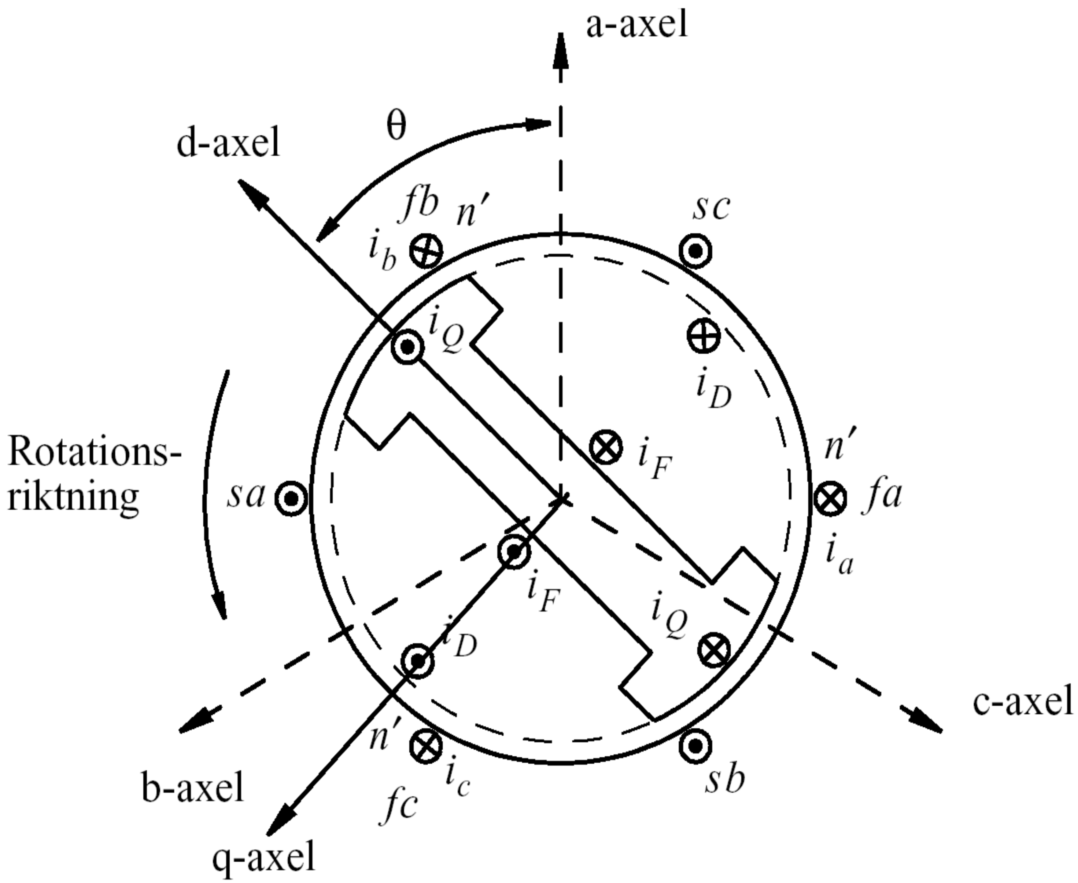
C1: Handling of the continuous balance.

C2: Low wind and solar power production and high power consumption. This issue is called ”capacity adequacy issue”.

C3: High wind and solar power production and low power consumption.

Lennarts view: Solve **C2** and **C3** ➔ needed resources. Then probably there is enough resources to handle **C1**

Synchronous machine



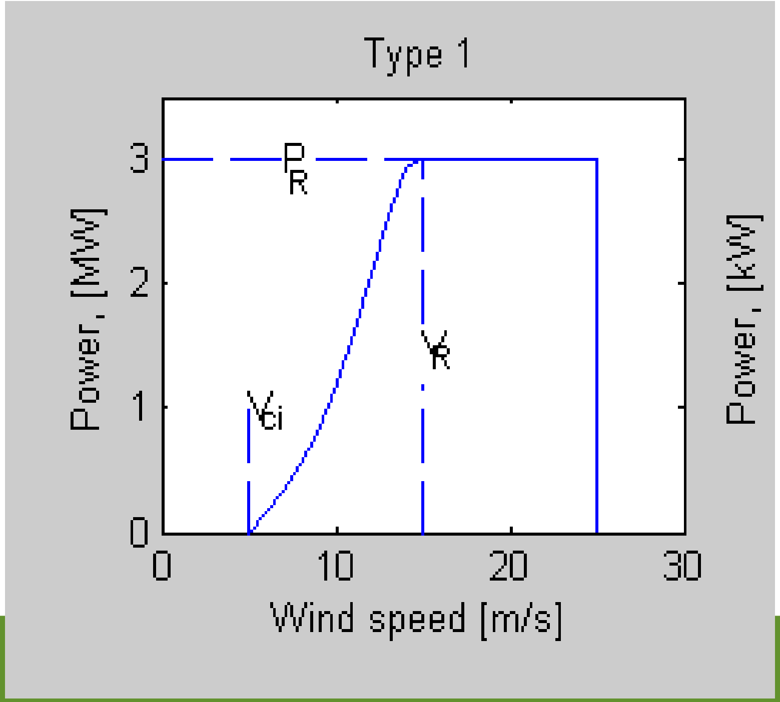
$$\text{Electric frequency in Hz} = \frac{\text{nr of poles}}{2} \cdot \frac{\text{rotor speed in rpm}}{60}$$

Wind power and primary control

1) Wind power plants do not (normally) contribute to keep reserves. **But they can!**

2) Wind speed changes between V-cut-in and V-rated

3) Wind speed changes around V-cut-out



Wind power and primary control

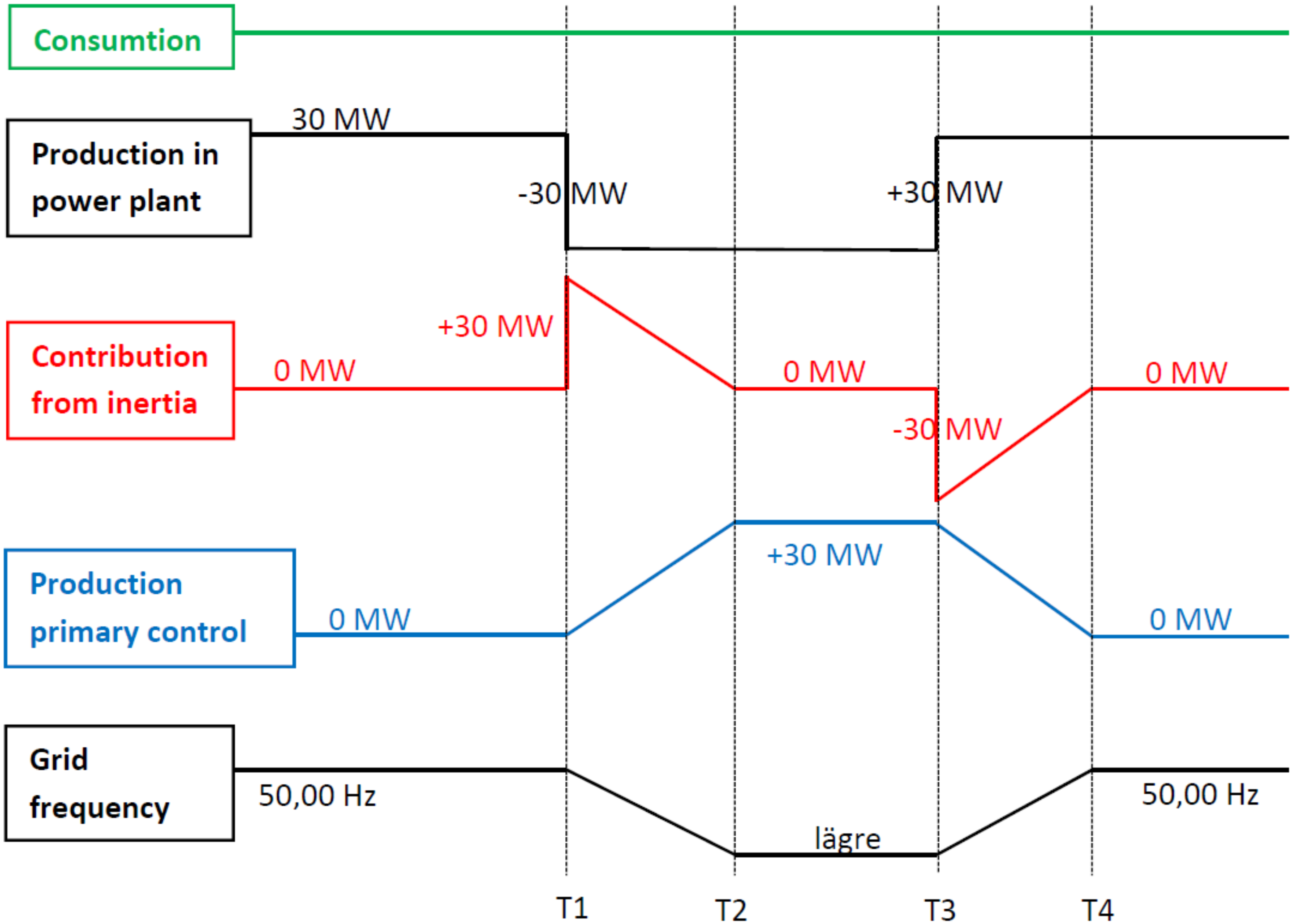
1) Wind speed changes between V-cut-in and V-rated. In this region the changes in different wind power plants are nearly independent concerning fast changes. The result is low total variation.
2) Wind speed changes around V-cut-out. If a lot of wind turbines are hit at the same time with a storm front, then there could be a large outage. The probability for this is though low.
3) Conclusion: Primary control is not a dominant problem for wind power.

Primary control value of wind power

”True” value: Balancing of second to minute variations. A slightly negative value. Result from a Swedish study: 3530 MW wind power => 10 MW of extra reserves.

Market value: In Sweden this is included in the ”balance responsibility”, where the system operator manage the variations within each hour. The cost for this is paid by the market actors.

Keep the balance in a power system



Secondary control, general function

- Adjust the frequency
- The power system should be ready for a new load or wind change
- The power system should be ready for a new disturbance.
- AGC (Automatic Generation Control) implies an economical reoptimization depending on new net load
- Adjust the time deviation.

3. Secondary control:

Function details in Nordic system:

- Secondary control implies that one at larger frequency deviations changes the production in order to correct the frequency. This is in the Nordic system called ”LFC-Load Frequency Control”. Decision from January 1 2013 to distribute at least 100 MW automatic LFC between the Nordic countries including 39 MW for Sweden.
- An automatic system.

Challenges:

- A new system (in the Nordic system), but needed.

Secondary control, wind power

- Wind power does not (normally) contribute to keep secondary control margins. **But possible!**
- Wind power causes extra needs of secondary control margins depending on not perfect wind speed forecasts.
- Secondary control is, as primary control, a part of the ”system responsibility”.

Secondary control value of wind power

”True” value: Balancing of minute to hour variations. A negative value. Result from a Swedish study: 3530 MW wind power => 230 MW of extra reserves (≠ ”new plants”).

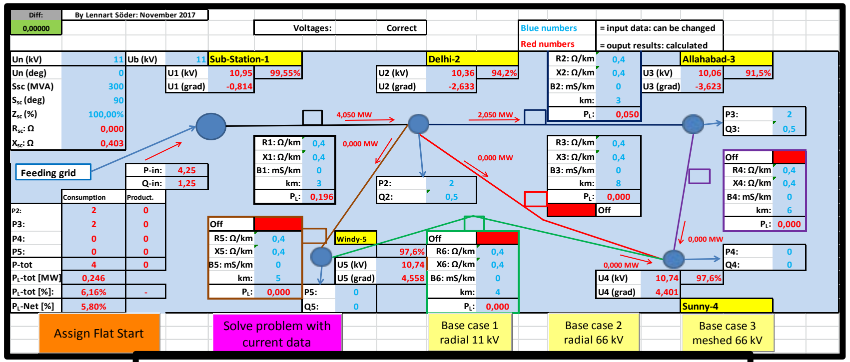
Market value: In Sweden this is included in the ”balance responsibility”, where the system operator manage the variations within each hour. The cost for this is paid by the market actors.

Tutorial T3 on power production expansion for high share renewables.

- **Impact from solar and wind power:**
  - o Selection of power factor
  - o Impact on local voltage
  - o Hosting capacity
  - o Impact on losses (where to produce reactive power?)
  - o Possibility to supply feeding grid with reactive power (from where?)
  - o Use of OLTC (On Load Tap Changers) in transformer
  - o Impact from grid strength.
  - o Impact from R/X quota of grid. Can be different in different lines.

Tutorial T2 on voltage control and wind power

- **Tool: Excel Load Flow program**



Power-system-2017.xlsm

Power grid simulation

by Lennart Soder, KTH-Stockholm-Sweden, lsod@kth.se

Grid calculations in Excel

This instruction is for the Excel sheet "Power-system-2017.xlsm". Data for different base-cases can be obtained with a clic on the corresponding button. The button "flat start", results in that all voltages are 1 p.u. and all voltage angles = 0 degrees. Data is shown in Figure 1.

- **Consumption/Production**: It is possible to introduce consumption (or production with negative sign) , active [MW] and reactive [MVAr]) in node 2, 3, 4 and 5.
- **Grid**: One can have data for the 6 different lines. For line 3, 4, 5 and 6 it is also possible to disconnect the lines by selecting "On" or "Off" in a menu which results in green or red color.
- **Feeding grid**: The feeding grid is represented with a short circuit power and a feeding voltage. One can also select to use a short circuit impedance in percent. One can select an angle for this one, where 0° refers to a resistive feeding grid while 90° refers to a purely inductive feeding grid. One can also see it as a fixed voltage behind a feeding transformer. If one considers the feeding grid as a fixed voltage behind a transformer, then the impedance refers to the impedance of the transformer, e.g. 4%. Instead of short circuit power, "S_{sc} (MVA)" one can select"S_{sc} (strong)" from a menu which implies that U1 becomes constant no matter the consumption/production in the grid.
- **Voltages**: These can be calculated by clic on "Solve problem with current data". This means that the corresponding non-linear system of equation is solved. The program calculates, except for voltage magnitudes and angles, also the grid losses and some currents and power transfers. The solver starts its solution from current voltages in the Excel sheet and adjusts these. Sometimes it is necessary to re-start these calculation and select all voltages are nominal and all angles =0°). This is obtained a clic on the button "Flat start". The voltages are also shown as percent of the the base level Ub", from cell D4. This implies, e.g., that one can select another feeding voltage in cell B4 which means that one uses voltage tap changers in the feeding transformer. At, e.g., high consumption one can increase this voltage in order to keep an acceptable voltage out in the grid. The opposite is valid in a situation with large amounts of distributed generation when the voltages otherwise may be too high.
- **Voltage reference**: In the sheet also the voltages are written as percent. These are the voltage in percent of the base voltage in cell D4.

The Excel sheet uses "Macros" which the buttons are linked to.

Excel-instructions-171031.pdf

Numerical examples, November 2017,

by Lennart Soder, KTH, lsod@kth.se

Tests A: Radial 11 kV grid

Based on EXCEL program "Power-system-2017.": Base-case 1. Here we assume that there are over-headlines with R=X= 0,4 Ω/km. These are typical values for around 11 kV. The R depends on the area of the conductors. The 11 kV system is fed from a comparatively strong grid with short circuit capacity of S_{sc}=300 MVA. The feeding grid is assumed to be "purely inductive". "Comparatively strong" means that the short circuit capacity is around 100 times the demand (4 MW) in the system. Total line length from sub-station to Allahabad is 6 km.

We here assume that voltage should be within ± 10% of nominal value

Assignments

Start with Base-case 1.

A1. How much can the active demand in Allahabad increase to keep voltage limits?

A2. How much can the demand increase if we allow local control of reactive power? What is the impact on system losses?

A3. Start with Base-case 1. How much can the demand increase if we assume a controllable transformer in the feeding point (this implies assign "Strong grid" and change the feeding voltage)? What is the impact on system losses?

Examples-171110.pdf

EG2220: Power Generation, Environment and Markets

Design of the future power system - 1

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Current (2017) challenges in Sweden and many other countries

1. Low Power Prices
2. Depends to high extent on low costs on fossil fuels
3. Difficulties to fund existing power plants, e.g., nuclear and other
4. **How to get rid of something cheap (current coal power etc)?**

Aim of future power system:

- **Competitive prices**
- **Sustainable**
- **Reliable**
  - Efficient regulation
  - Efficient operation
  - Efficient planning

”Competitive prices”:

- = ?

”Competitive prices”:

- Competitive for consumers (not too high)
- Competitive for producers (not too low)
- Prices set on ”competitive” markets, and/or regulation.
- State might be involved concerning subsidies and/or taxes etc

”Sustainable power system”:

- = ?

”Sustainable power system”:

- Sustainable from **environmental** point of view ➔
  - **Low CO2 emissions**
  - **High share of renewable power**
  - **Low NOX, SOX etc.**
- Sustainable from **economic** point of view
- Sustainable from **social** point of view

What is ”sustainable”?

World Commission on Environment and Development (UN 1987), the Brundtland Commission, defined in ”Our common future” sustainable development as

”Development that meets the needs of the present generation without compromising the needs of future generation”

”Reliable power system”:

- =?

”Reliable power system”:

- Defined as the ”adequacy challenge”
- Conciders ”capacity value”
- Low Loss of load probability - LOLP
- Enough margins for operation
- High ”security” (low risk of black-out) = stable power system.

Important factors in studies for future power systems:

Important factors in studies for future power systems:

Set-up: - Green field study - Additional investments	**Objective:** - Minimum cost - Market driven
Requirements: - Reliability - Share of renewables - Maximum CO_2 emissions	**Variables:** - MW in each power plant - taxes or subsidies - CO_2 prices

Important factors in studies for future power systems: 1) Set-up

Set-up: - Green field study - Additional investments	**Objective:** - Minimum cost - Market driven
Requirements: - Reliability - Share of renewables - Maximum CO2 emissions	**Variables:** - MW in each power plant - taxes or subsidies - CO2 prices

Common set-ups:

- **Green field studies** where it is assumed that the future system is built up from the beginning. It may also refer to a future situation which is so far in the future so all power plants can be assumed to be new.
- An alternative set-up is **Additional investments** where it is assumed that a certain amounts of today investments still exists.
- The difference between these two types is whether all (in **Green field**) or not all (in **Additional investments**) investment costs are included in the analysis.

Important factors in studies for future power systems:
2) Objective

Set-up:	Objective:
- Green field study - Additional investments	- Minimum cost - Market driven
Requirements:	**Variables:**
- Reliability - Share of renewables - Maximum CO2 emissions	- MW in each power plant - taxes or subsidies - CO2 prices

Common set-ups:

- **Minimum cost** where the aim of the study is to select the combination of future sources which provides the lowest total cost for the society. One can hear, e.g., include CO2 costs or not, reliability target etc
- Another possible objective is **market driven**. This is then based on the assumption that a power plant is **NOT** built if the costs for it is not covered by the income. There can then be different set-ups of markets including, e.g., energy-only market (only income from produced energy) or different kinds of capacity payments.

Important factors in studies for future power systems:
3) Requirements

Set-up:	Objective:
- Green field study - Additional investments	- Minimum cost - Market driven
Requirements: - Reliability - Share of renewables - Maximum CO2 emissions	**Variables:** - MW in each power plant - taxes or subsidies - CO2 prices

Common set-ups:

- There can also be different combinations of system requirements:
- These can be, e.g., **Reliability**, where there is a restriction concerning how many hours of the year when the capacity is not enough to cover the demand, i.e., causing curtailments.
- Common requirements also include **Share of renewables**
- or **Maximum CO_2 emissions** where, e.g., EU or different countries have goals to be considered.

Important factors in studies for future power systems: 4) Variables

Set-up:	Objective:
- Green field study - Additional investments	- Minimum cost - Market driven
Requirements:	**Variables:**
- Reliability - Share of renewables - Maximum CO2 emissions	- MW in each power plant - taxes or subsidies - CO2 prices

Common set-ups:

- A question is then what **the aim of the study** is. The aim then controls what is classified as **variables**, i.e., what kind of results is the output of the results.
- Some common results, i.e., classified as variables before the study, are, e.g., **a) MW in each power plant**, **b) taxes or subsidies** or **c) CO2 prices**.
- **MW in each power** plant is the result in most studies,
- Reliability as a requirement, ➔ use some kind of extra payment or market design, i.e., **subsidies as a variable**.
- **Share of renewables** or maximum CO_2$emissions}, and at the same time has an assumption on {\it market driven}, then there must be a possibility to achive this. A possibility is then to, e.g., study the possibility of using {\it subsidies} or {\it CO2 prices}, to make this possible. I.e., to use {\it subsidies} or {\it CO2 prices} as {\it variables}.

Important factors in studies for future power systems:

4) Variables

Set-up:	Objective:
- Green field study - Additional investments	- Minimum cost - Market driven
Requirements: - Reliability - Share of renewables - Maximum CO2 emissions	**Variables:** - MW in each power plant - taxes or subsidies - CO2 prices

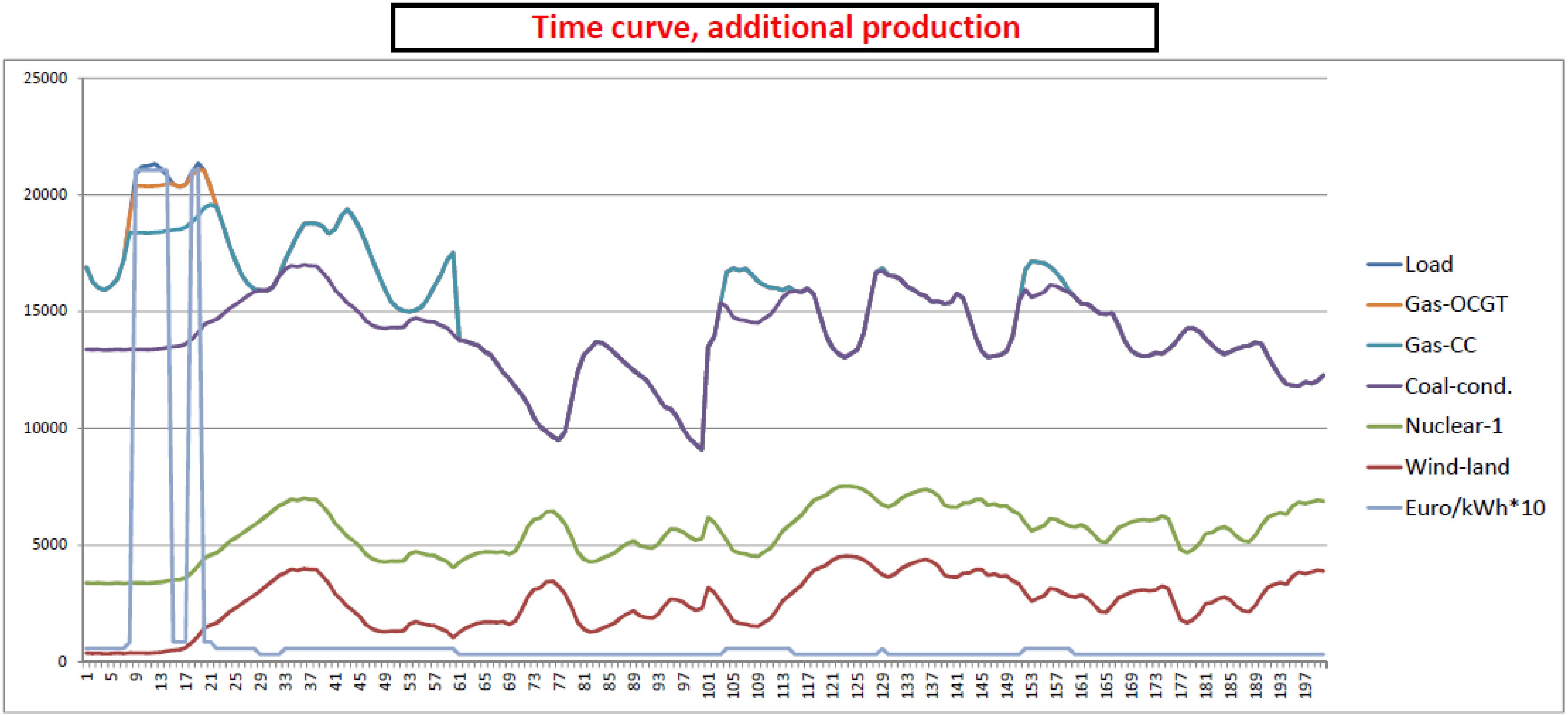
Common set-ups:

Requirement	Variable
Meet the demand	MW in each plant
Profitable plants	Add extra income to last unit in merit order = a margin on the marginal cost.
Reliability	Subsidize level of some plants
Share of renewables	Subsidize level of these
Max CO_2 emissions	Needed CO_2 tax

Case studies of
new power systems



Base case - 1


Time curve, additional production
25000
20000
15000
10000
5000
0
1
5
9
13
17
21
25
29
33
37
41
45
49
53
57
61
65
69
73
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117
121
125
129
133
137
141
145
149
153
157
161
165
169
173
177
181
185
189
193
197
Load
Gas-OCGT
Gas-CC
Coal-cond.
Nuclear-1
Wind-land
Euro/kWh*10

Base case - 2

Mean price:	123,4	€ / MWh		Total cost	Profit	CO2	Utilization time
Source:	MW	MWh	MWh [%]	kEuro	kEuro/MWh	tons	hours
Wind-land	8000	504498	16,8%	28255	-0,2	0	200
Nuclear-1	3000	600000	19,9%	31728	70,5	0	200
Gas-OCGT	2000	24684	0,8%	3983	1231,0	12485	14
Gas-CC	5000	183473	6,1%	18360	407,0	64000	76
Coal-cond.	10000	1691135	56,2%	90733	86,6	1200412	200
Curtailments	956	4631	0,2%	9750	0,0	0	8
Total:	28956	3008421	100,0%	182808	1794,8	1276898	

Excel program: Set-up - 1

Future system design

		From Source data - Sweden			Parameter		Calculated					CO2: Euro/ton:	10	
Production system data					Base cost			Base cost			Operation costs			
				Interest	Euro/MW		Euro/MW	Op. Cost		Margin	Subs./ tax	CO2	Total	Op. Cost
Nr	Source	Old MW	Max MW	rate	/year	Factor	/period	Euro/MWh	Factor	Euro/MWh	Euro/MWh	Euro/MWh	Euro/MWh	order
1	Wind-land	0	15000	6%	129982	1	2967,6	8,9	1	0	0	0,00	8,9	1
4	Nuclear-1	0	15000	6%	322141	1	7354,8	16,1	1	0	0	0,00	16,1	2
6	Gas-OCGT	0	15000	6%	44656	1	1019,6	73,7	1	0	0	5,06	78,7	5
7	Gas-CC	0	15000	6%	69324	1	1582,7	53,4	1	0	0	3,49	56,9	4
9	Coal-cond.	0	20000	6%	168890	1	3855,9	23,8	1	0	0	7,10	30,9	3
12	Curtailments	0	20000	6%	0	1	0,0	2105,3	1	0	0	0,00	2105,3	6
		0						kr/MWh-el						

Base case: C-o

Production system result

Capacity		Energy		Cap. Cost	En. Cost	Tot. Cost	Revenue	Profit		Mean cost	CO2	Util. Time
MW-new	MW-tot	MWh	%	kEuro	kEuro	kEuro	kEuro	kEuro	€/MWh	Euro/MWh	tons	hours
8000	8000	504498	16,8%	23741	4514	28255	28148	-107	-0,2	56,0	0	200
3000	3000	600000	19,9%	22064	9663	31728	74010	42283	70,5	52,9	0	200
2000	2000	24684	0,8%	2039	1944	3983	34368	30385	1231,0	161,4	12485	14
5000	5000	183473	6,1%	7914	10446	18360	93034	74674	407,0	100,1	64000	76
10000	10000	1691135	56,2%	38559	52173	90733	237173	146440	86,6	53,7	1200412	200
955,8	956	4631	0,2%	0	9750	9750	9750	0	0,0	2105,3	0	8
28956	**28956**	**3008421**	**100,0%**			**182808**			**1795**		**1276898**	

Load	1	1=original, 2=simplified		
Source	Factor	row	Cap. Fact	CF-org
W-land	1,507	1	0,315311194	0,315
W-sea	0,000	-	-	0,315
Solar	0,000	-	-	0,012
Period lenght [h]:		200	2,4	2,5
				0,012
LOLP:	4,0%			0,012
Mean price €/MWh		123,4		

Plot 2

1 Time curve, production/type
2 Time curve, additional production
3 Duration curve

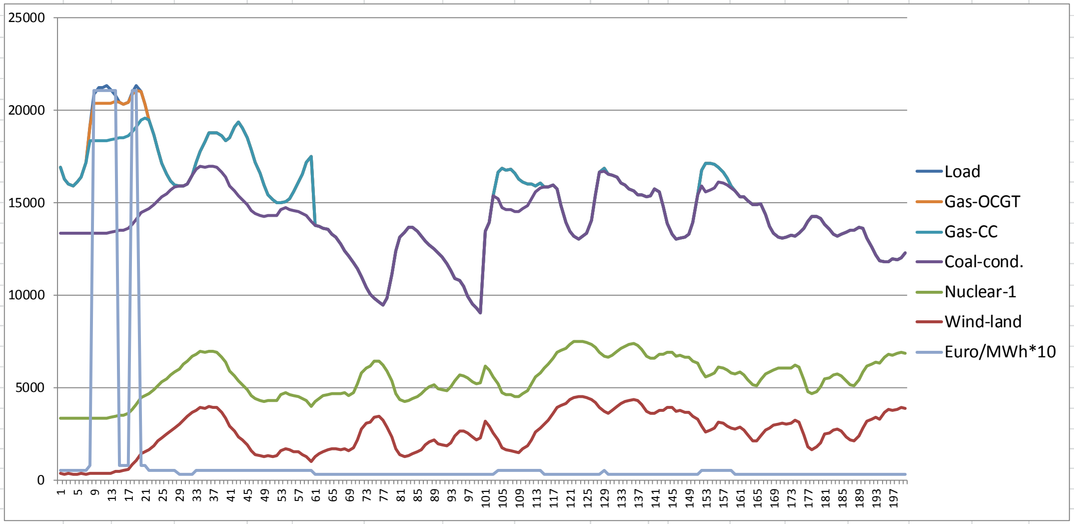
Wind 1 1=original, 2=simplified

2: Assumes that 'Wind-land' is included and has the lowest operation cost.

"Simplified" load or wind =>
Straigth lines for duration curves.

Simplified data		

Time curve, additional production



Data analysis of thermal power plants

Op. Cost	Unit	Source	Next	Min hours	Result [h]
1	1	Wind-land	-	Not thermal	200,0
2	2	Nuclear-1	5	237,3	200,0
3	5	Coal-cond.	4	87,1	200,0
4	4	Gas-CC	3	25,8	76,0
5	3	Gas-OCGT	6	0,5	14,0
6	6	Curtailments			8,0

Not thermal or more expensive than some other units

	Hour step:	1	1, 2 or 3 is possible	
Per.	Load day	Wind day	Solar day	Nr of hours
1	22	22	15	60
2	180	180	23	40
3	100	100	48	100
1	2015-01-22	2015-01-22	2015-01-15	
2	2015-06-29	2015-06-29	2015-01-23	
3	2015-04-10	2015-04-10	2015-02-17	

Excel program: Set-up – 2
Input (details in other sheet)

CO2 cost

Future system design

From Source data - Sweden	Parameter	Calculated	CO2: Euro/ton:	10

Production system data

Nr	Source	Old MW	Max MW	Interest rate	Base cost Euro/MW /year	Factor	Euro/MW /period	Base cost Op. Cost Euro/MWh	Factor	Margin Euro/MWh	Operation costs: Subs./ tax Euro/MWh	Operation costs: CO2 Euro/MWh	Operation costs: Total Euro/MWh	Op. Cost order
7	Gas-CC	0	15000	6%	69324	1	1582,7	53,4	1	0	0	3,49	56,9	4
1	Wind-land	0	15000	6%	116824	0,9	2400,5	14,7	0,5	0	0	0,00	7,4	1
4	Nuclear-1	0	15000	6%	322141	1	7354,8	16,1	1	0	0	0,00	16,1	2
6	Gas-OCGT	0	15000	6%	44656	1	1019,6	73,7	1	0	0	5,06	78,7	5
9	Coal-cond.	0	20000	6%	168890	1	3855,9	23,8	1	0	0	7,10	30,9	3
12	Curtailments	0	20000	6%	0	1	0,0	2105,3	1	0	0	0,00	2105,3	6
		0												

Change sources

Existing plats

Max Capacity

Interest rate

Changed fixed cost

Changed operation cost

Extra operation margin

operation subsidy or tax

Excel program: Set-up – 3
Some results + Print options

Some solar and wind data

LOLP

Mean price

Parameters for LDC-NLDC

Original or linear LDC

Print time curve or LDC

Original or linear NLDC

Load	2	1=original, 2=simplified		
Source	Factor	row	Cap. Fact	CF-org
W-land	1,507	2	0,2116875	0,315
W-sea	0,000	-	-	0,315
Solar	0,000	-	-	0,012
Period lenght [h]:		200	2,4	2,5
				0,012
LOLP:	6,5%			0,012
Mean price €/MWh		181,0		

Plot: 2

1 Time curve, production/type

2 Time curve, additional production

3 Duration curve

Wind: 2 1=original, 2=simplified

2: Assumes that 'Wind-land' is included and has the lowest operation cost.

"Simplified" load or wind =>
Straigth lines for duration curves.

Simplified: LDC=a-b*(t-1)		
	a	b
LDC	21360	61
NLDC	20960	74

Excel program: Set-up – 4 Output

Production system result

Capacity		Energy		Cap. Cost	En. Cost	Tot. Cost	Revenue	Profit		Mean cost	CO_2	Util. Time
MW-new	MW-tot	MWh	%	kEuro	kEuro	kEuro	kEuro	kEuro	€/MWh	Euro/MWh	tons	hours
5000	5000	371428	12,1%	7914	21148	29062	157233	128171	345,1	78,2	129564	108
8000	8000	338700	11,1%	19204	2496	21700	25420	3720	11,0	64,1	0	178
3000	3000	600000	19,6%	22064	9663	31728	108613	76886	128,1	52,9	0	200
2000	2000	53972	1,8%	2039	4250	6289	56939	50650	938,5	116,5	27299	40
10000	10000	1687292	55,2%	38559	52055	90614	352397	261783	155,1	53,7	1197684	200
960,0	960	6708	0,2%	0	14122	14122	14122	0	0,0	2105,3	0	13
28960	**28960**	**3058100**	**100,0%**			**193514**			**1578**		**1354547**	

New Capacity

Total Cost

Total Profit

CO_2 emissions

Excel program: Set-up – 5
Output summary
Excel sheet: *Table for Compendium*

Mean price:	123,4	€ / MWh		Total cost	Profit	CO2	Utilization time
Source:	MW	MWh	MWh [%]	kEuro	kEuro/MWh	tons	hours
Wind-land	8000	504498	16,8%	28255	-0,2	0	200
Nuclear-1	3000	600000	19,9%	31728	70,5	0	200
Gas-OCGT	2000	24684	0,8%	3983	1231,0	12485	14
Gas-CC	5000	183473	6,1%	18360	407,0	64000	76
Coal-cond.	10000	1691135	56,2%	90733	86,6	1200412	200
Curtailments	956	4631	0,2%	9750	0,0	0	8
Total:	28956	3008421	100,0%	182808	1794,8	1276898	

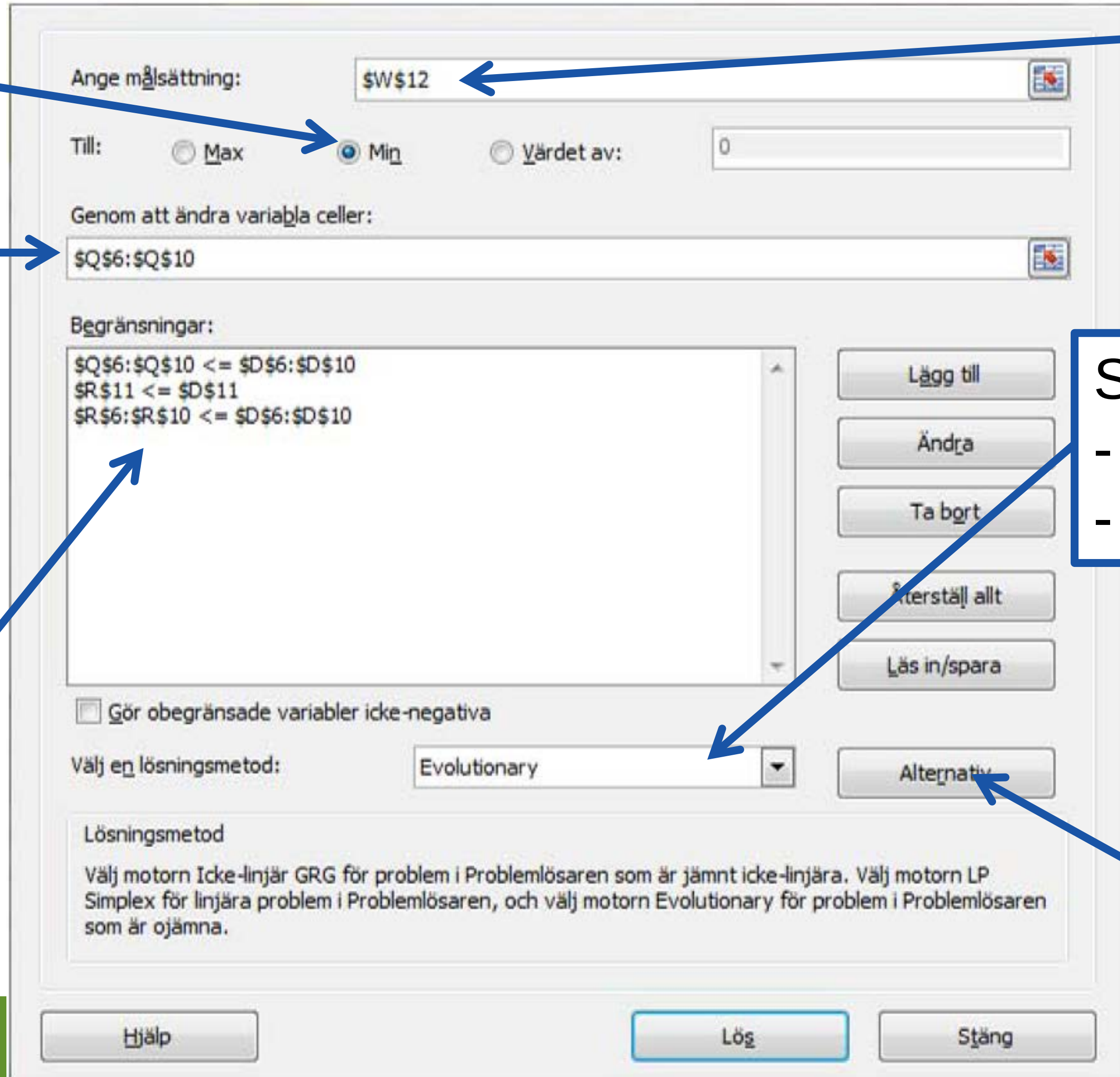
Excel program: Set-up – 6
Apply optimization: “Data” => “Solver”

Minimize objective

Objective e.g. cost

Variables MW/source

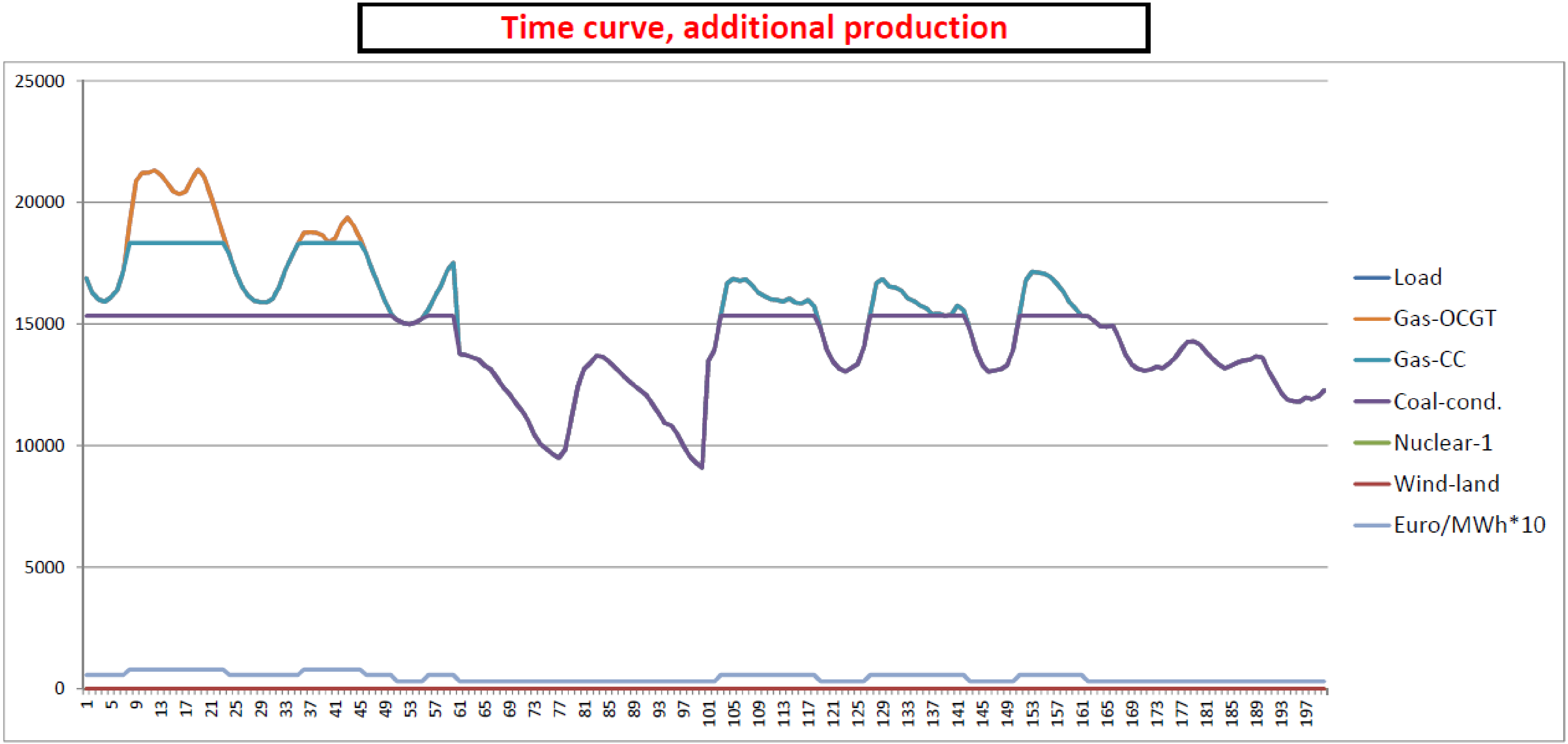
Constraints e.g. max capacity per source



Solvers:
- non-linear
- Evolutionary

Solvers: Change parameters

Case: Min cost - 1



Case: Min cost - 2

Mean price:	46,5	€ / MWh		Total cost	Profit	CO2	Utilization time
Source:	MW	MWh	MWh [%]	kEuro	kEuro/MWh	tons	hours
Wind-land	0	0	0,0%	0	-	0	0
Nuclear-1	0	0	0,0%	0	-	0	0
Gas-OCGT	3023	39848	1,3%	6220	-77,3	20155	26
Gas-CC	3002	150073	5,0%	13296	-20,3	52350	98
Coal-cond.	15339	2818500	93,7%	146101	-4,0	2000645	200
Curtailments	0	0	0,0%	0	-	0	0
Total:	21364	3008422	100,0%	165617	-101,7	2073150	

Comparison

Cost decrease: -10%

CO2: +62%

Price: -63%

Profit: From OK to BAD

LOLP: -100%

Base case

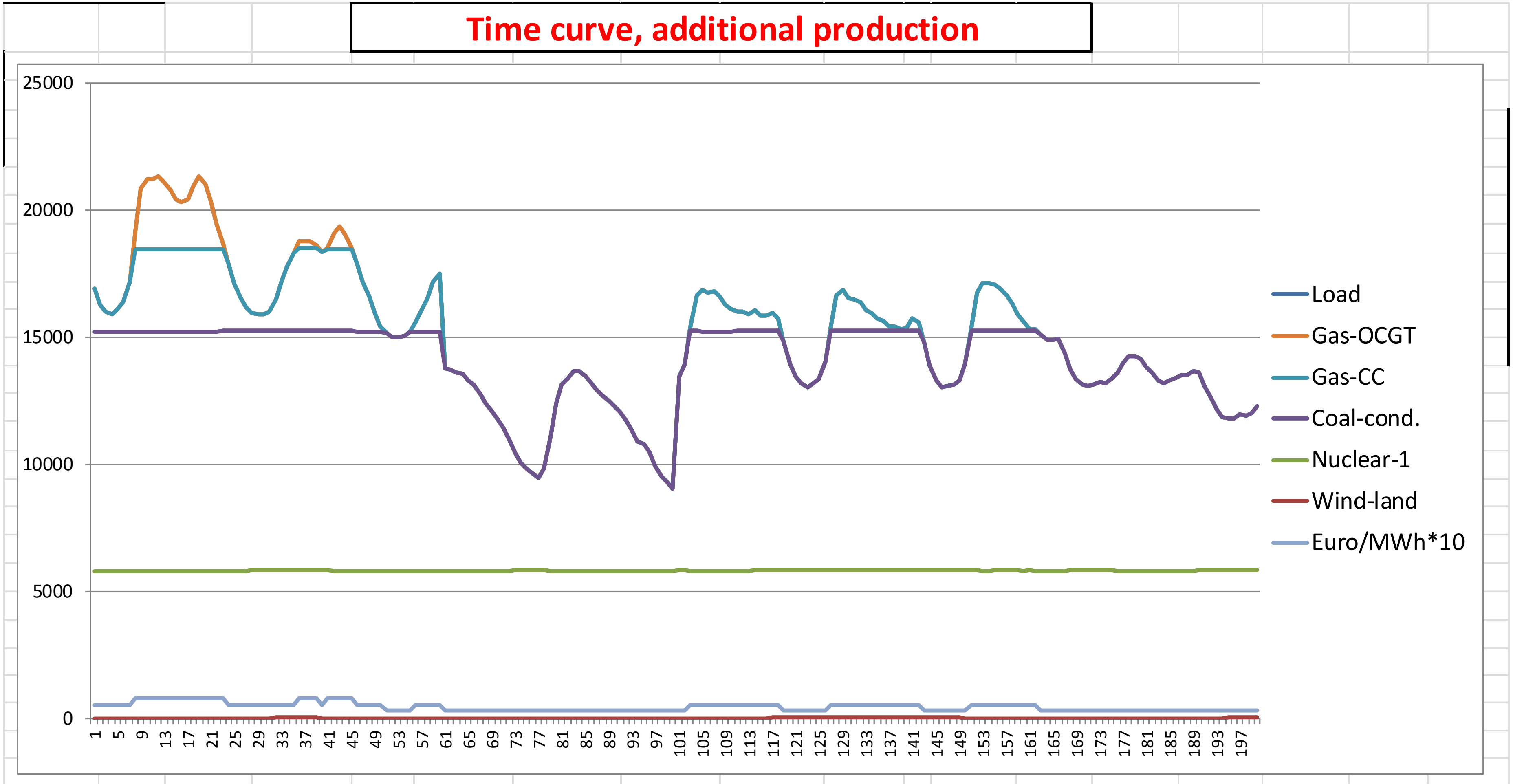
Mean price:	123,4	€ / MWh		Total cost	Profit	CO2	Utilization time
Source:	MW	MWh	MWh [%]	kEuro	kEuro/MWh	tons	hours
Wind-land	8000	504498	16,8%	28255	-0,2	0	200
Nuclear-1	3000	600000	19,9%	31728	70,5	0	200
Gas-OCGT	2000	24684	0,8%	3983	1231,0	12485	14
Gas-CC	5000	183473	6,1%	18360	407,0	64000	76
Coal-cond.	10000	1691135	56,2%	90733	86,6	1200412	200
Curtailments	956	4631	0,2%	9750	0,0	0	8
Total:	28956	3008421	100,0%	182808	1794,8	1276898	

Min cost

Mean price:	46,5	€ / MWh		Total cost	Profit	CO2	Utilization time
Source:	MW	MWh	MWh [%]	kEuro	kEuro/MWh	tons	hours
Wind-land	0	0	0,0%	0	-	0	0
Nuclear-1	0	0	0,0%	0	-	0	0
Gas-OCGT	3023	39848	1,3%	6220	-77,3	20155	26
Gas-CC	3002	150073	5,0%	13296	-20,3	52350	98
Coal-cond.	15339	2818500	93,7%	146101	-4,0	2000645	200
Curtailments	0	0	0,0%	0	-	0	0
Total:	21364	3008422	100,0%	165617	-101,7	2073150	

Case: Min cost + No CO2 increase + LOLP=0

Insert this as constraints in optimization ➔



Case: Min cost + No CO_2 increase + LOLP=0

Insert this as constraints in optimization ➔

Mean price:	46,5	€ / MWh		Total cost	Profit	CO2	Utilization time
Source:	MW	MWh	MWh [%]	kEuro	kEuro/MWh	tons	hours
Wind-land	87	5458	0,2%	306	-11,3	0	200
Nuclear-1	5805	1160978	38,6%	61392	-6,4	0	200
Gas-OCGT	2893	36444	1,2%	5819	-80,9	18433	25
Gas-CC	3229	161654	5,4%	14315	-20,7	56389	99
Coal-cond.	9426	1643887	54,6%	87062	-4,2	1166874	200
Curtailments	0	0	0,0%	0	-	0	0
Total:	21439	3008421	100,0%	168892	-123,5	1241697	

Comparison: Base Case - New

Base case

Mean price:	123,4	€ / MWh		Total cost	Profit	CO2	Utilization time
Source:	MW	MWh	MWh [%]	kEuro	kEuro/MWh	tons	hours
Wind-land	8000	504498	16,8%	28255	-0,2	0	200
Nuclear-1	3000	600000	19,9%	31728	70,5	0	200
Gas-OCGT	2000	24684	0,8%	3983	1231,0	12485	14
Gas-CC	5000	183473	6,1%	18360	407,0	64000	76
Coal-cond.	10000	1691135	56,2%	90733	86,6	1200412	200
Curtailments	956	4631	0,2%	9750	0,0	0	8
Total:	28956	3008421	100,0%	182808	1794,8	1276898	

Min cost, same CO2, LOLP=0

Mean price:	46,5	€ / MWh		Total cost	Profit	CO2	Utilization time
Source:	MW	MWh	MWh [%]	kEuro	kEuro/MWh	tons	hours
Wind-land	87	5458	0,2%	306	-11,3	0	200
Nuclear-1	5805	1160978	38,6%	61392	-6,4	0	200
Gas-OCGT	2893	36444	1,2%	5819	-80,9	18433	25
Gas-CC	3229	161654	5,4%	14315	-20,7	56389	99
Coal-cond.	9426	1643887	54,6%	87062	-4,2	1166874	200
Curtailments	0	0	0,0%	0	-	0	0
Total:	21439	3008421	100,0%	168892	-123,5	1241697	

Cost decrease: -8%

CO2: -3%

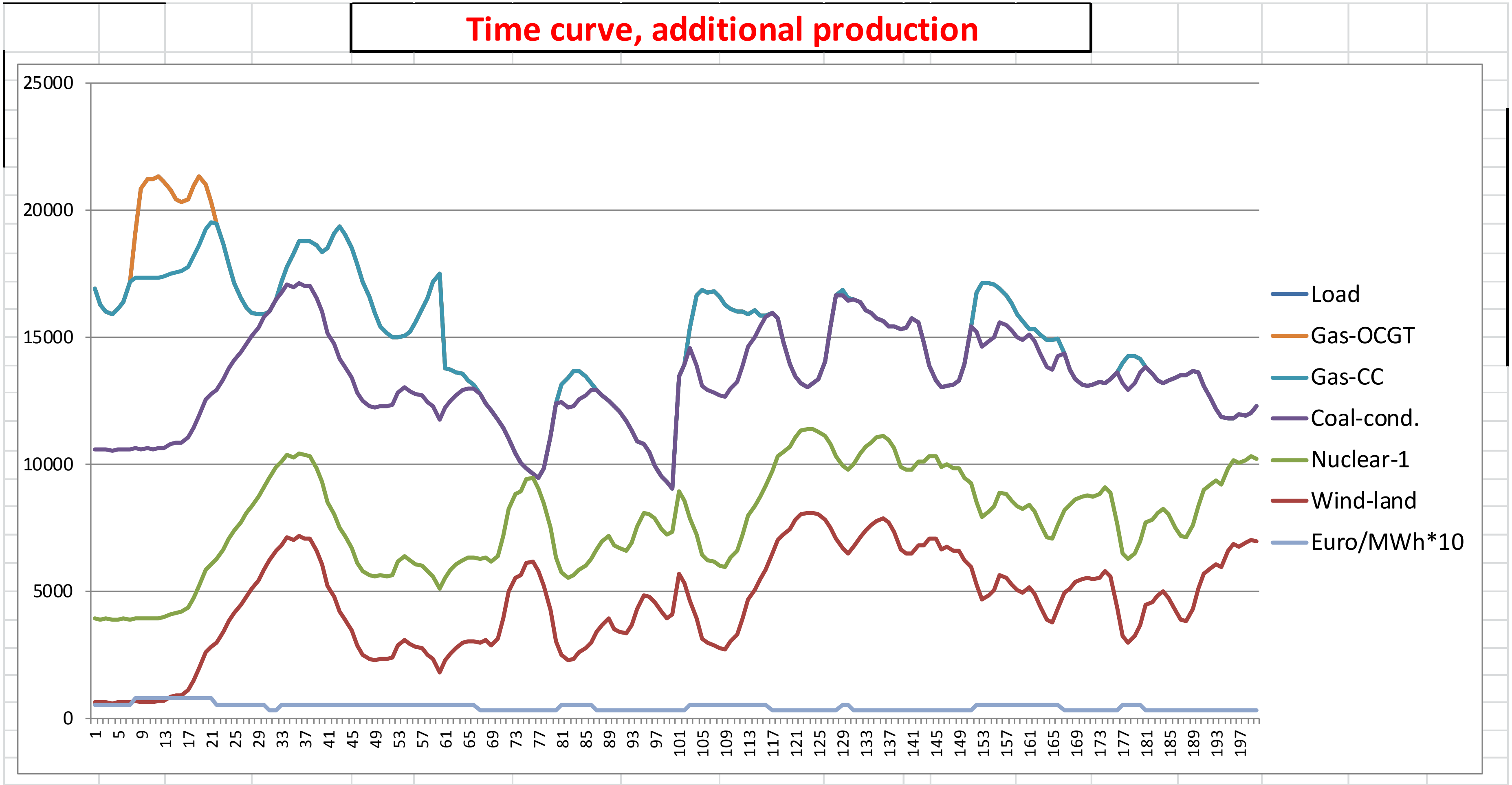
Price: -62%

Profit: From OK to BAD

LOLP: -100%

Min cost + No CO2 increase + LOLP=0, Wind>30%

Insert this as constraints in optimization ➔



Min cost + No CO2 increase + LOLP=0, Wind>30%

Insert this as constraints in optimization ➔

Mean price:	46,1	€ / MWh		Total cost	Profit	CO2	Utilization time
Source:	MW	MWh	MWh [%]	kEuro	kEuro/MWh	tons	hours
Wind-land	14355	905275	30,1%	50701	-14,3	0	200
Nuclear-1	3268	653635	21,7%	34564	-6,8	0	200
Gas-OCGT	4015	40386	1,3%	7273	-101,4	20427	14
Gas-CC	6730	313579	10,4%	28505	-27,4	109385	105
Coal-cond.	6681	1095547	36,4%	59559	-4,9	777648	200
Curtailments	0	0	0,0%	0	-	0	0
Total:	35048	3008422	100,0%	180602	-154,8	907460	

Comparison: Base Case – New (wind>30%)

Base case

Mean price:	123,4	€ / MWh		Total cost	Profit	CO2	Utilization time
Source:	MW	MWh	MWh [%]	kEuro	kEuro/MWh	tons	hours
Wind-land	8000	504498	16,8%	28255	-0,2	0	200
Nuclear-1	3000	600000	19,9%	31728	70,5	0	200
Gas-OCGT	2000	24684	0,8%	3983	1231,0	12485	14
Gas-CC	5000	183473	6,1%	18360	407,0	64000	76
Coal-cond.	10000	1691135	56,2%	90733	86,6	1200412	200
Curtailments	956	4631	0,2%	9750	0,0	0	8
Total:	28956	3008421	100,0%	182808	1794,8	1276898	

Min cost, same CO2, wind>30%

Mean price:	46,1	€ / MWh		Total cost	Profit	CO2	Utilization time
Source:	MW	MWh	MWh [%]	kEuro	kEuro/MWh	tons	hours
Wind-land	14355	905275	30,1%	50701	-14,3	0	200
Nuclear-1	3268	653635	21,7%	34564	-6,8	0	200
Gas-OCGT	4015	40386	1,3%	7273	-101,4	20427	14
Gas-CC	6730	313579	10,4%	28505	-27,4	109385	105
Coal-cond.	6681	1095547	36,4%	59559	-4,9	777648	200
Curtailments	0	0	0,0%	0	-	0	0
Total:	35048	3008422	100,0%	180602	-154,8	907460	

Cost decrease: -1,2%

CO2: -29%

Price: -62%

Profit: From OK to BAD

LOLP: -100%

Min cost + No CO_2 increase + LOLP=0, Wind>30%, a margin on OCGT (102 Euro/MWh)

Only increase this margin, until there is a profit in OCGT:

➔ All power plants profitable, except wind power.

Mean price:	53,2	€ / MWh		Total cost	Profit	CO2	Utilization time
Source:	MW	MWh	MWh [%]	kEuro	kEuro/MWh	tons	hours
Wind-land	14355	905275	30,1%	50701	-12,4	0	200
Nuclear-1	3268	653635	21,7%	34564	0,3	0	200
Gas-OCGT	4015	40386	1,3%	7273	0,6	20427	14
Gas-CC	6730	313579	10,4%	28505	3,2	109385	105
Coal-cond.	6681	1095547	36,4%	59559	3,8	777648	200
Curtailments	0	0	0,0%	0	-	0	0
Total:	35048	3008422	100,0%	180602	-4,4	907460	

Comparison: With and without OCGT margin

Min cost, same CO2, wind>30%

Mean price:	46,1	€ / MWh		Total cost	Profit	CO2	Utilization time
Source:	MW	MWh	MWh [%]	kEuro	kEuro/MWh	tons	hours
Wind-land	14355	905275	30,1%	50701	-14,3	0	200
Nuclear-1	3268	653635	21,7%	34564	-6,8	0	200
Gas-OCGT	4015	40386	1,3%	7273	-101,4	20427	14
Gas-CC	6730	313579	10,4%	28505	-27,4	109385	105
Coal-cond.	6681	1095547	36,4%	59559	-4,9	777648	200
Curtailments	0	0	0,0%	0	-	0	0
Total:	35048	3008422	100,0%	180602	-154,8	907460	

Same as above + OCGT bidding margin

Mean price:	53,2	€ / MWh		Total cost	Profit	CO2	Utilization time
Source:	MW	MWh	MWh [%]	kEuro	kEuro/MWh	tons	hours
Wind-land	14355	905275	30,1%	50701	-12,4	0	200
Nuclear-1	3268	653635	21,7%	34564	0,3	0	200
Gas-OCGT	4015	40386	1,3%	7273	0,6	20427	14
Gas-CC	6730	313579	10,4%	28505	3,2	109385	105
Coal-cond.	6681	1095547	36,4%	59559	3,8	777648	200
Curtailments	0	0	0,0%	0	-	0	0
Total:	35048	3008422	100,0%	180602	-4,4	907460	

Same "cost":

Same CO2:

Price: +15%

Profit: From BAD to OK

Same LOLP