Sustainable Power Generation MJ2405

Energy Economics
and
Power Generation System Aspects

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Perspectives in economic evaluations

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Business (private) focus

Time frame: Project life

Costs:
All costs paid by project owner. Includes taxes.

Environmental costs assumed equal to environmental fees.

Revenues:
All revenues to be earned by project owner. Includes subsidies.

Problem:
- Cost projections

Community (public) focus

Time frame: Often beyond project life

Costs:
All costs paid by community as a result of project plan. Includes project owner.

Taxes paid by community members are not direct costs.

Often includes environmental costs = actual cost of damage caused.

Revenues:
All revenues earned by community. Includes also non-monetary benefits.

Additional problems:
- Time frame
- How to value non-monetary benefits and costs of environmental damage

Energy Production Cost (Levelized Cost of Electricity = LCOE)

Per $/kWh of electricity output

$$LCOE = \frac{\xi}{\eta} + \frac{\beta C_o}{kWh} + \frac{O\&M}{kWh}$$

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η – overall plant efficiency
ξ – unit cost of fuel ($ / kWh input)
kWh – plant annual utilization (operation hours)
β – capital charge factor (cost of money)
C_o – capital cost of plant ($)
O&M – annual cost of operation and maintenance ($)

ENERGY ECONOMICS - OVERVIEW

The challenge:

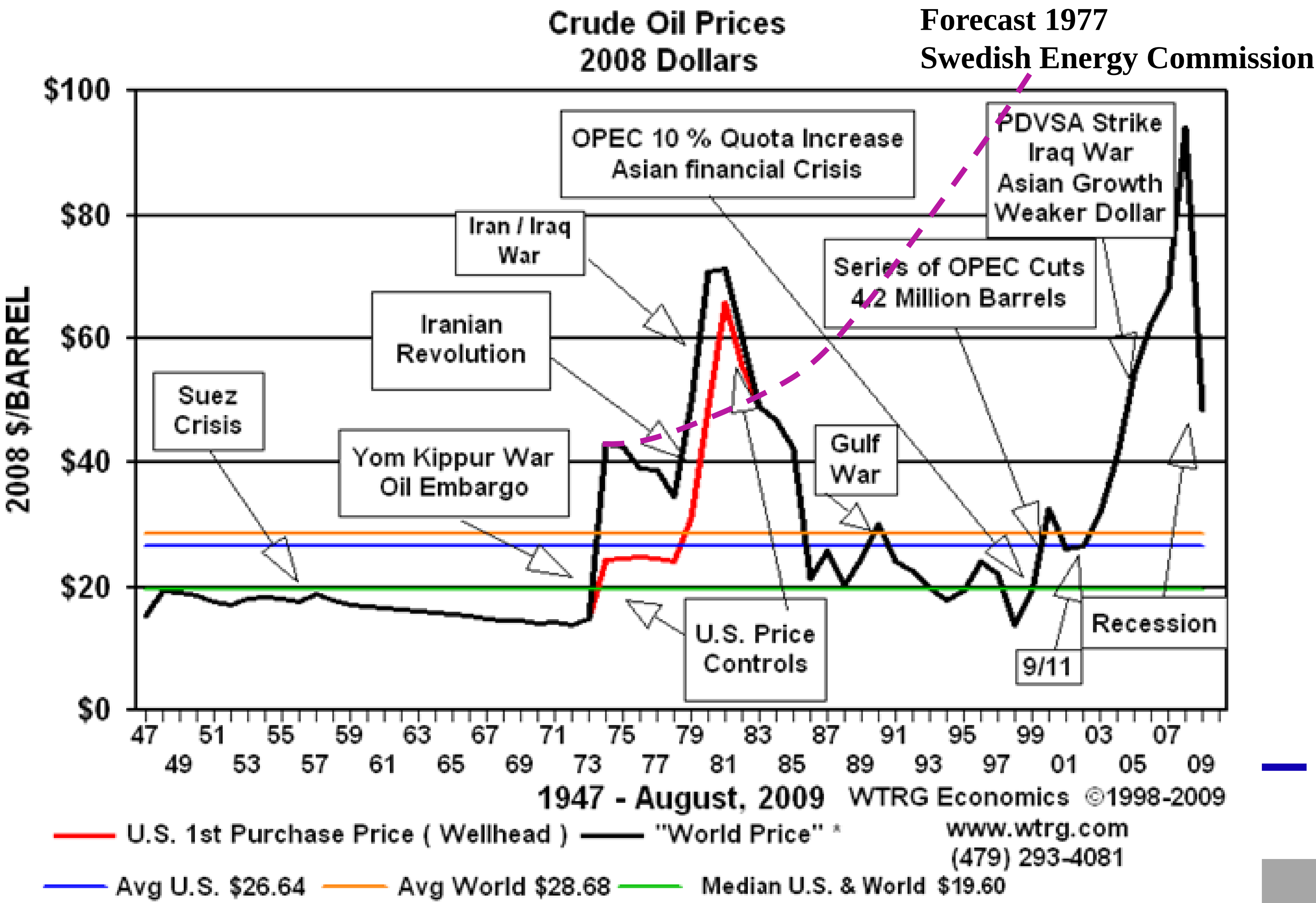
To find the technical solution that will provide the amounts of heat and/or electricity needed <u>at the least cost</u> and with consideration to various restrictions imposed by laws and environmental regulations.

Economic evaluation must often cover a long period of time - usually 10 years and often up to 25 - 40 years.

This leads to <u>uncertainties</u>:

- **Future inflation rate**
- **Future fuel prices**
- **Future taxes**
- **More strict environmental laws**
- **Economic lifetime, maintenance/repair costs and readiness for or reliability of new technologies**

UNCERTAINTIES ABOUT FUEL COSTS



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UNCERTAINTY ABOUT ENVIRONMENTAL COSTS

Emission rights for CO_2

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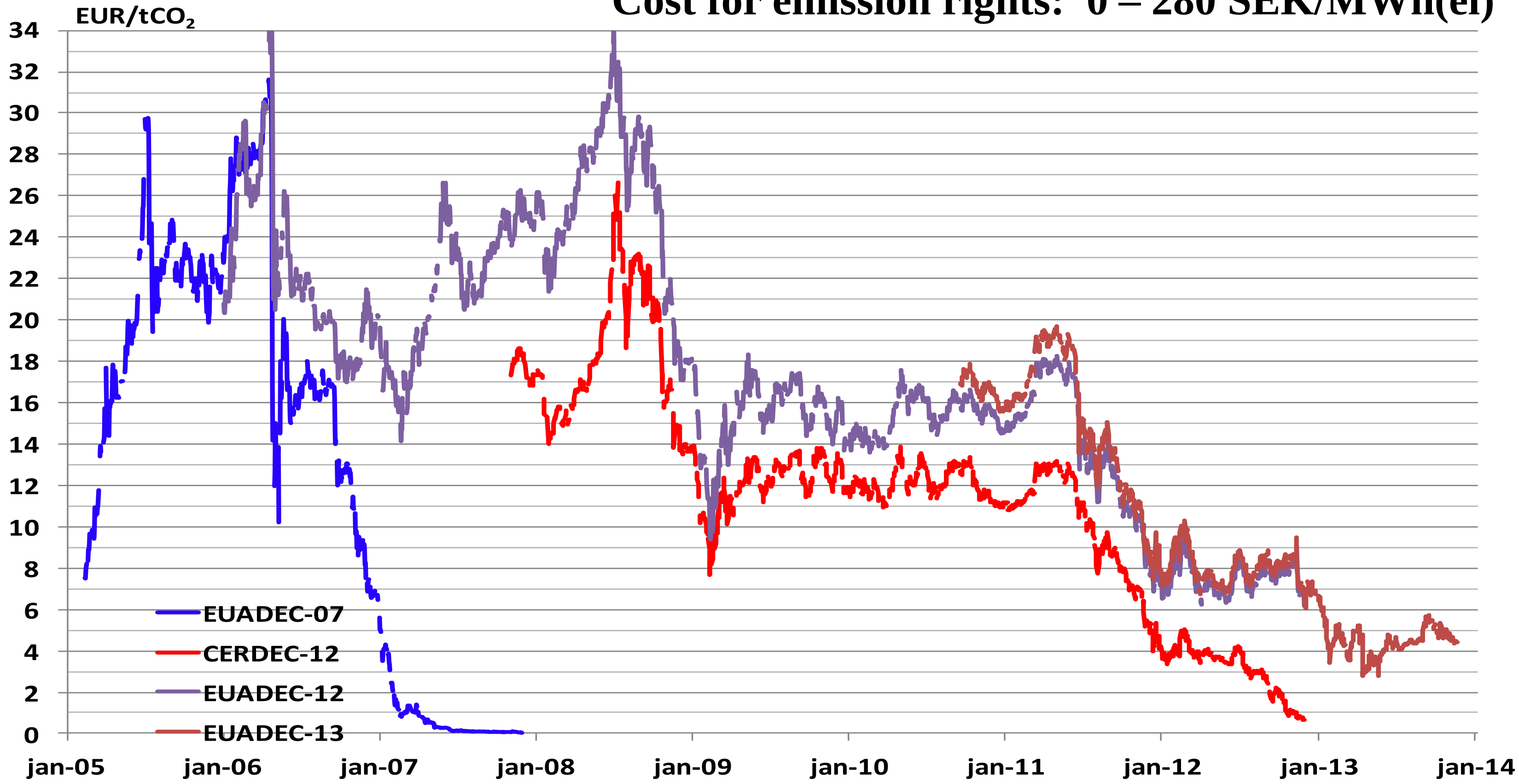
CO_2 emission from steam plant burning coal 330 kg/MWh(f) gives about 750 -900 kgCO_2 /MWh(el).
Cost for emission rights: 0 – 280 SEK/MWh(el)



Source: Nasdaq/OMX Commodities; Svensk Energi

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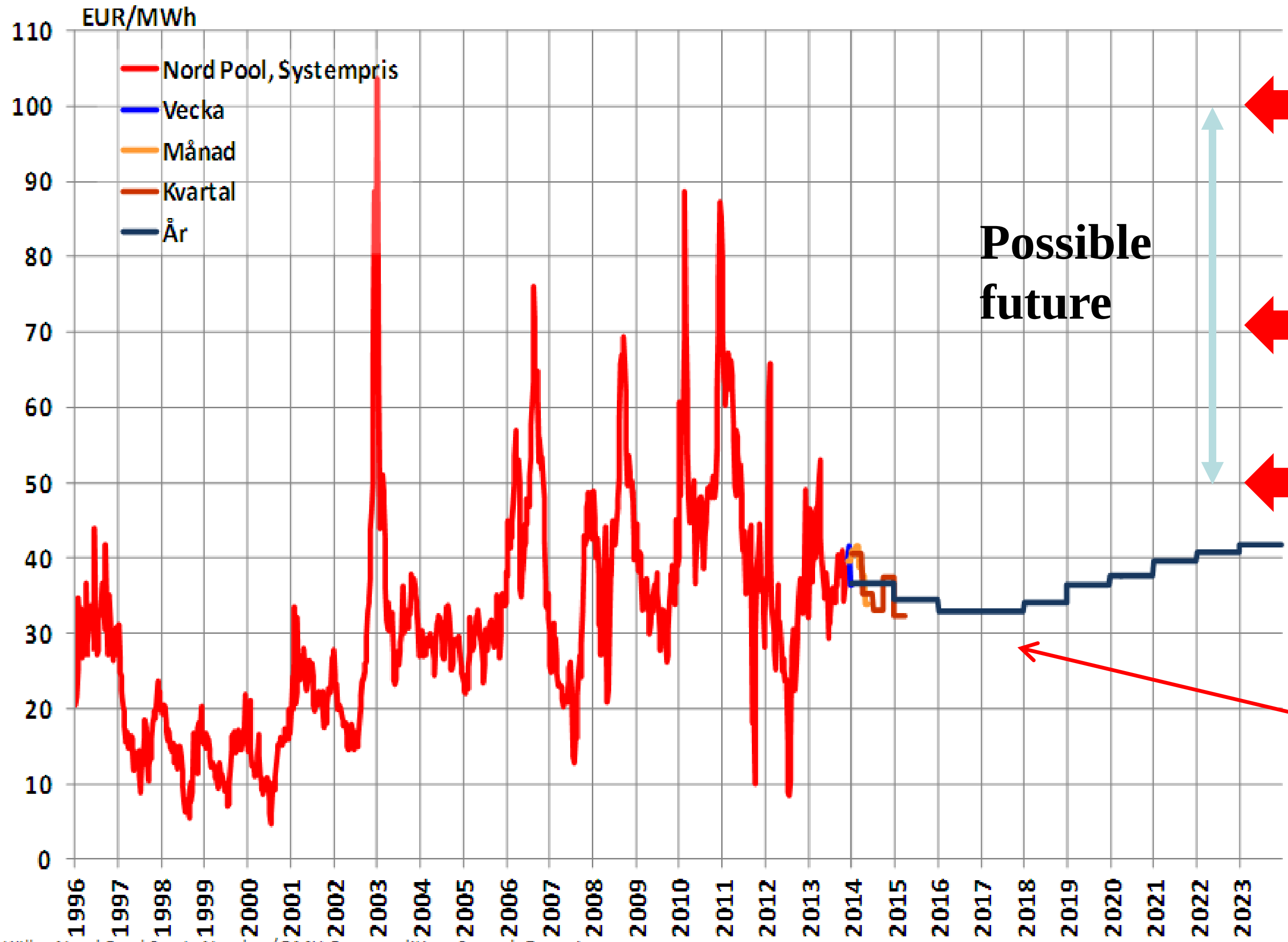
UNCERTAINTY ABOUT ELECTRICITY PRICE



Källa: Nord Pool Spot, Nasdaq/OMX Commodities, Svensk Energi

SEK/MWh

950 Price guarantee new nuclear power in England

675 Offshore wind power Elforsk report 11:26

500 New coal or bio power Elforsk report 11:26

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Reasons for low price:
- Low prices for coal and emission rights
- Low demand

UNCERTAINTY ABOUT ENVIRONMENTAL SUBSIDIES

Price for Swedish electricity certificates

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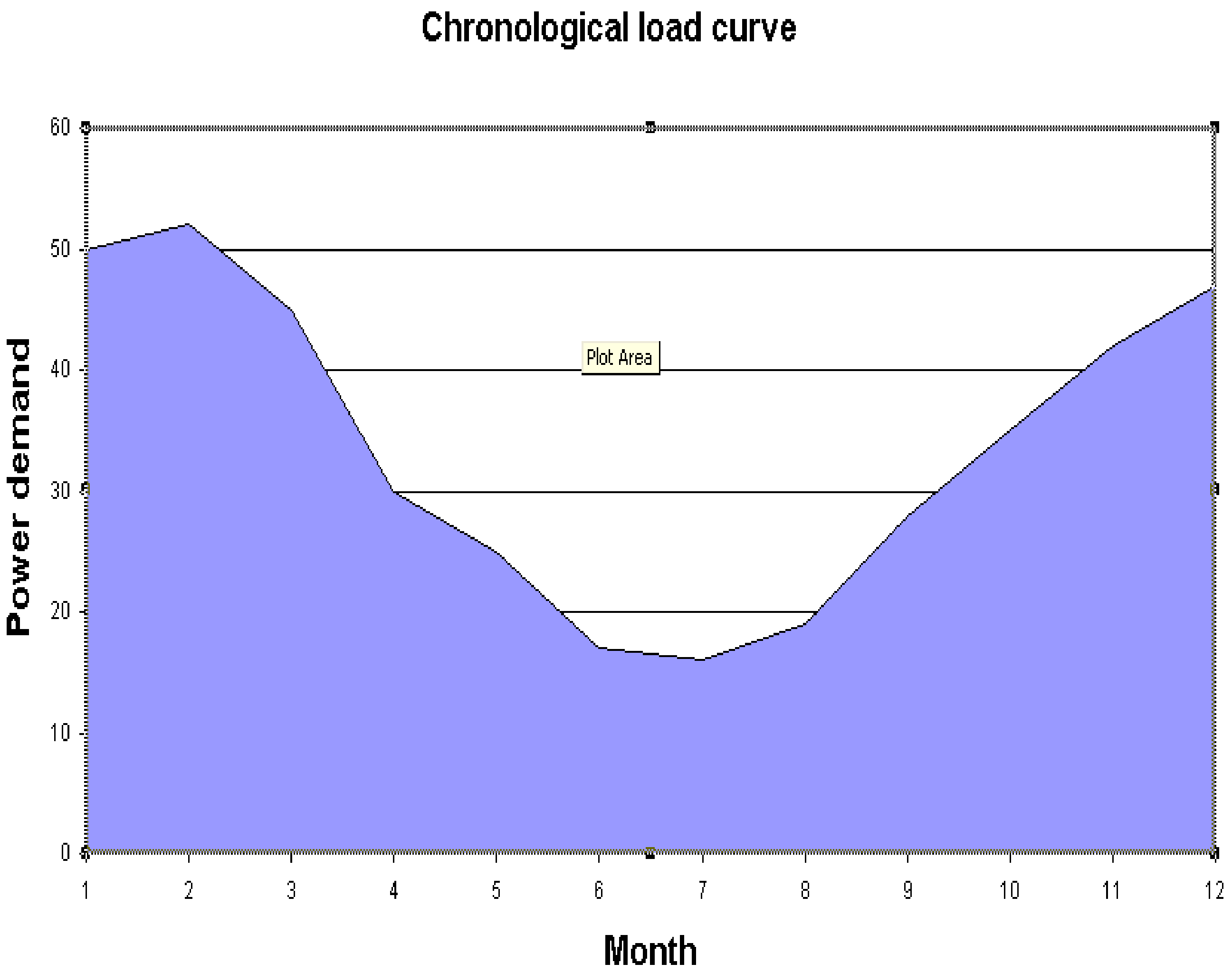
In Sweden, all companies selling electricity need to buy ”electricity certificates” for a fraction of the sold amount of electric energy (now about 18%), to support renewable energy sources.
Those generating power with renewable sources receive 1 certificate per MWh el sold on the market.

Other countries (like Germany) use fixed feed-in tariffs. Leads to less uncertainty.

LOAD INFORMATION NEEDED FOR OPTIMIZING THE CAPACITY AND TYPE OF ENERGY SUPPLY PLANTS

Peak load, total annual energy and load variation must be known.



The power demand will vary with time.

Energy plant must serve energy demand and peak power demand.

Energy = ∫ Power dt

Q = ∫ P dt

Define utilisation time τ $\tau = \dfrac{Q}{P_{max}}$

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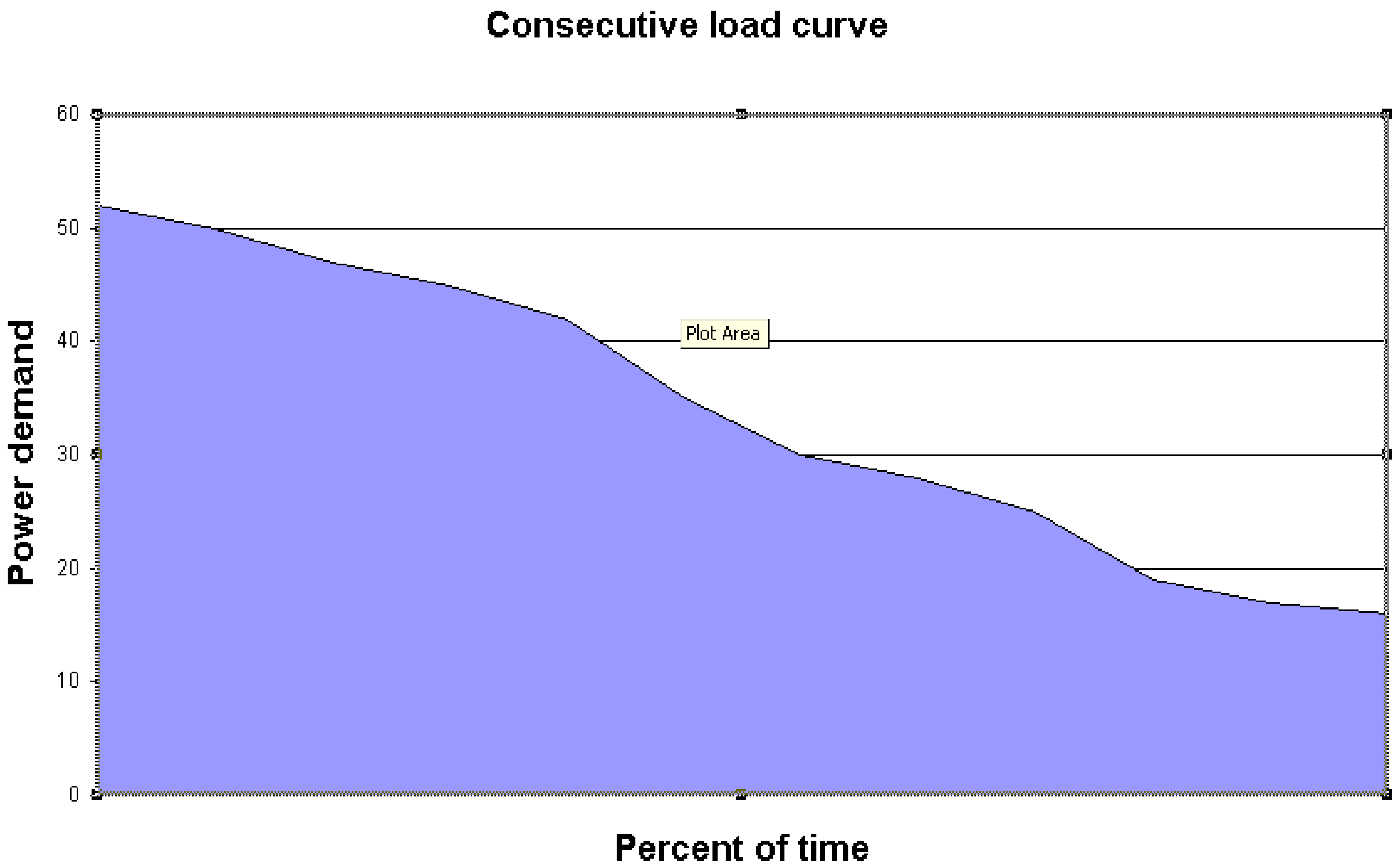
ALTERNATIVE PRESENTATION OF THE LOAD VARIATION



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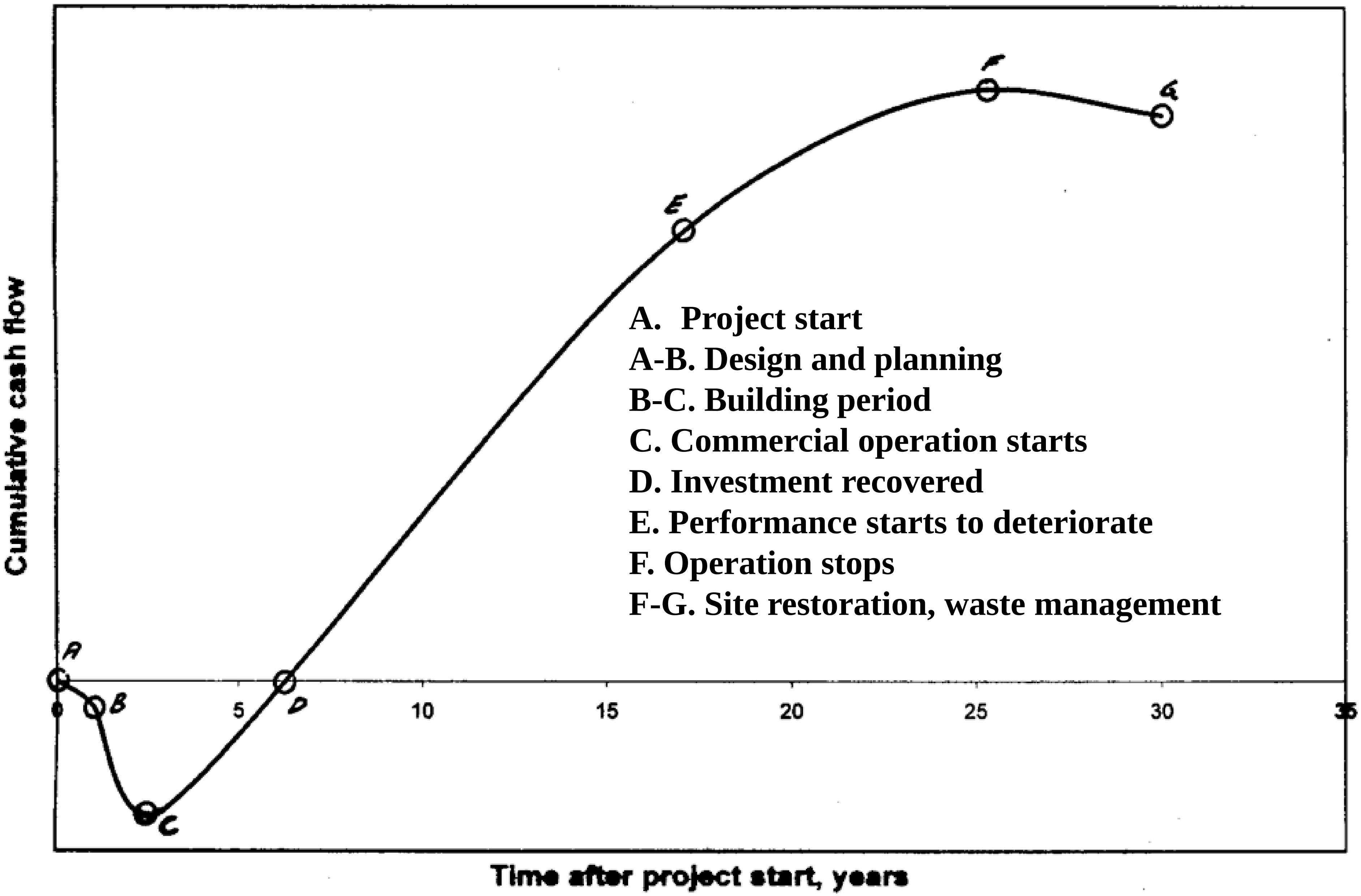
CASH FLOW IN AN ENERGY PROJECT



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DIFFERENT TYPES OF COSTS

Initial investment:

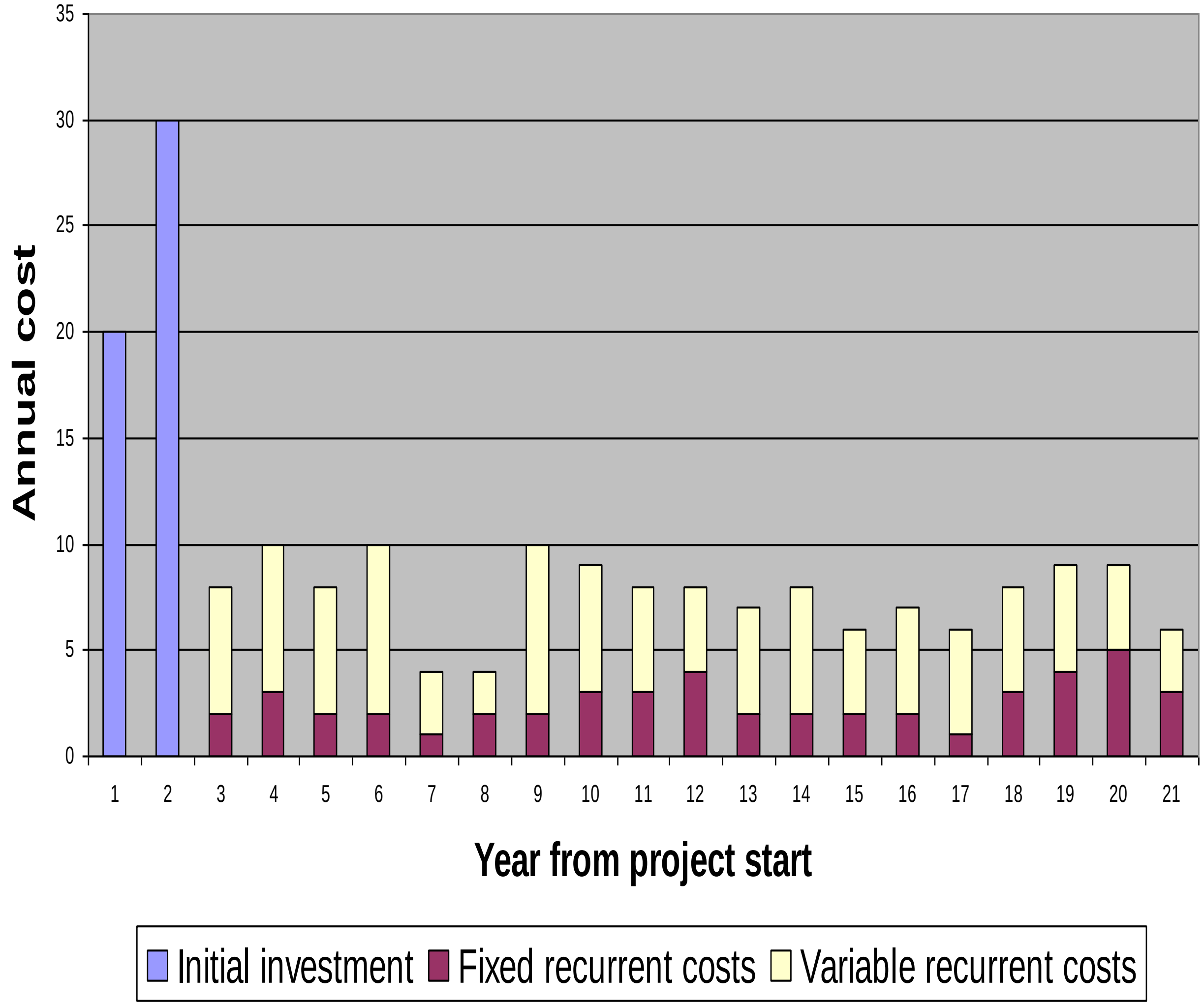
- **All expenditure before commercial operation**

Fixed recurrent costs

- **Expenditure during operating period that are independent of the plant output**

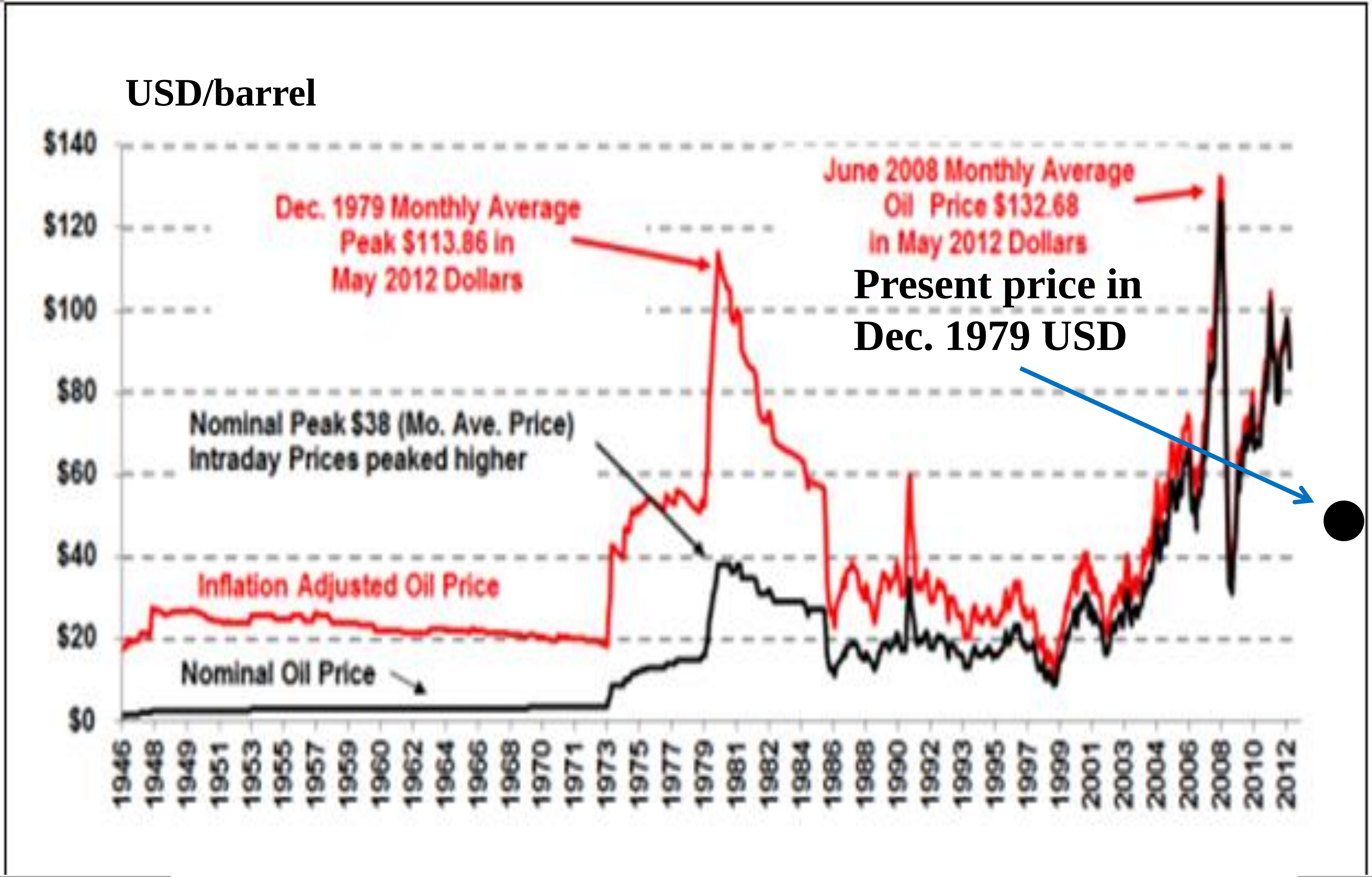
Variable recurrent costs

- **Expenditure during operating period that depend on the plant output**



Effects of inflation can be important!

One 2012 USD is equivalent to 38/113,86 = 0,33 Dec.1979 USD



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ADJUSTMENT OF THE INTEREST RATE FOR INFLATION

Nominal interest rate (actually paid) i_n
Inflation rate f
"Real" interest rate i_r

The value C_1 after 1 year of a cost C_0 without inflation:

$$C_1 = (1+i_n) \cdot C_0$$

The value C_1 after 1 year of a cost C_0 with inflation:

$$C_1 = (1+i_n) \cdot (1-f) \cdot C_0 = [1+(i_n - f) - i_n \cdot f] \cdot C_0 \approx [1+(i_n - f)] \cdot C_0$$

Approximately

$$i_r = i_n - f$$

Factors that determine the nominal interest rate used for evaluations:
- Bank interest rate
- Desired profit
- Risk assessment
- Competing investments

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COSTS ASSOCIATED WITH THE INITIAL INVESTMENT

The investment is the cost paid in the beginning of the project. A practical approach if the costs of different options are compared on basis of net present values.
Another approach:
Investment as just an exchange from money value to equipment value. Then the investment is not really a cost.

The cost appears when the value of the equipment deteriorates with time and use.
The capital shall be paid back by annual "instalments" or "amortization".

Depreciation cost can be calculated in different ways:
- **constant amount for each year of the plant lifetime,**
- **constant fraction of the remaining value,**
- **or by some other formula (like constant amounts each year "annuities").**

There is also a cost associated with borrowing the capital – from external source or from internal funds. (Interest on loan or Internal rate of return)

The sum of amortization/depreciation and the interest is "the capital cost".

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Amortisation = pay back of borrowed money Depreciation = loss of equipment value (Ideally they should be the same)

Capital costs as constant annuities

Constant fraction, a, of investment, I, paid each year.

How can "a" be calculated?

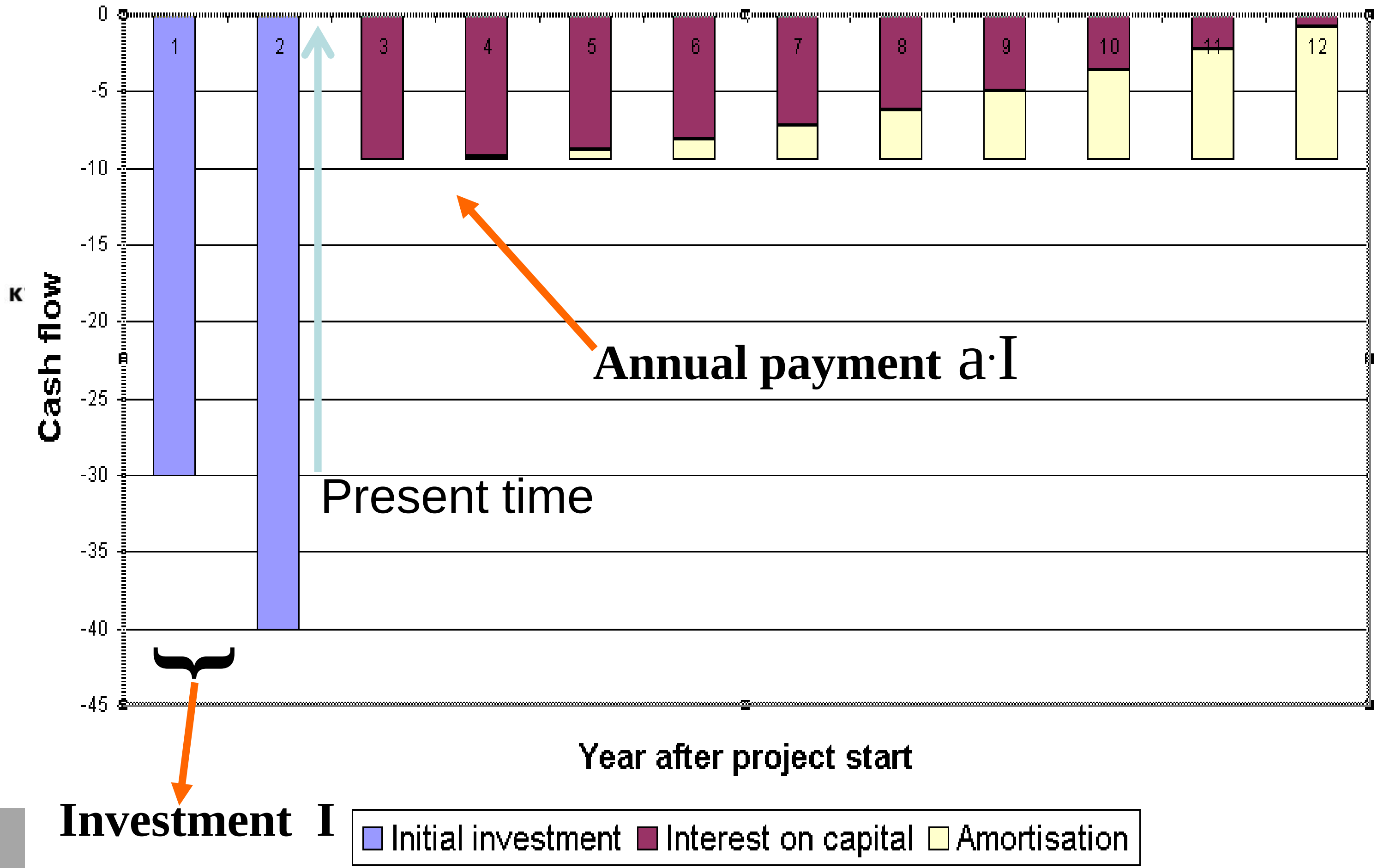
Net present value

$$NPV = \sum_z \frac{a * I}{(1+i)^z}$$

$$NPV = I = \sum_n \frac{\Delta I}{(1+i)^n}$$

z project life years

n project implementation years



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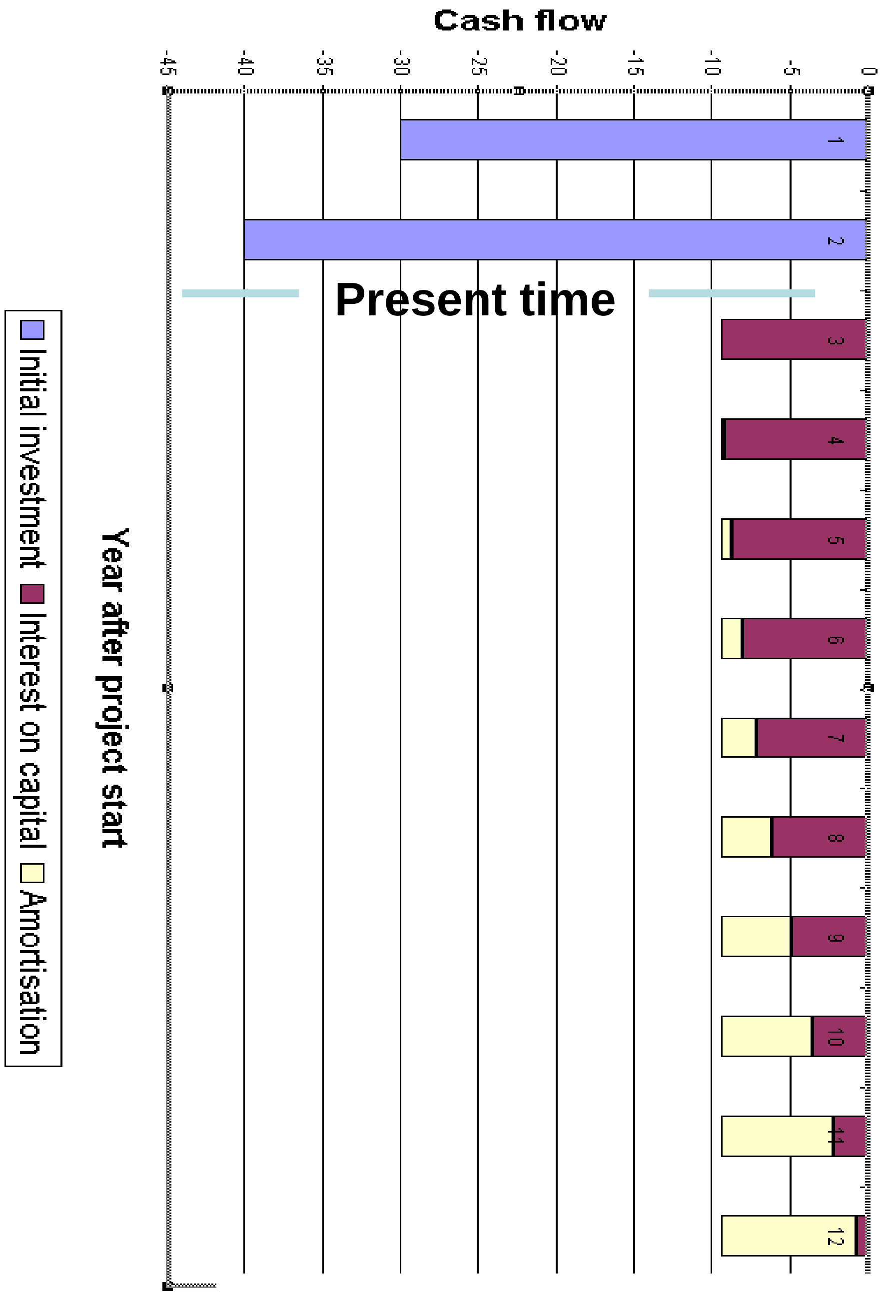

Interest during construction time

$$\} = \text{Present value } I = I_1 + I_2 + \underbrace{I_1 * i^2 + I_2 * i}_{}$$

Payment	Present value
a*I	$a*I/(1+i)$
a*I	$a*I/(1+i)^2$
a*I	$a*I/(1+i)^3$
a*I	$a*I/(1+i)^4$
a*I	$a*I/(1+i)^5$
a*I	$a*I/(1+i)^6$
a*I	$a*I/(1+7)^7$
a*I	$a*I/(1+i)^8$
a*I	$a*I/(1+i)^9$
a*I	$a*I/(1+i)^{10}$

$$Net\ \ present\ value = (\,first\ term) * \frac{1-q^z}{1-q} = \frac{a}{(1+i)} * I * \frac{1-1/(1+i)^{10}}{1-1/(1+i)} = I \quad if \ \ a = \frac{i*(1+i)^{10}}{(1+i)^{10}-1}$$

FIXED RECURRENT COSTS

Fixed recurrent costs must be paid in all cases, regardless if the plant is operated or not.

Examples:

- **Recovery of the capital costs**

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Certain operation and maintenance costs (Fixed O&M costs)

- **Insurance**
- **Salaries to staff**
- **Some maintenance independent of plant operating time**
- **Some taxes**

Annual fixed recurrent O&M costs are often expressed as a fraction of the initial investment, I.

$$C_{rf} = c \cdot I$$

"c" often in range 1 – 3% , but depends on the technology

TYPICAL POWER PLANT CAPITAL COSTS

- The main maschinery equipment, such as the boiler, turbine, generator, etc, often constitutes less than half of the total
- Remaining parts are, for example:
  - Fuel handling and storage, ash handling, electrical switchyard, flue gas treatment, water treatment, etc.
  - Auxilliary equipment
  - Foundations, buildings, ground lease, roads, cooling water
  - Instrumentation and Control, Lighting, Ventilation…

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- Investment costs are typically (2015) in **€/kW** installed capacity:

• New large GT Combined Cycle	700 - 800
• Conventional large coal-fired steam	1500
• Biomass CHP	3000
• Gas Turbine open cycle or ICE engine	300 - 600
• Nuclear ???	6000 - 8000
• Wind (onshore/offshore)	1000 / 3000

Capital cost as a function of capacity utilization factor

Capital costs for a unit expressed in €/MWh electrical output

The example is calculated for 10 % interest rate, 25 years

Operating hours →	1500	3000	5000	7000	7500	8000
Specific investment €/kWe						
100	**6**	**3**	**2**	**1**	**1**	**1**
500	**30**	**15**	**9**	**6**	**6**	**6**
1000	**60**	**30**	**18**	**13**	**12**	**11**
1500	**90**	**45**	**27**	**19**	**18**	**17**
2000	**120**	**60**	**36**	**26**	**24**	**23**
3500	**210**	**105**	**63**	**45**	**42**	**39**

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VARIABLE RECURRENT COSTS

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Variable re-current costs depend on the operation of the plant

Examples:

- Fuel costs (b SEK/MWh$_{fuel}$)

- Lubricants and other consumables
- Some maintenance costs (Ψ SEK/MWh$_{fuel}$)
- Some taxes
- Waste handling costs

Annual variable re-current cost will be:

$$C_{rv} = \frac{b + \Psi}{\eta} \cdot P_{rated} \cdot \tau$$

P$_{rated}$ is the rated output of the plant
η is the average efficiency

FUEL COSTS

- Fuel costs are subject to large variations. Proper forecasts are always vital for project survival.
  - **Natural Gas price** is subject to new pricing mechanisms. Roughly around 28 EUR/MWh in central Europe, almost stable.
  - **Coal prices** (bituminous coal) are relatively stable around 40-80 USD/ton, or 4 - 8 EUR/MWh.
  - **Lignite price** is 13 EUR/ton or 5 EUR/MWh.
  - **Biomass (wood) price** is stable at ~20 EUR/MWh for fresh woodchip and 30 EUR/MWh for dried wood pellets.
- All fuel costs are more or less dependent on and vary with the international crude oil prices

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Typical O&M costs [€/MWh el]

Can vary much

- Onshore wind has half the O&M cost of offshore wind
  17 €/MWh vs. 30 €/MWh

Power Rating [MW]		Thermal power plants for solid fuels		Gas fired
	Wind	Complicated units	Simple units	Combined Cycle
1 - 3	15 - 30			
30		16	10	
100		13	8	5
500		7	6	4
1000		5	3,5	

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ANNUAL COSTS

***Annual cost breakdown*:**

Fixed costs (independent of operation)

- **Amortization / Depreciation**
- **Interest on invested capital**
- **Salaries, insurance, some maintenance, some taxes**

Variable costs (proportional to energy output or time of operation)

- **Fuel**
- **Some maintenance, repairs, some taxes**

$$C_{annual} = C_{fixed} + C_{var} = (F + D \cdot \tau)\, P_{rated}$$

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Costs' overview for different power plants

The numbers below stem from the tables in the slides above. Costs are given in €/MWh

	Biomass small	Biomass large	Bio CHP	Coal	Gas	Lignite	Nuke	Wind
Fuel	60	53	25	18	51	11	10	0
O&M	16	13	17	5	4	5	15	17
Capital	36	30	30	18	9	18	42	55
Generation cost	112	96	72	41	64	34	67	72
Consumables	3	3	3	5	1,7	5	4	1
CO_2 cost				16	8	17		0
Total generation cost	115	99	75	62	74	56	71	73
Marginal cost	75	65	40	41	63	35	22	15

EXAMPLES OF TYPICAL COST DATA

Cost level 2010-2011; KPI about 306

Process	Gas Turbine Natural gas	Combi Cycle Natural gas	Steam Condensing Coal	Nuclear Uranium
Capacity MW	20	420	740	1600
Specific investment SEK/kW	3600	7000	14500	28000
Fuel price SEK/MWh(f)	320	250	90	14,4
Efficiency %	30	58	46	36
Fixed O&M % of investment	1,3	2,9	2,0	Included in variable O&M cost
Other variable O&M costs SEK/MWh(f)	10	10	7	36

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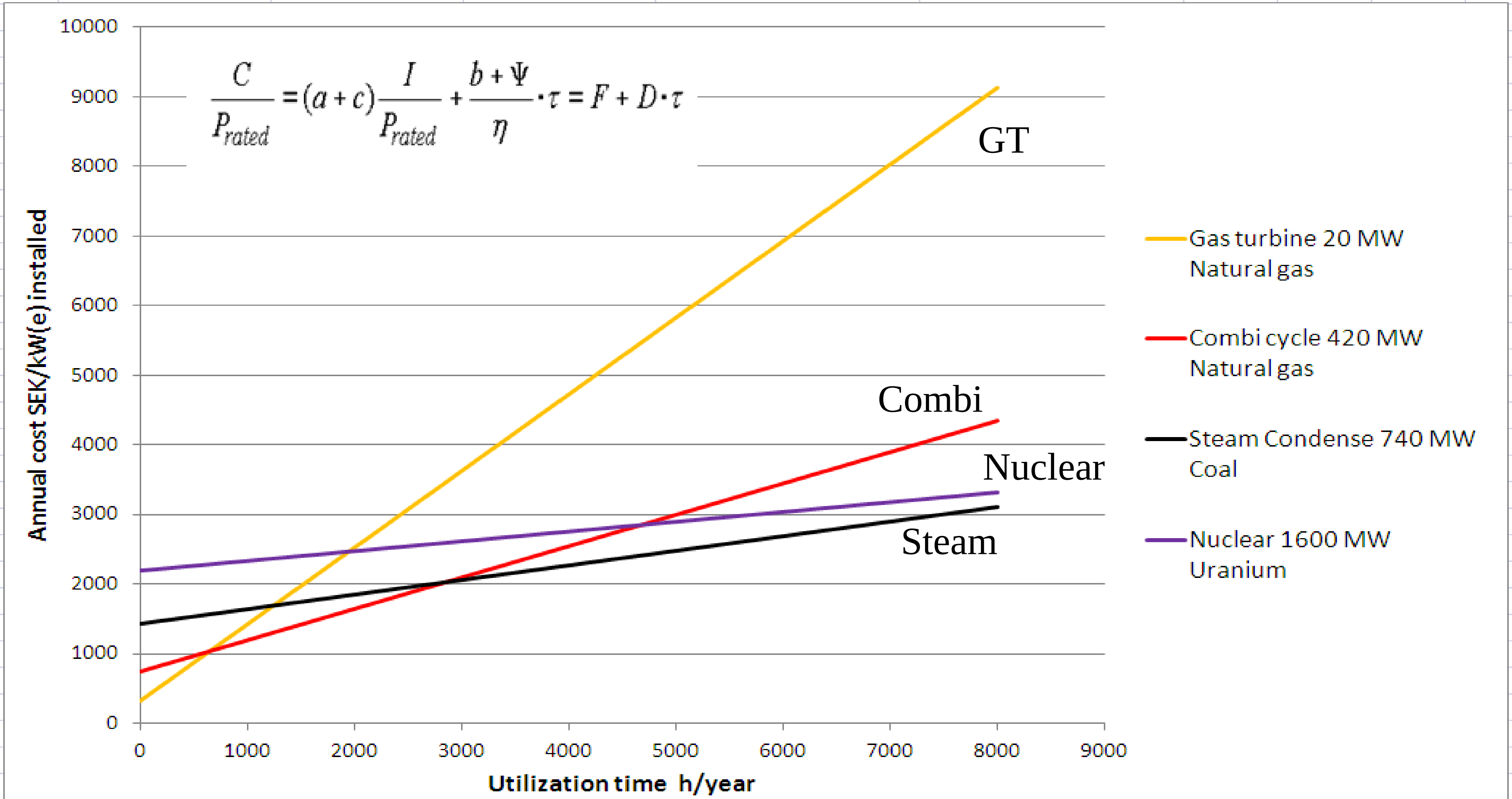
Source: Elforsk report 11:26, except for gas turbines where data obtained from suppliers
KPI is Swedish Consumer Price Index

COMPARISON OF ANNUAL COSTS

Calculated for interest rate 6% and 25 years economic life
No environmental penalties



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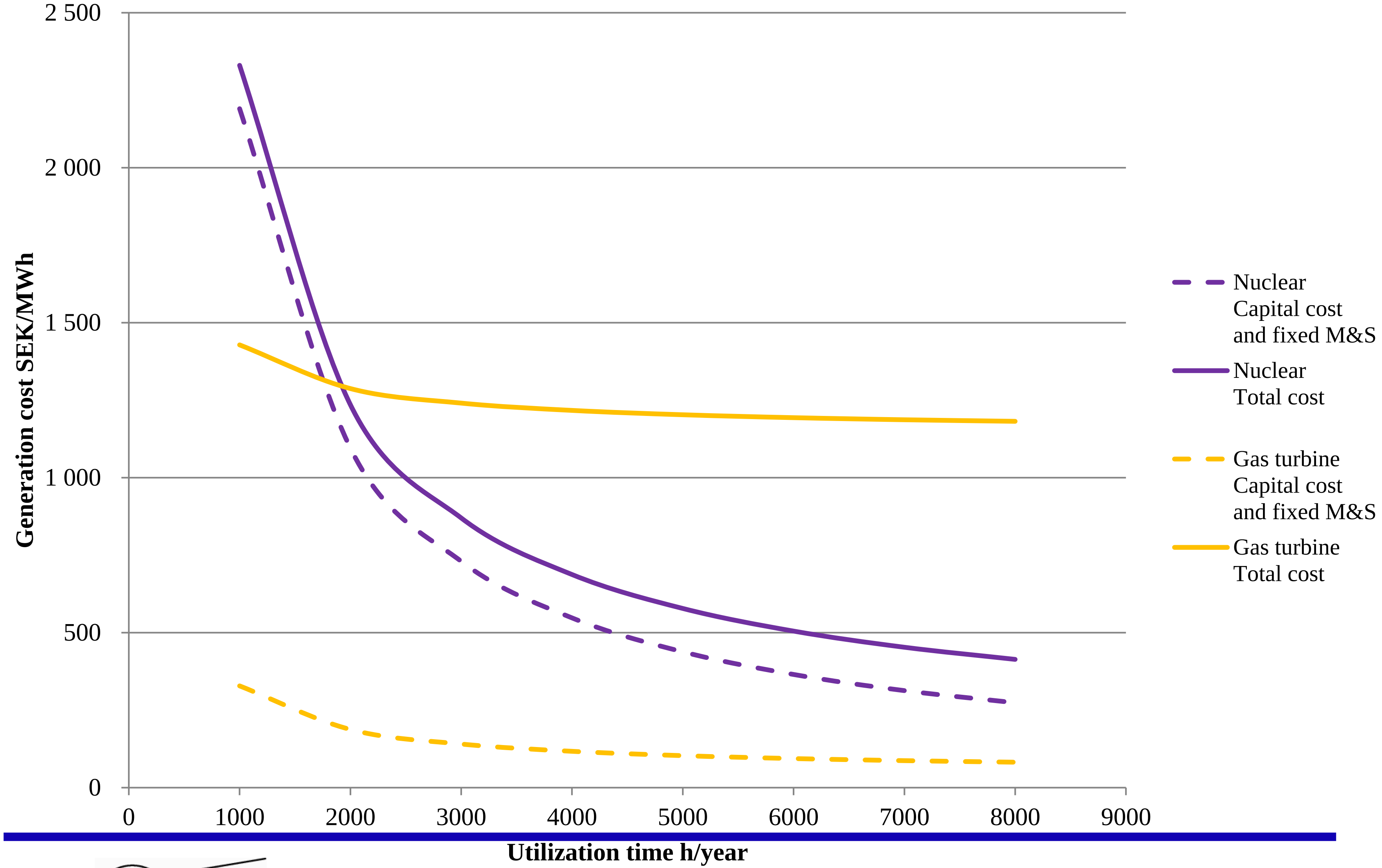
Contribution of fixed and variable costs to the total cost of electricity generation



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COMPARISON OF ANNUAL COSTS, if
200 SEK/ton CO_2 Emission Right Cost, ERC
144 SEK/MW(th) annually for nuclear plant, thermal tax

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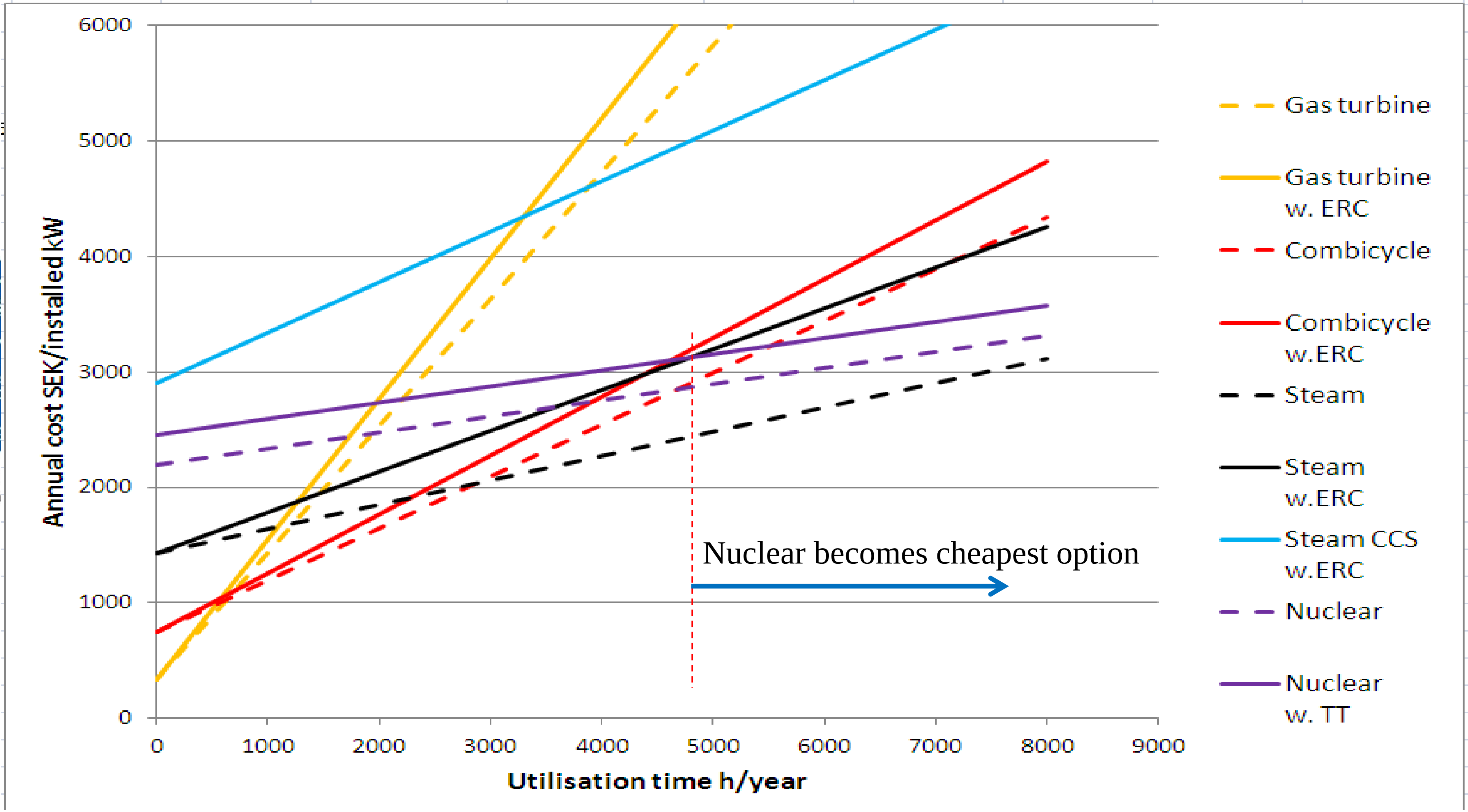
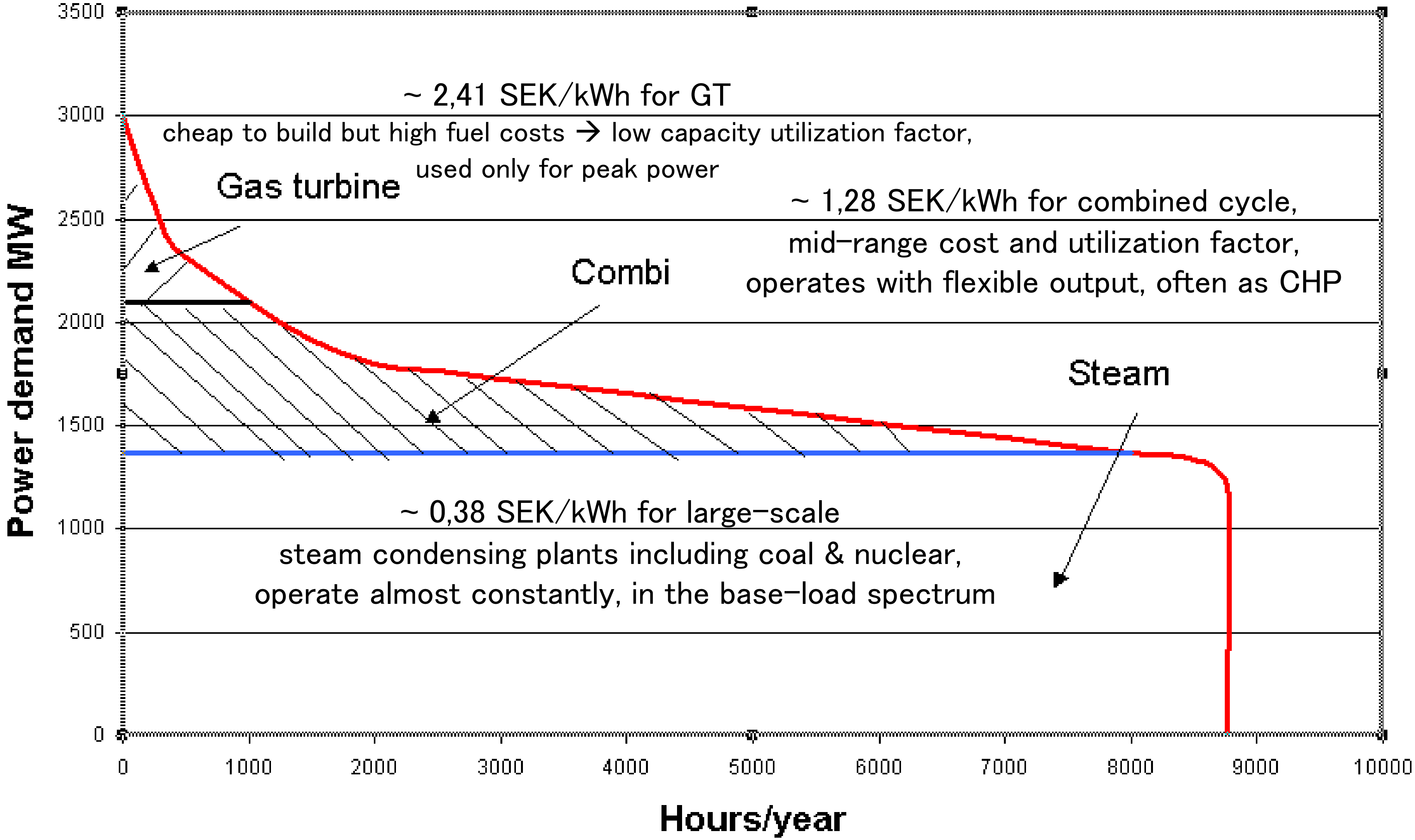


ERC at 200 SEK/tonCO2 makes nuclear very interesting.
Break-even at about 85 SEK/ton. ERC varies between 7 - 30 EUR/tonCO2

LOAD SHARING and CAPACITY FACTOR

Optimum mix of generation technologies → average generation cost 0,434 SEK/kWh



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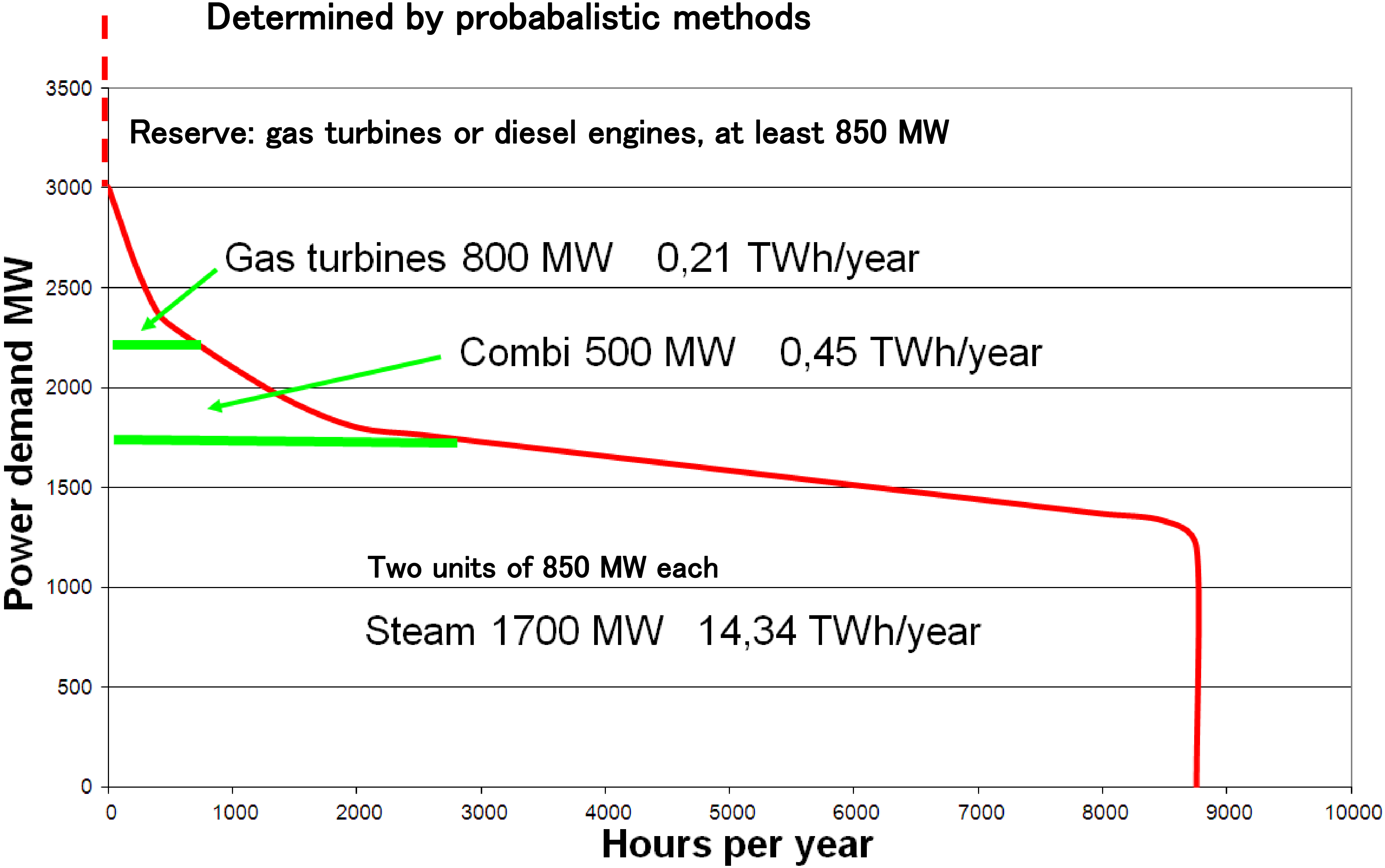
RESERVE CAPACITY

The installed generation capacity shall exceed the expected peak demand.
Size of reserve: At least the capacity of the largest plant in the system.
Determined by probabalistic methods



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How much is reasonable to charge for the electricity?

Some options:

a) All consumers pay the average cost for generating the electricity

b) The tariff is set as the <u>average</u> or <u>maximum</u> generation cost at the time when the electricity is used

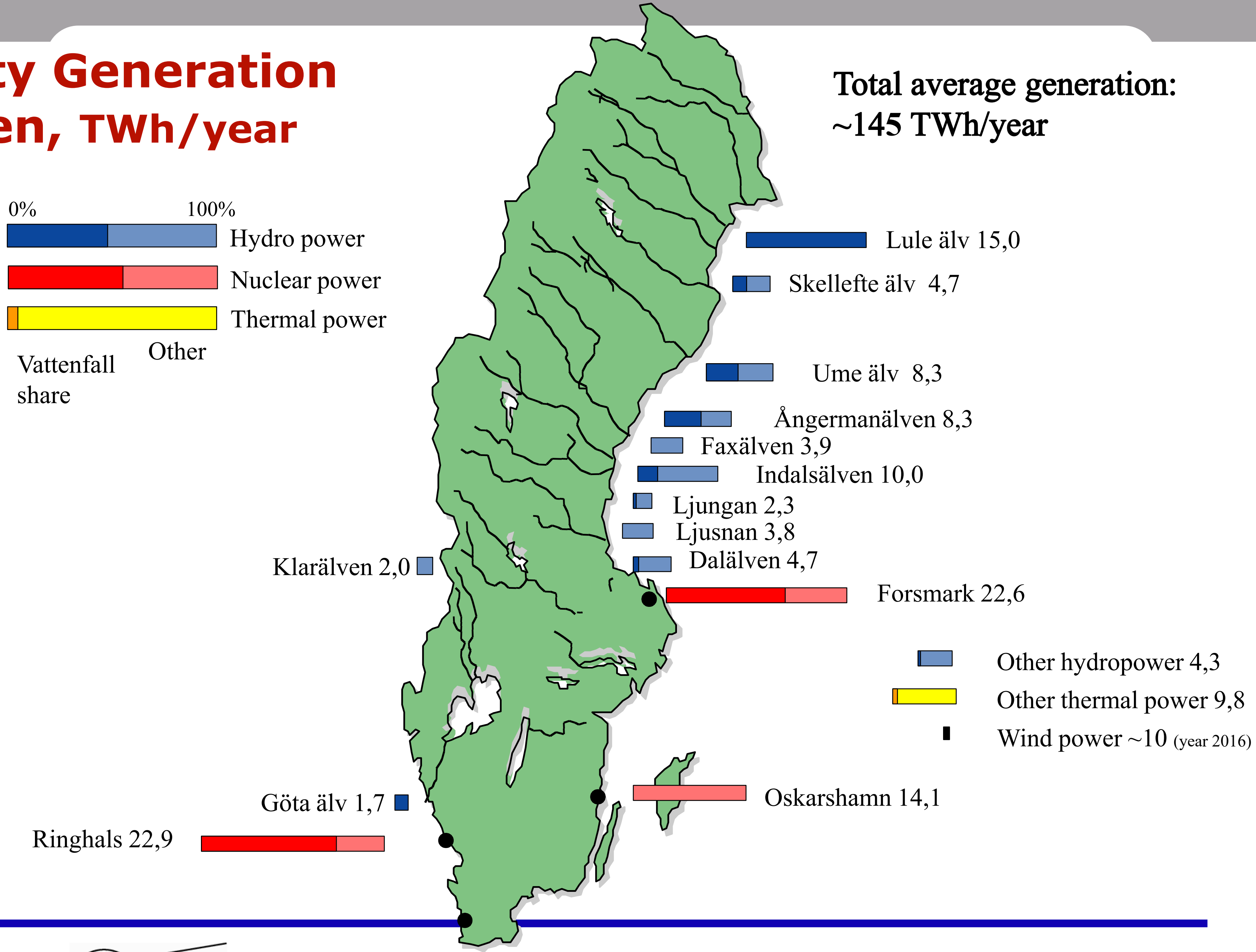
c) The tariff is set as the cost for supplying the additional load of each consumer considering the characteristics of the load. (The new load curve will change the operation of existing plants and may require more capacity)

d) The tariff is set according to the estimated paying power of the different consumer groups

Criteria:

- Costs must be recovered (option d may need government subsidies)
- Tariff shall encourage energy efficiency (options b and c)
- Tariff must be socially acceptable (option d)

Electricity Generation in Sweden, TWh/year



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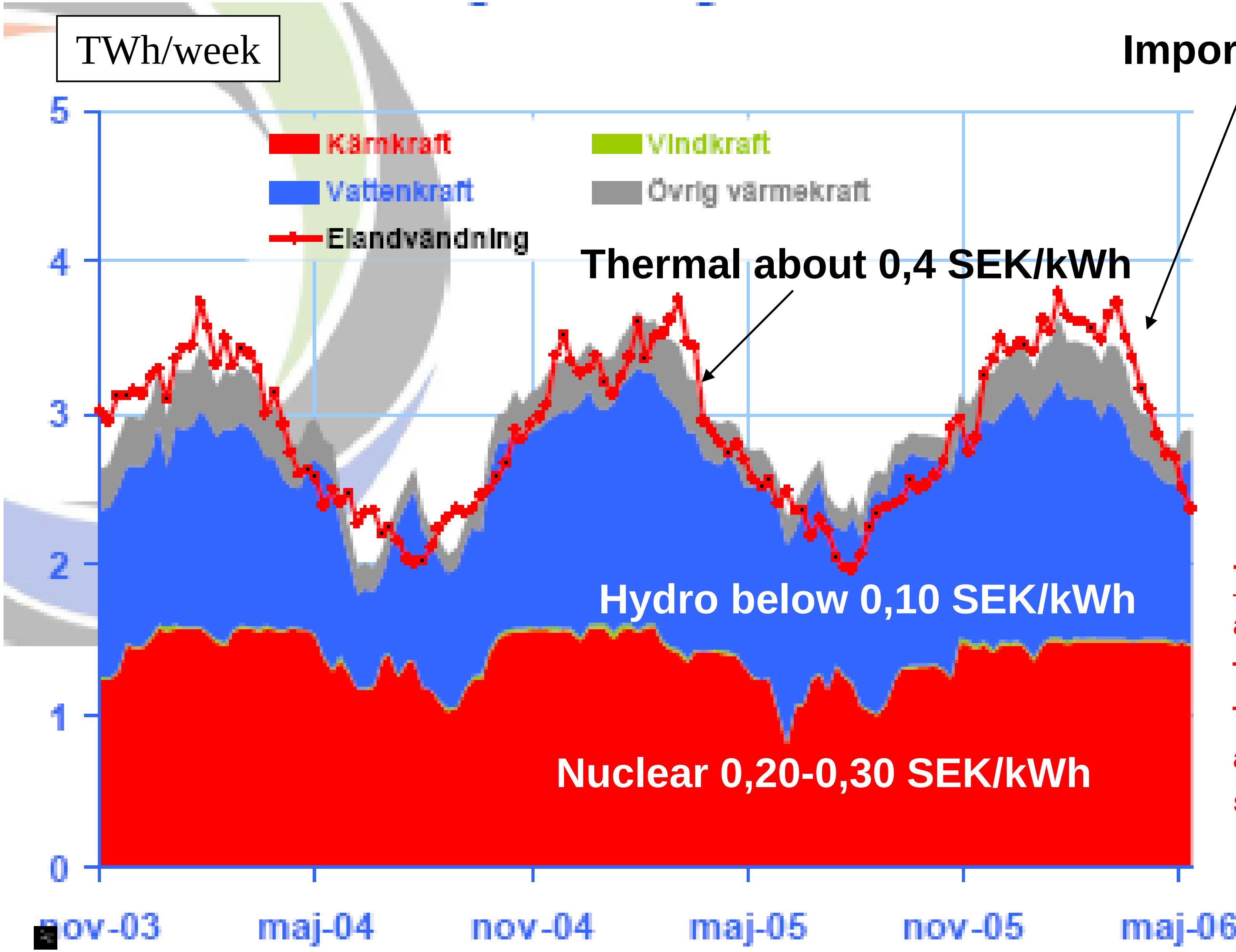
Electric power generation and use in Sweden



Utilization times 2005

Nuclear	7340 h
Thermal	960 h
Import	582 h

Tariff charged in 2016:
about 0.30–0.45 SEK/kWh + taxes about 0.33 SEK/kWh + transmission & grid charge of about 0.20 – 0.40 SEK/kWh + sales tax 25% on top

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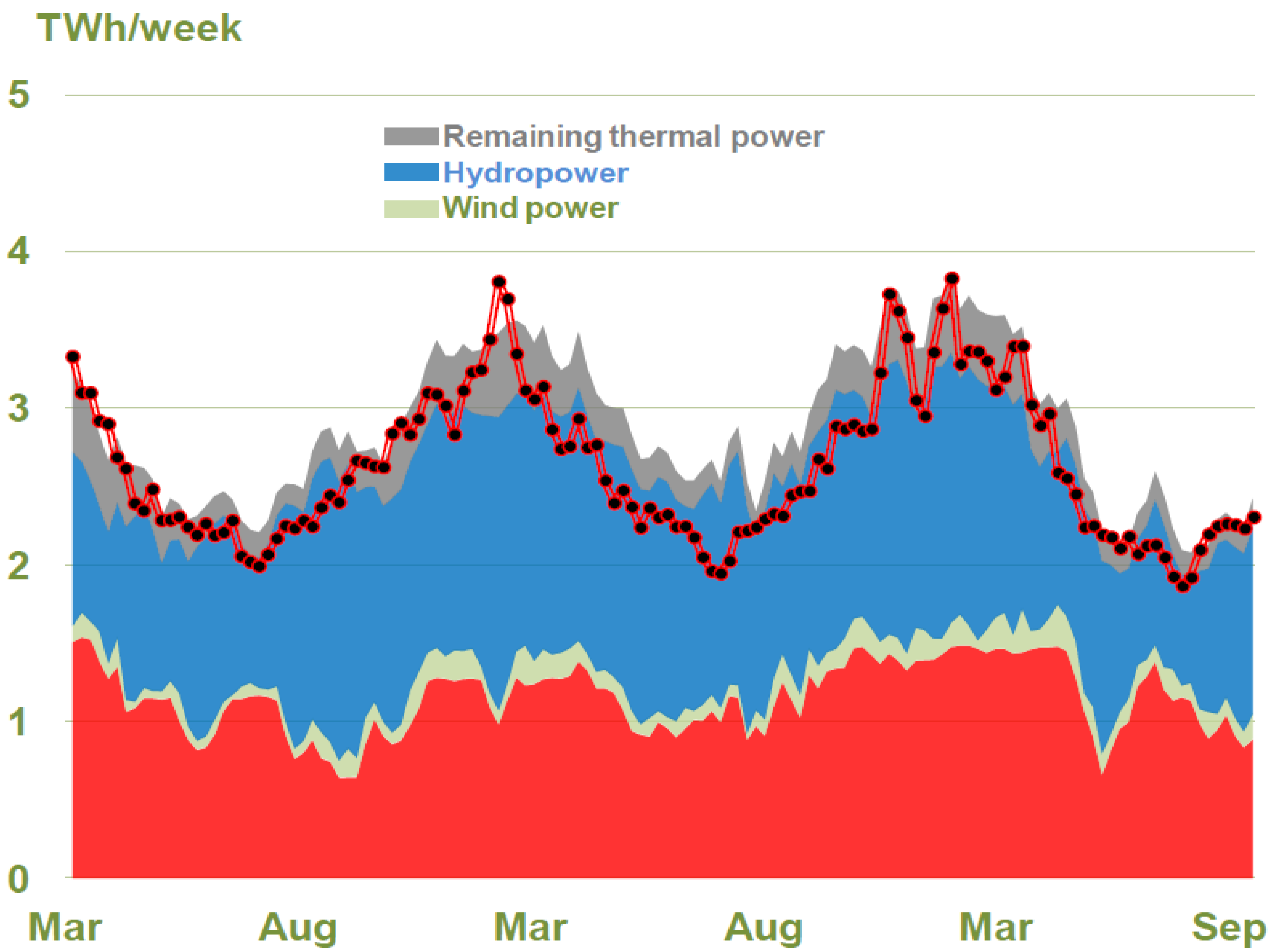
Tariff essentially based on cost for generation of the peak kWh used

Typical seasonal variations for Sweden



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Hydro dams/reservoirs relative filling
(100% = 34 TWh; Max, min & average for 1960-2013)

Sweden and Norway are interesting cases, with lots of hydropower available, however the biggest availability is from snow melting in spring and rain in summer, while the highest demand for power is in the coldest season (winter). Thus, the water dams are crucial for the system stability. They are emptied in winter and filled up in spring/summer.

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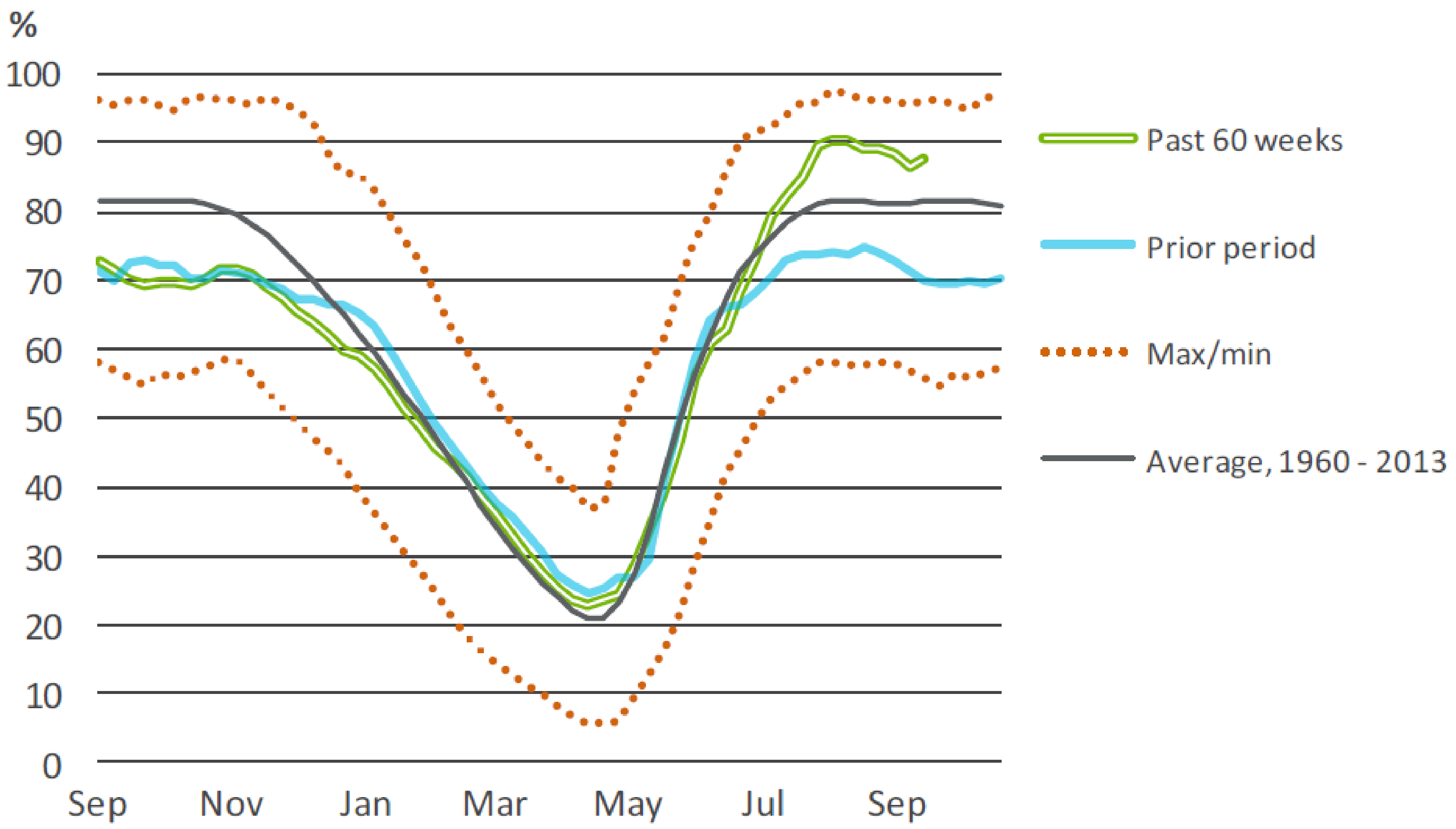
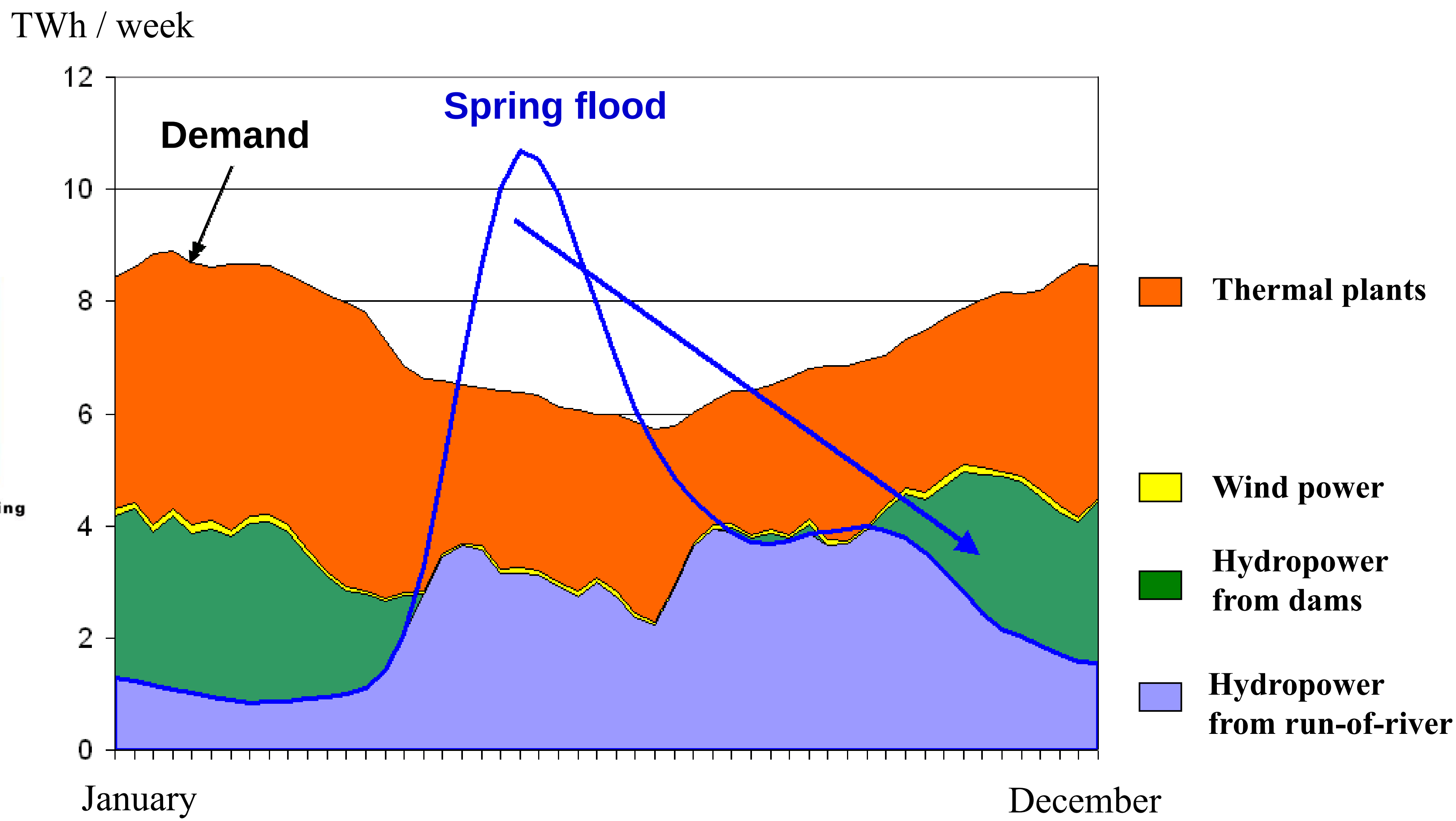


Seasonal hydrostorage in dams



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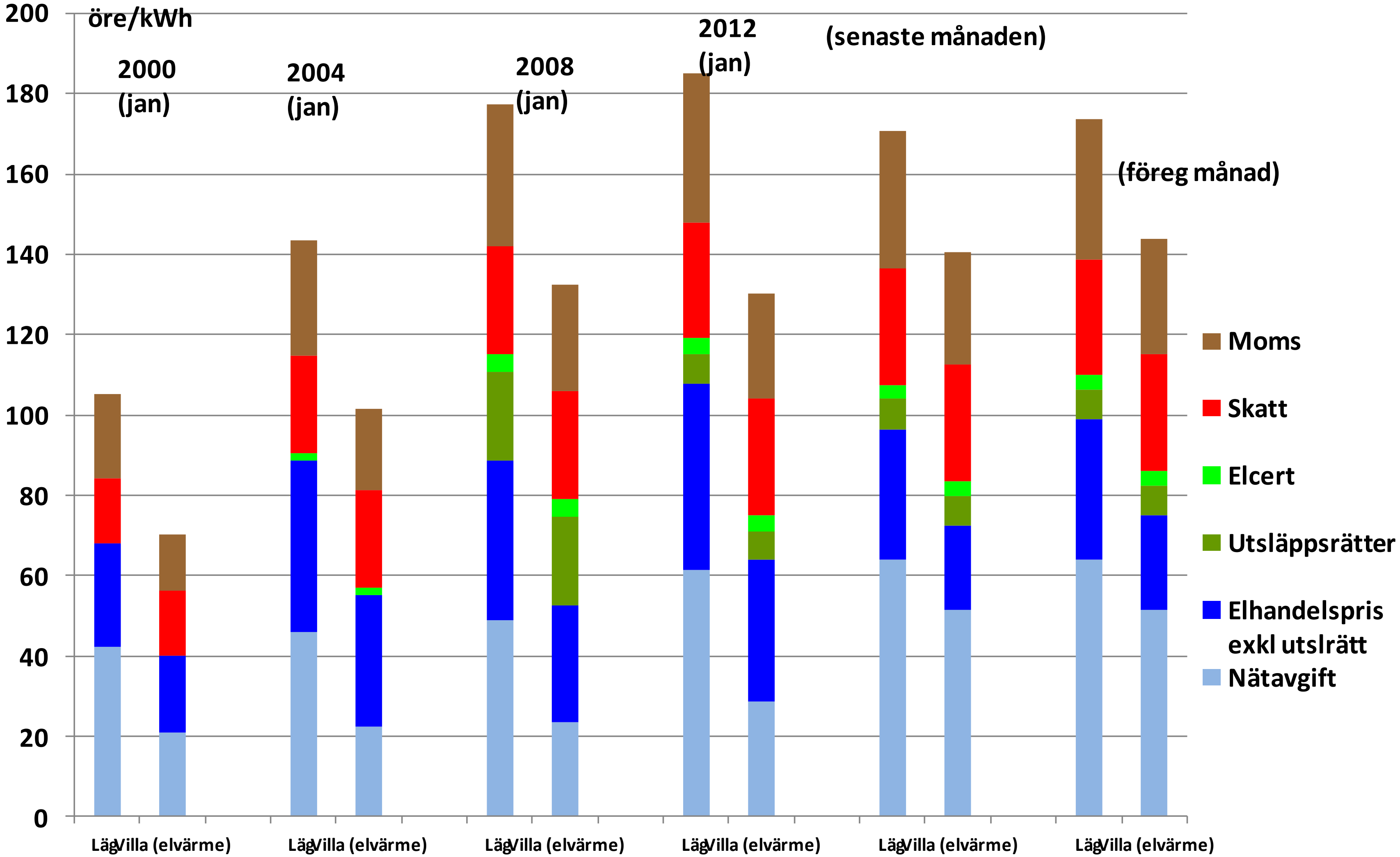
Customer’s Electricity prices in Sweden
(by August 2016)



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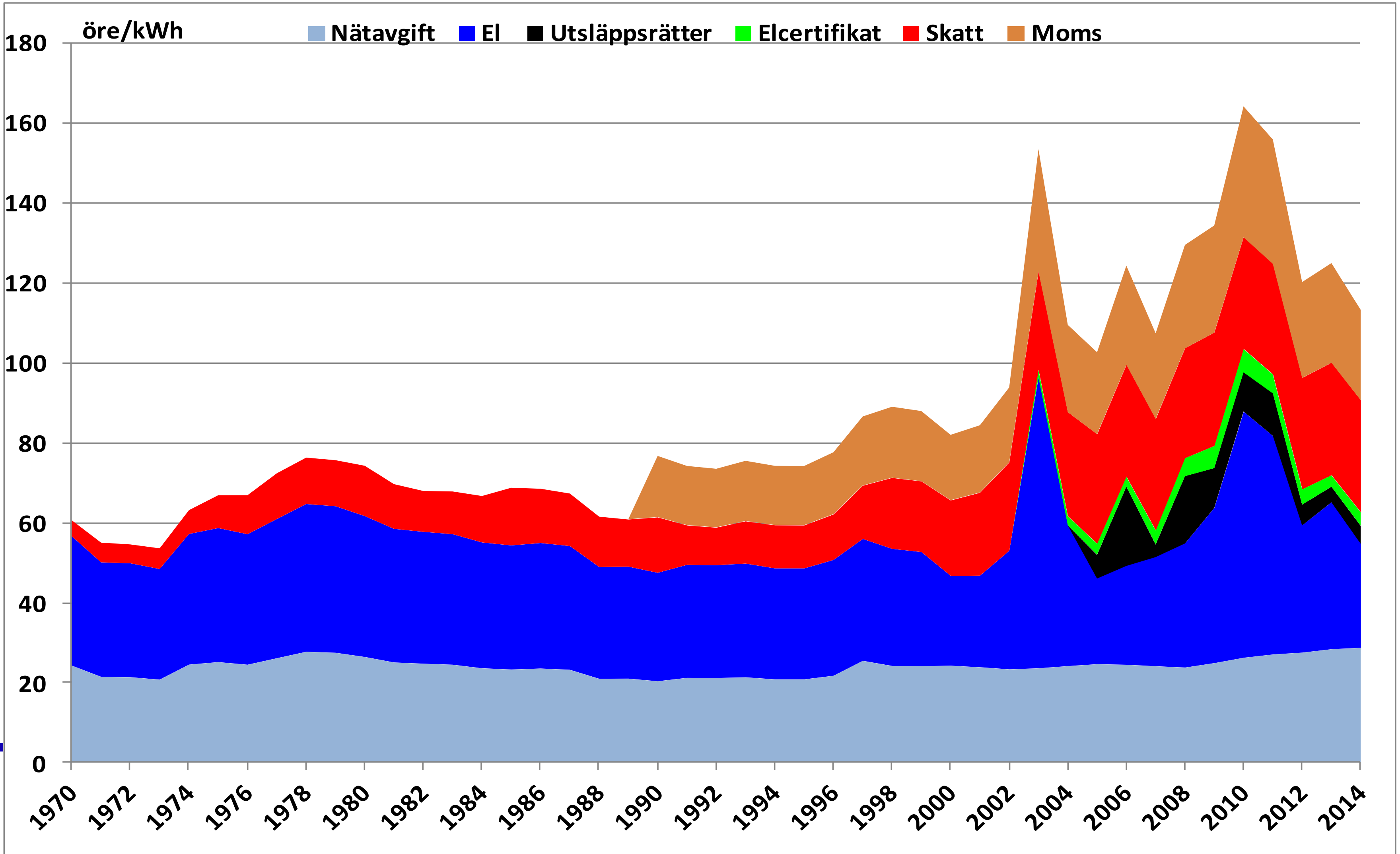
Historical electricity price since 1970 - (20’000 kWh/year, normalized to 2010 year’s prices)



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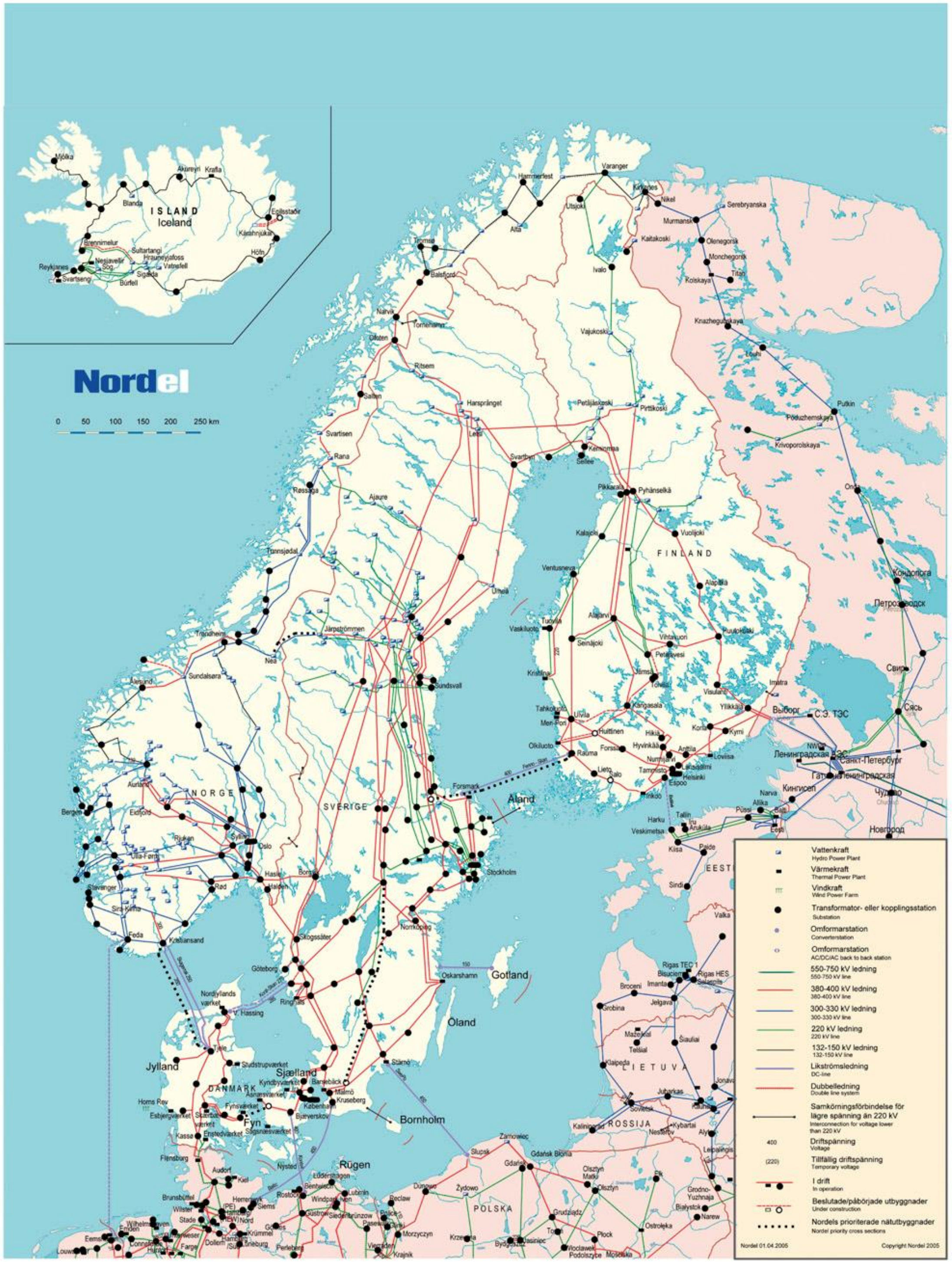
Source: SCB (Swedish Bureau of Statistics), Svensk Energi

DET NORDISKA ÖVERFÖRINGSNÄTET
The transmission grid in the Nordic countries



The Nordic region's Transmission Grids

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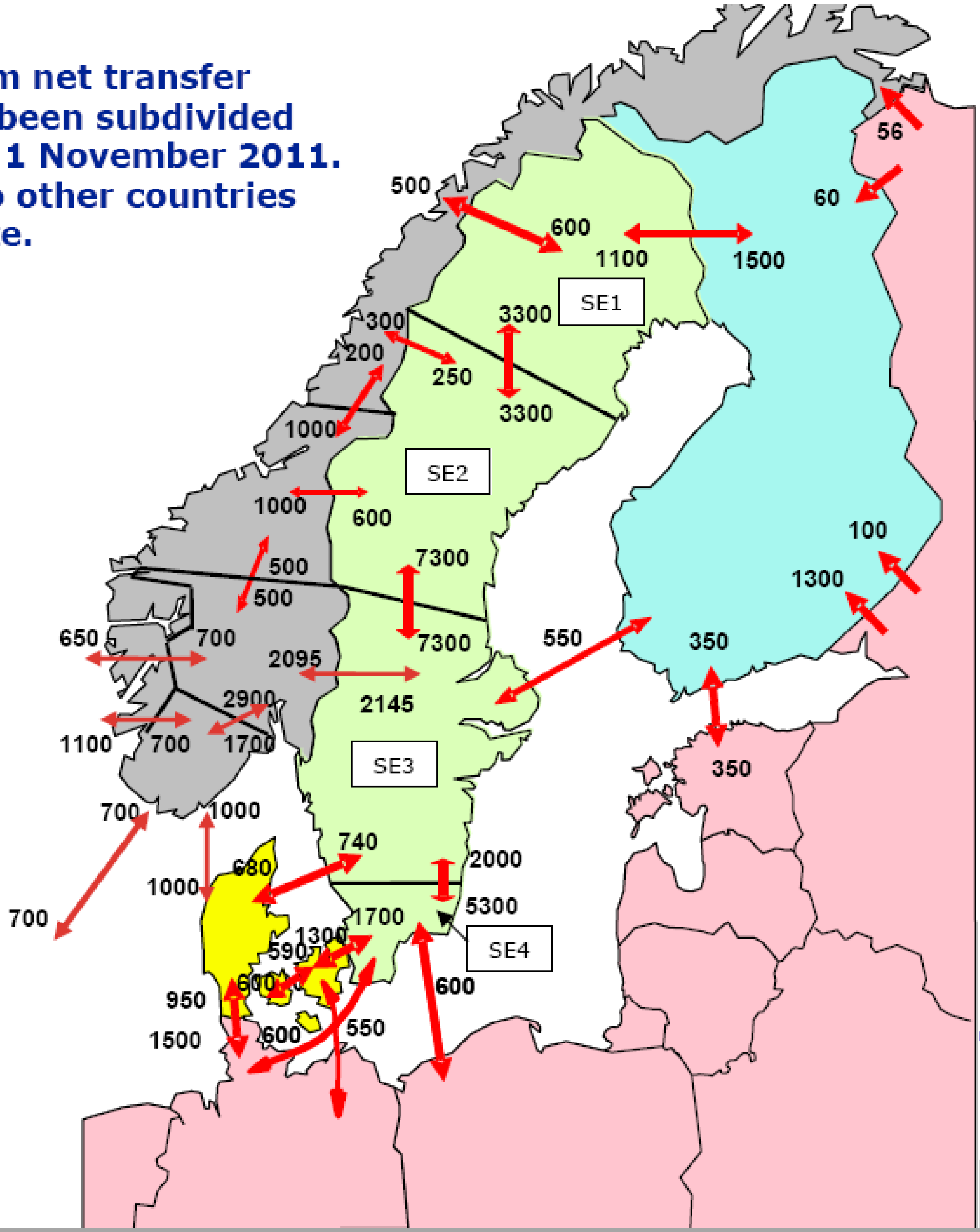
Nordic systems' interconnections

The picuture shows maximum net transfer capacities after Sweden has been subdivided into four bidding zones from 1 November 2011. Values for interconnectors to other countries might change before this date.



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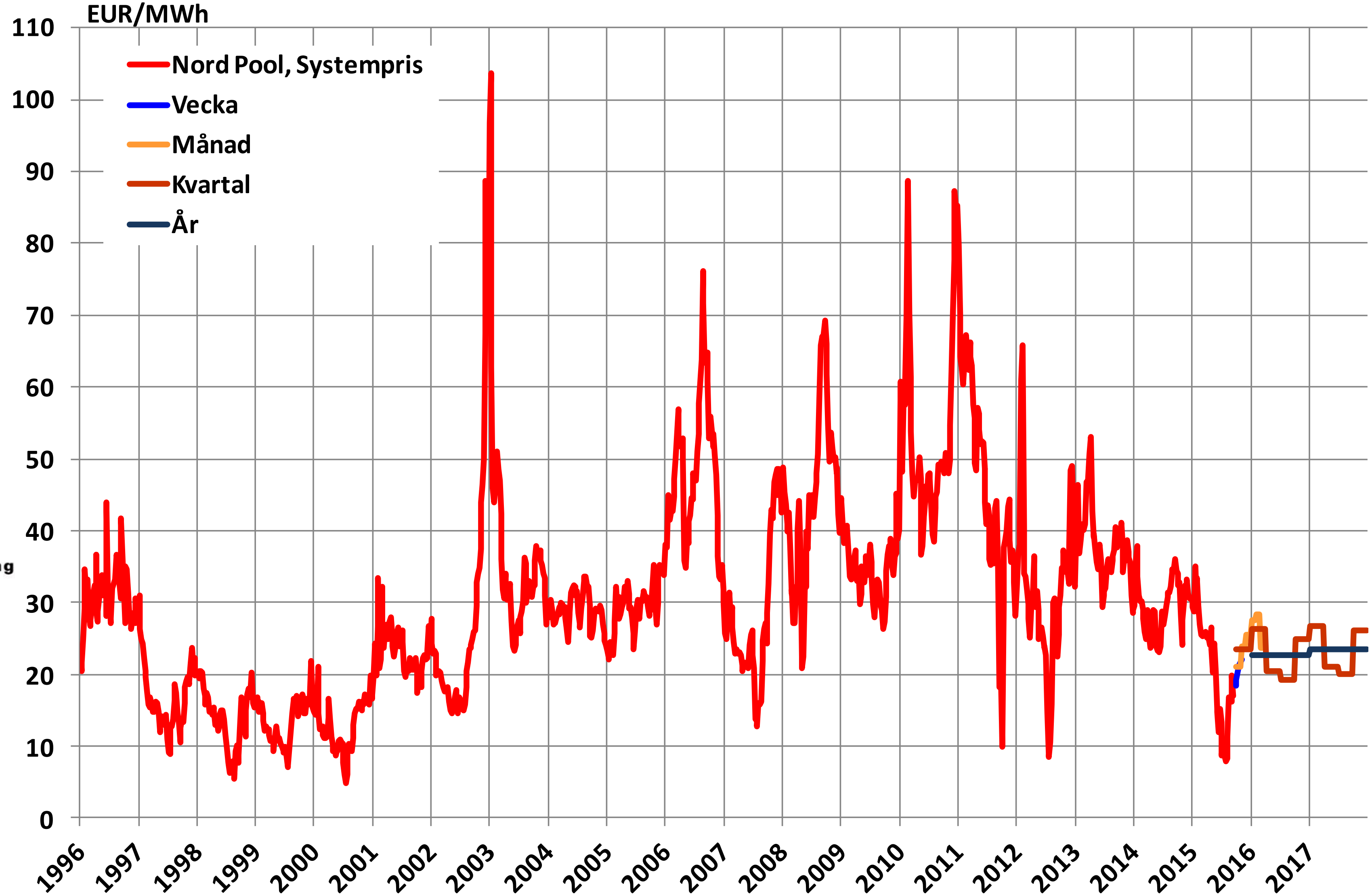
Electricity prices at NordPool market



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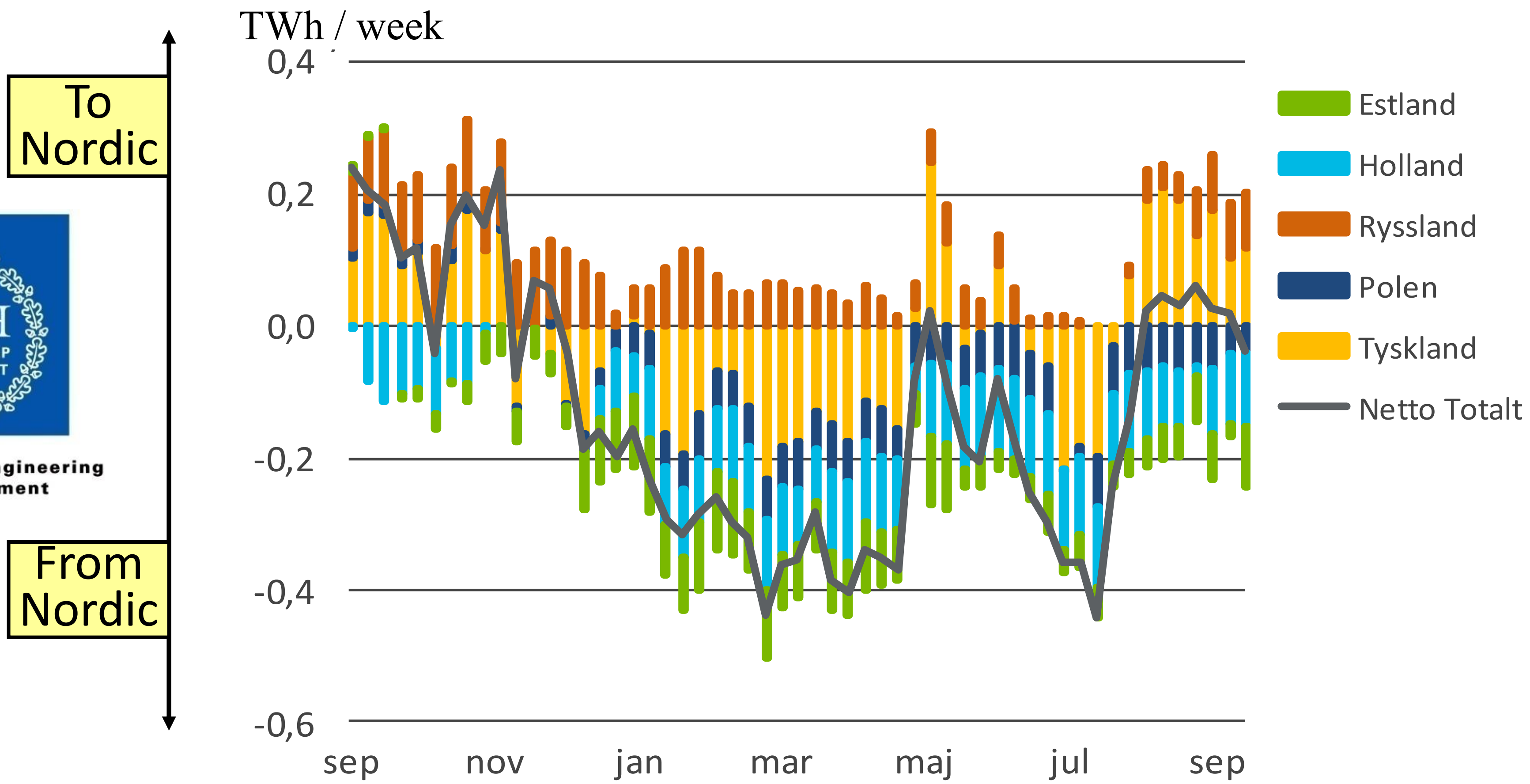
Typical annual exchange flows to/from the NordPool market



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Estimated generation cost for future power plants

Capital costs calculated for 6% investment . Lifetimes per Elforsk report 11:26
Present emission penalties and taxes. Green certificates at 280 SEK/kWh

Process	Power MW	Fuel	Invest-ment SEK/kW	η %	Annual operat. hours	Generation cost SEK/MWh	
						Direct	Owners
Nuclear	1600	UO_2	28 000	0,36	7600	440	500
CHP Steam	30	Biomass	23 250*)	0,83*	4 800	720***)	510***)
CHP Engine	0,05	Biomass	31 400*)	0,85*	3 000	1300	1020
Wind, land	60	None	13 700	-	3 250	590	340
Wind, offshore	150	None	21 000	-	3 150	870	620
Solar PV	0,003	None	35 700	-	862	3280	1600

COSTS ESTIMATION is never correct…
Take it always with a pinch of salt!

EXAMPLE: Olkiluoto 3, a 1600 MW PWR nuclear power plant, initiated in 2003

Energy Commission 1995:
Specific investment 25000 SEK/kW for 1000 MW plant
KPI ratio = 278,1/254,8 = 1,091

Logical investment 2003 for 1600 MW plant:
$I = 25000*1.091*1000*(1600/1000)^{0.7} = 37.9*10^9$ SEK

Oskarshamn 3 (BWR) 1060 MW:
Actual investment $1*10^9$ SEK, price level 1983
KPI ratio = 278,1/132,6 = 2.097

18 400 SEK/kW

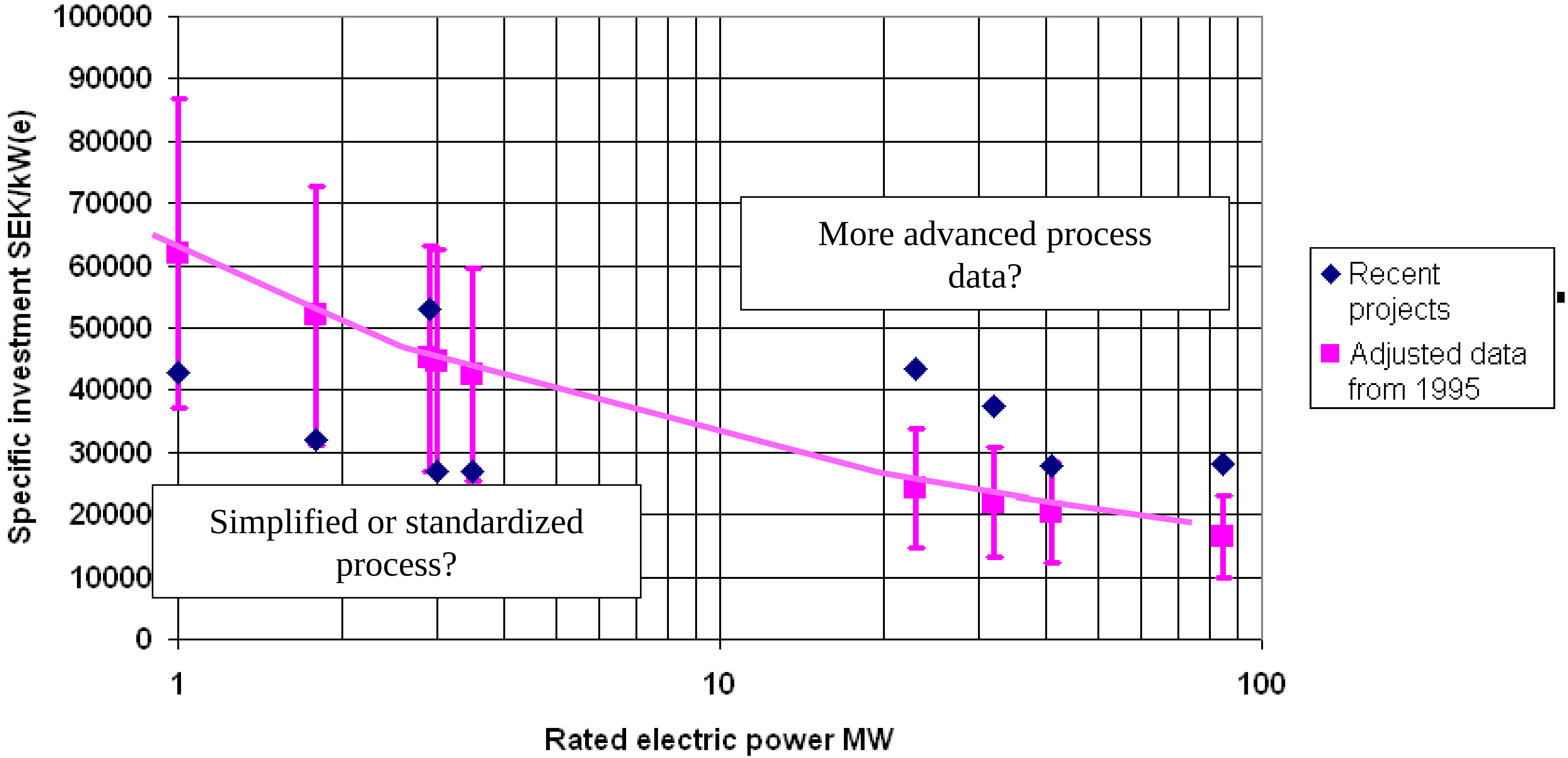
Expected investment 2003 for proposed 1600 MW plant in Finland:
$I = 1*10^9*2.097*(1600/1060)^{0.7} = 30.8*10^9$ SEK

27 500 SEK/kW

Actual proposed price from Framatom $3.2*10^9$ EUR = $29.4*10^9$ SEK
(Rumours that price is subsidised and actual cost would be higher)

Later information: at least 50% higher investment, i.e. > $44 \cdot 10^9$ SEK

Specific investment for some biofuelled CHP plants with back pressure steam turbine built in Sweden and Finland



$I/P = 19200 * (50/P)^{(1-0.7)}$

error bars ∓40%

Inflation corrected specific investment

For 50 MW(el) cogeneration plant 19200 SEK/kW

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Operational situation for a power plant

- Generally, the plants on the energy market are dispatched in order of merit related to marginal cost. (Bidding price)
- Power plants will have a place in the dispatch order related to marginal cost only, including any CO_2 or other added costs.
- CHP and renewables (Bio, Wind, Solar) are prioritized in the dispatch order when they are able to operate.
- CHP is prioritized in commercial terms during heating season, but will have a high marginal cost at other times.
- A plant with a higher marginal cost than the actual market price will not run at all.
- The profitability of a plant must be calculated in terms of running time, determined by its marginal operational cost.
- Dispatch is not only related to the home market any more, and not clearly defined.

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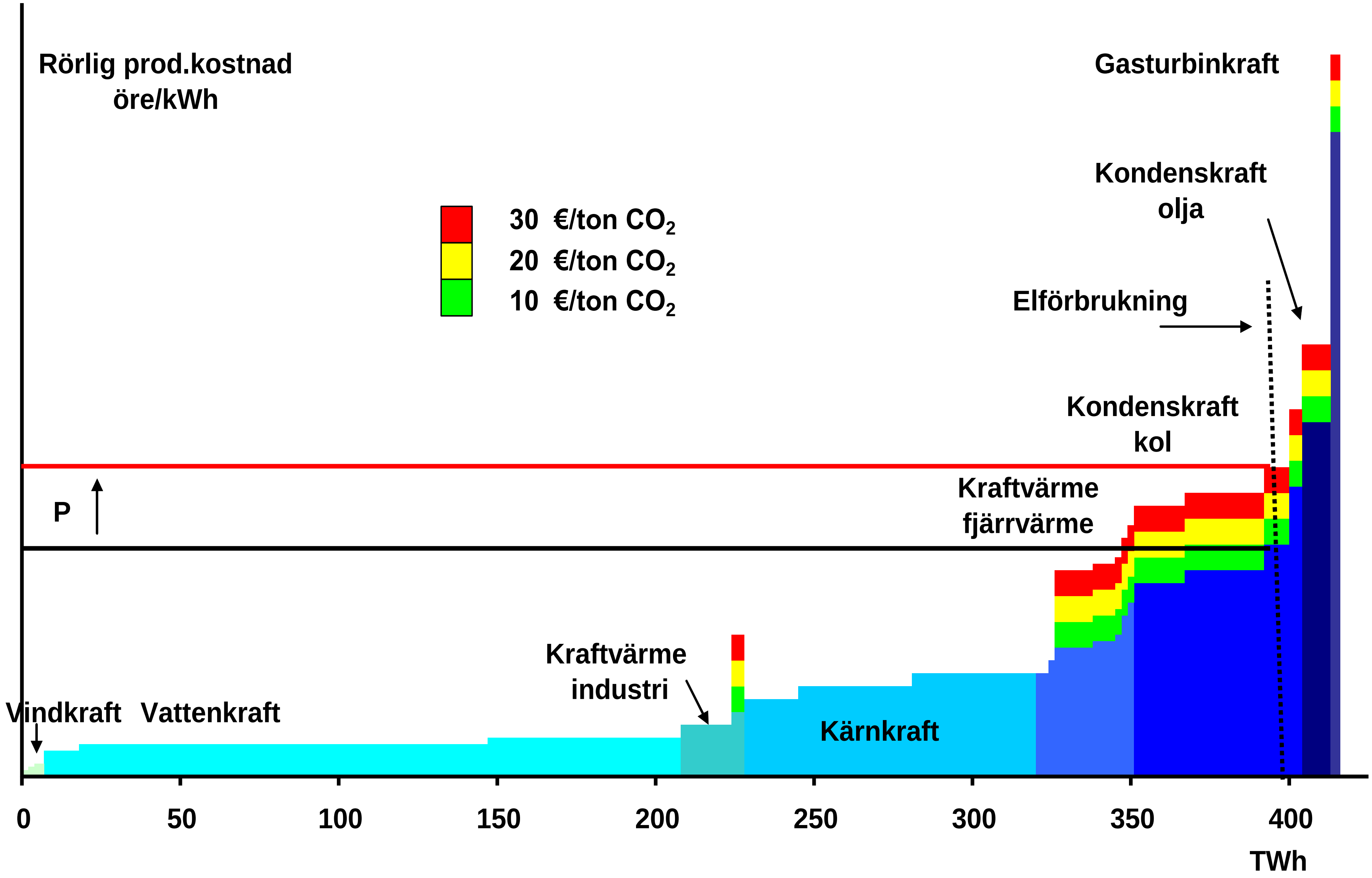
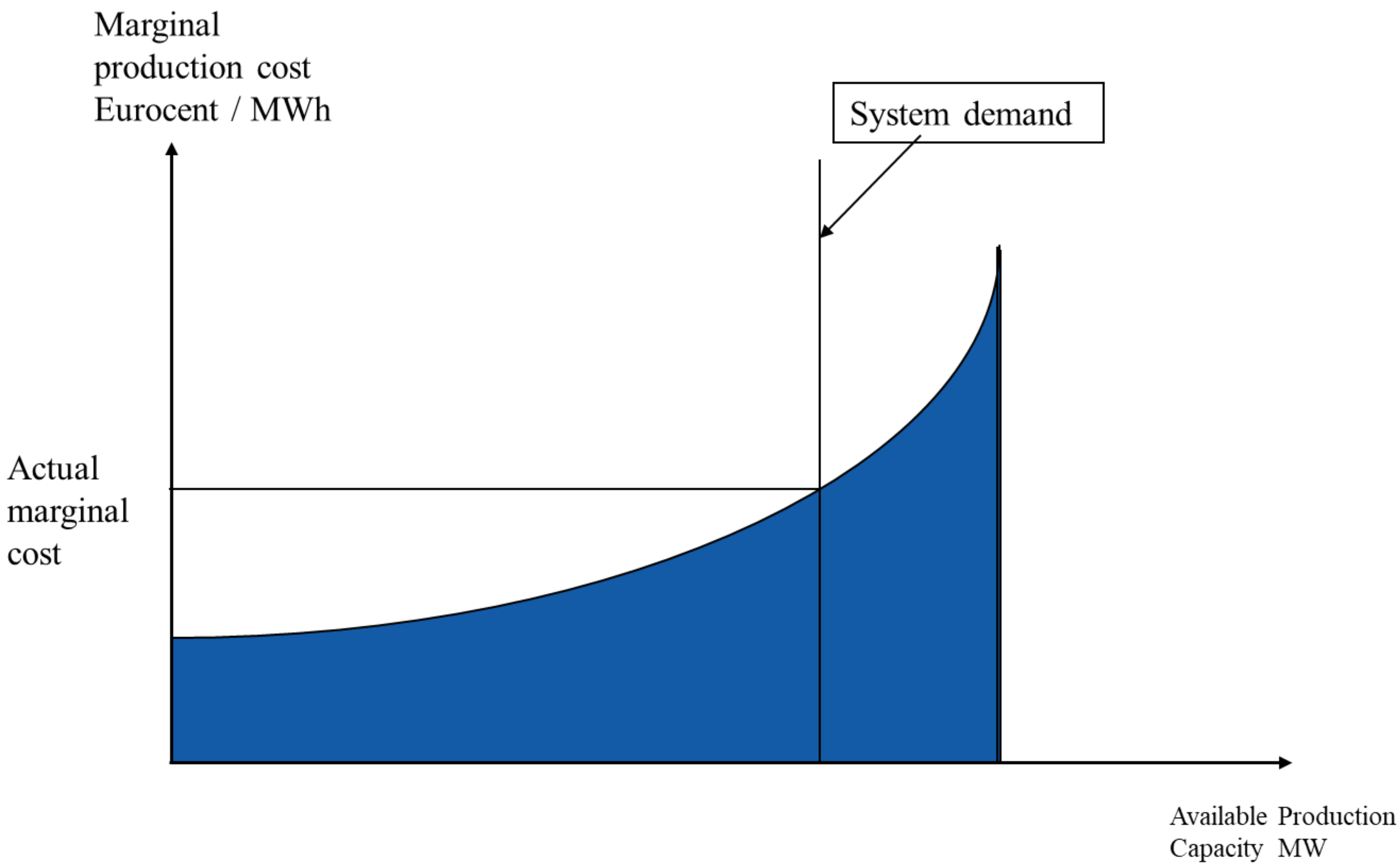
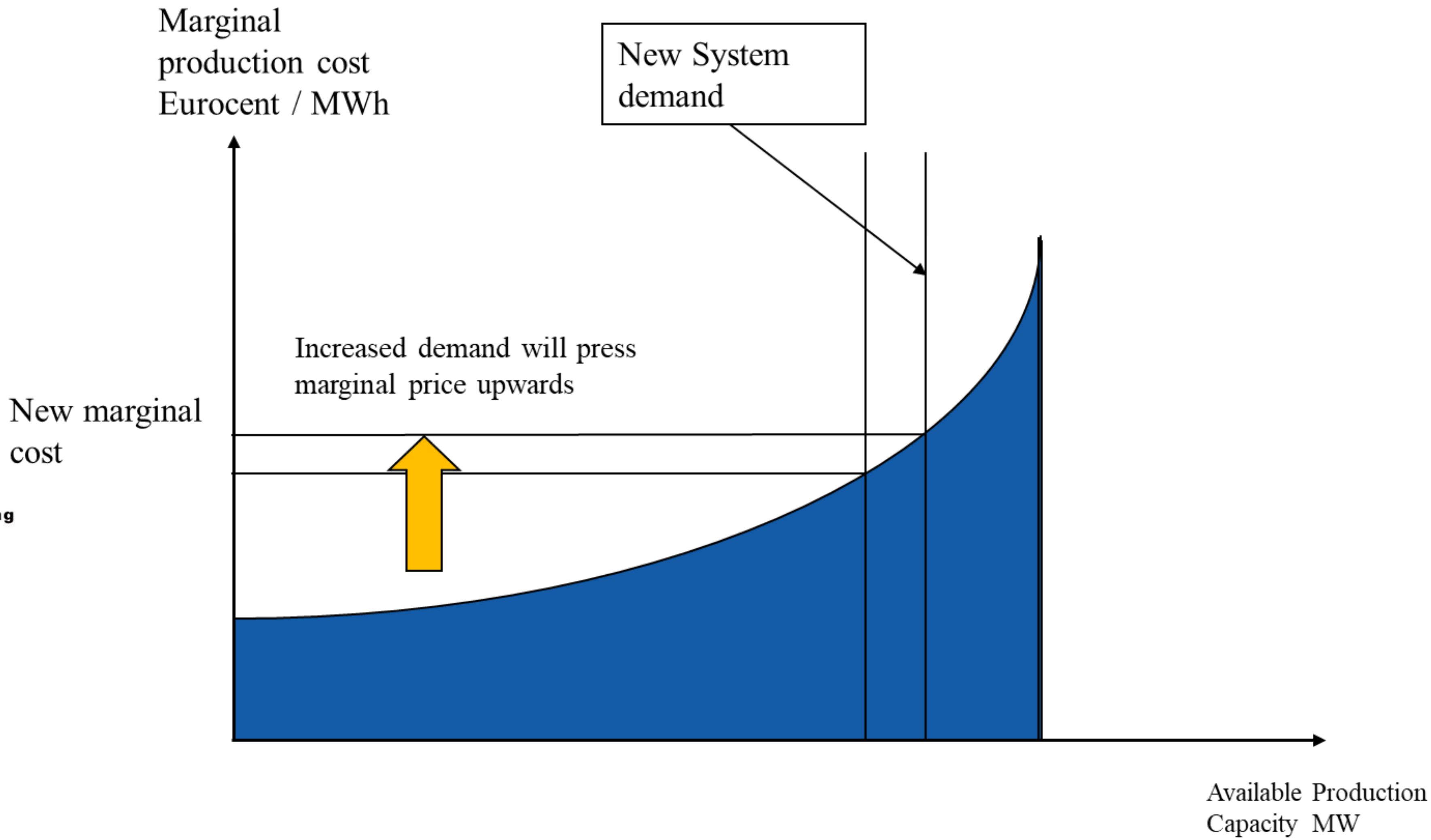
Capacity dispatch in the Nordic market



Principal supply curve



Principal supply curve adaptation



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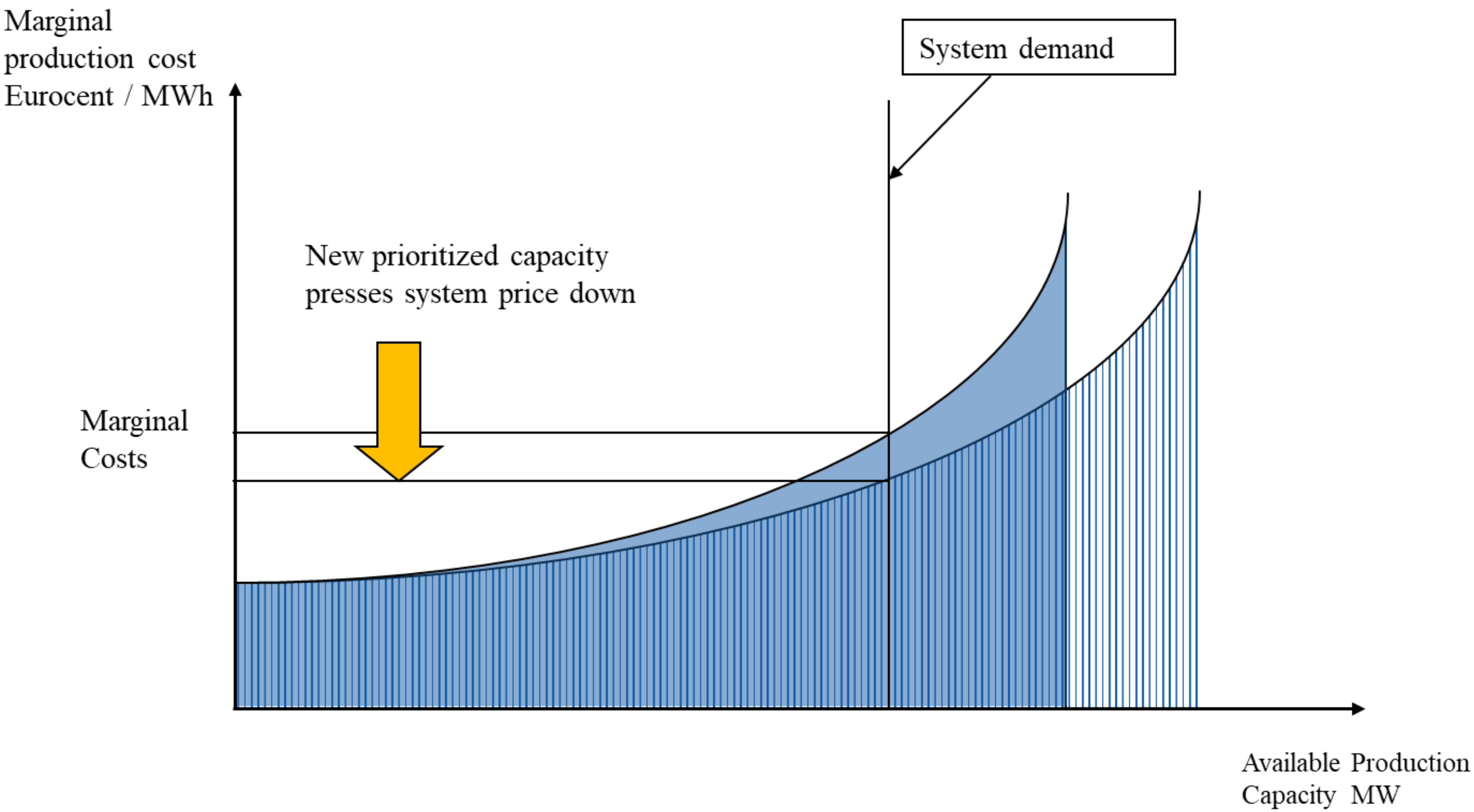
New prioritized capacity is introduced through subsidies



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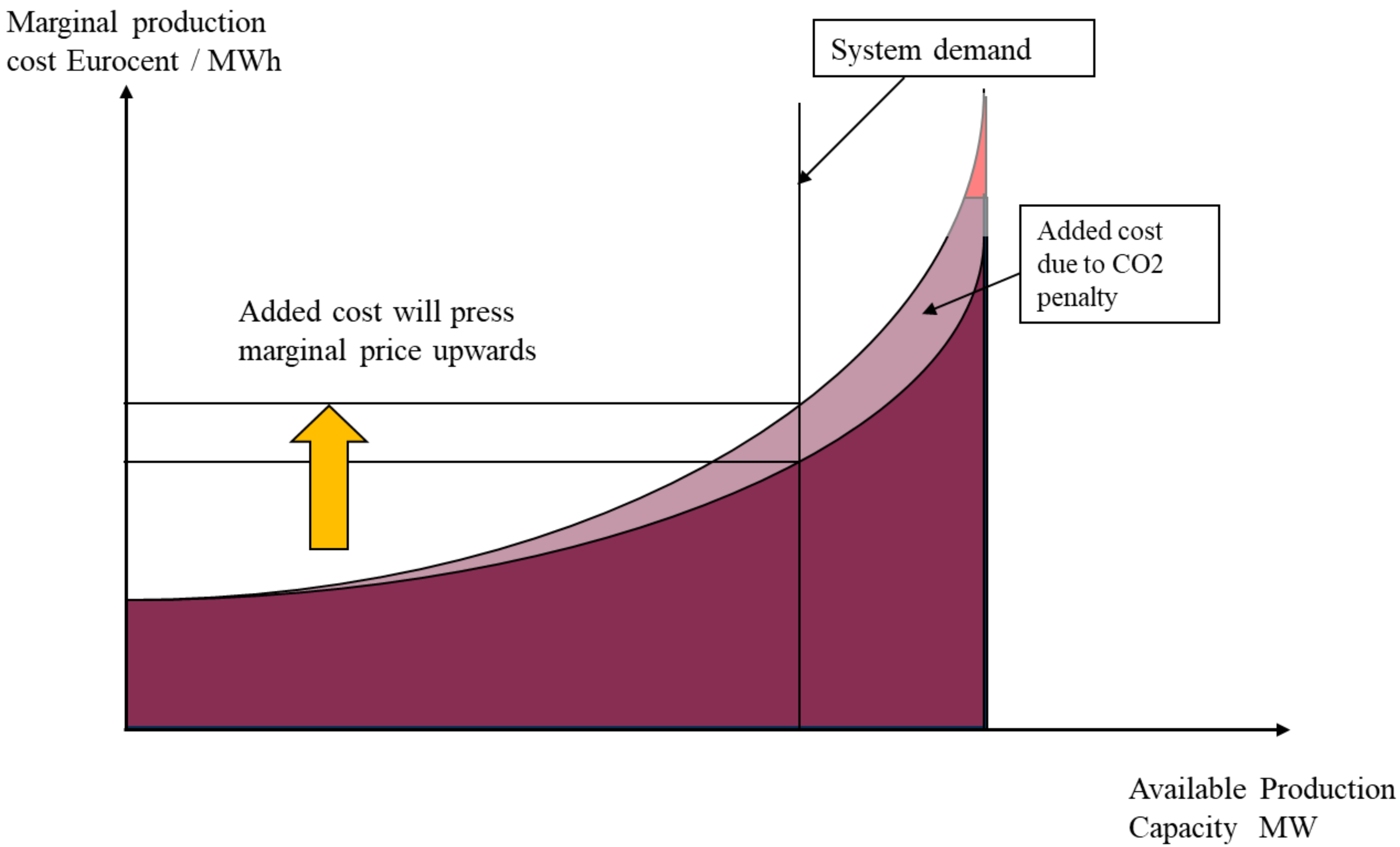
If CO2 cost is imposed on producers



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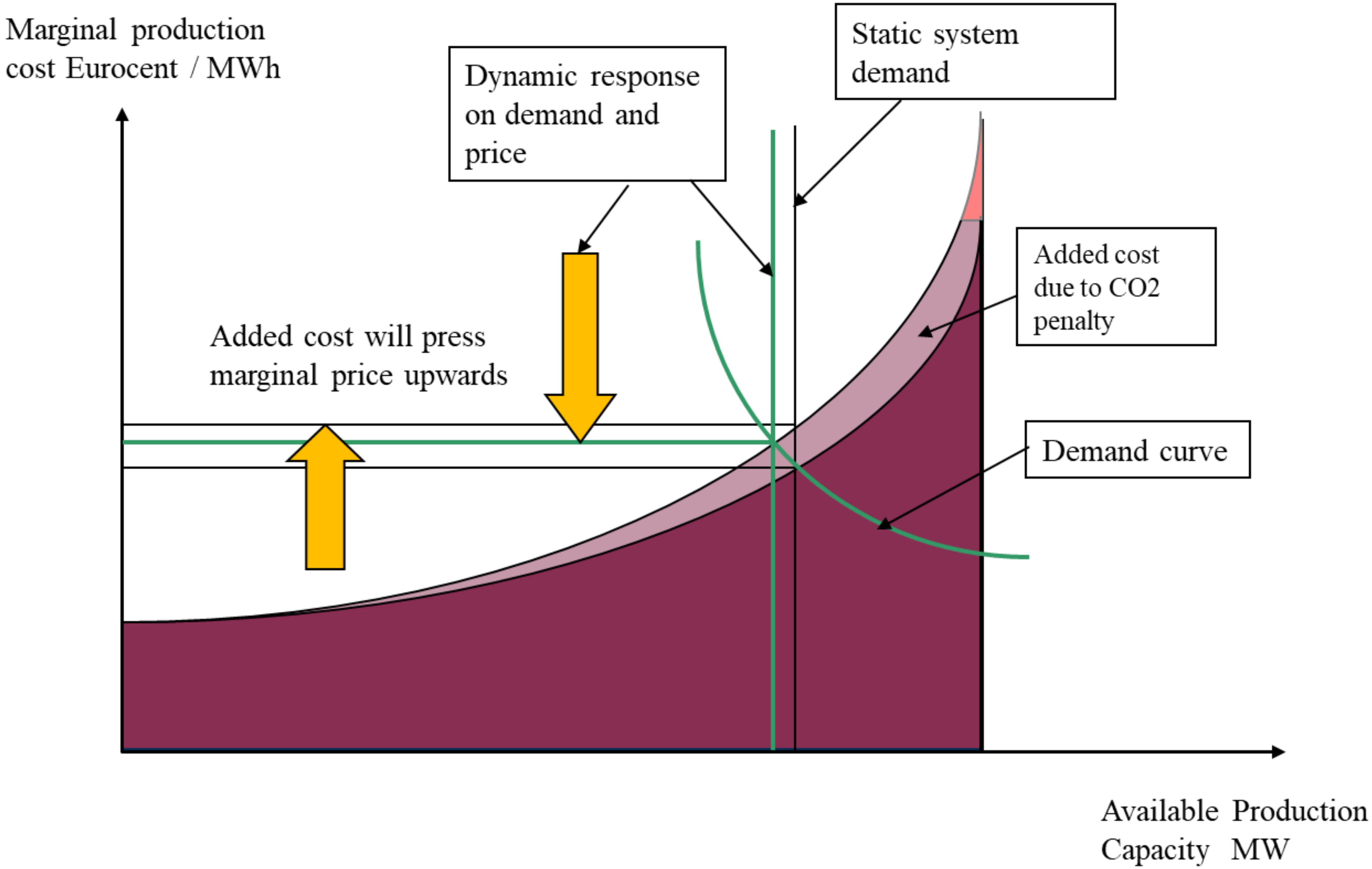
Principal supply curve:
Demand reacts on increased cost



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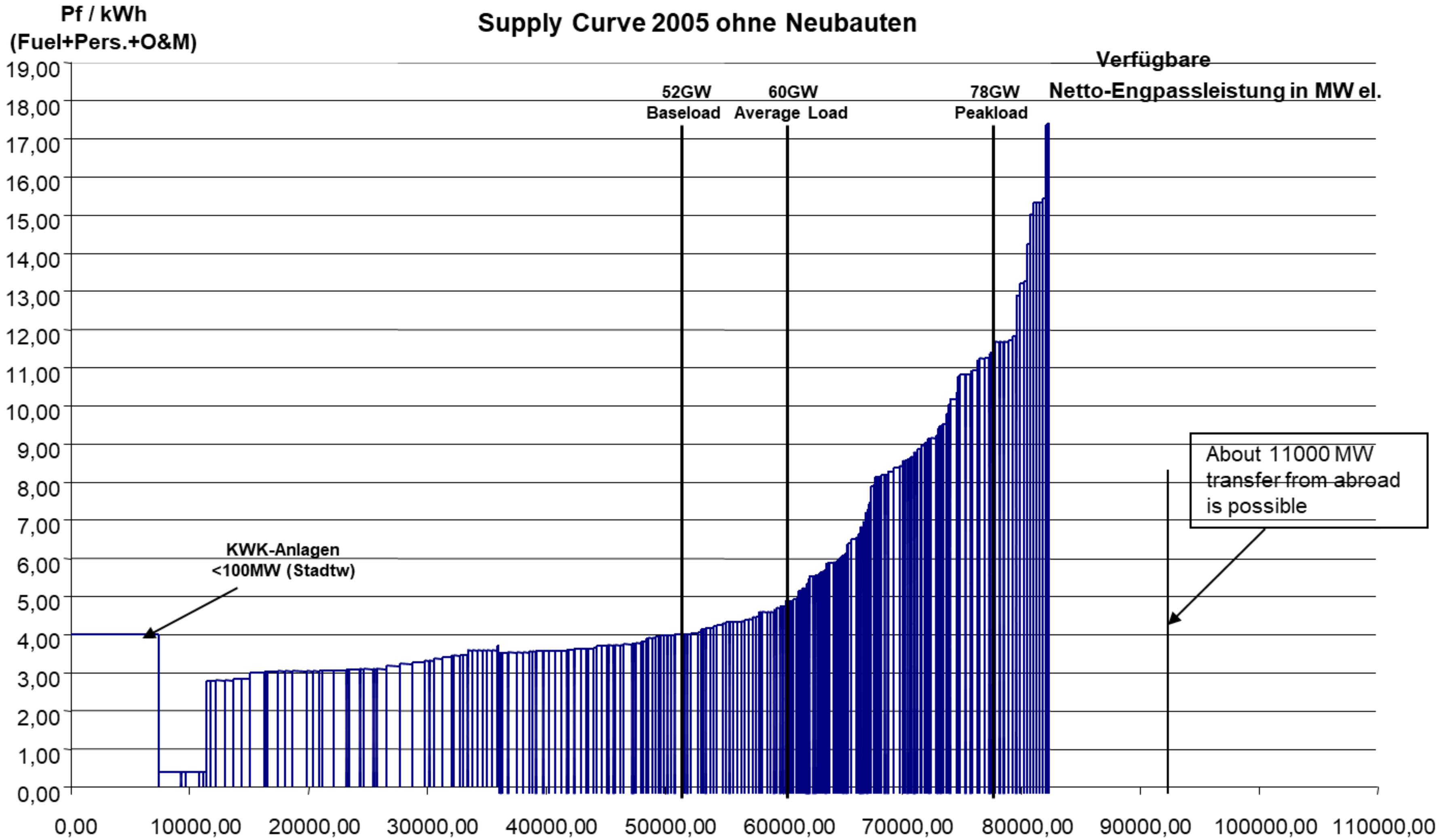
Supply Curve in Germany 2005, after DECOMMISSIONING Long-term variable costs



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Swedish Power System (2014)

Practically installed capacity is about 35 GW, maximum ever used is about 28 GW

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Power Source	TWh	Share %	Installed Capacity MW	Operati-onal Hours
Hydro	64,2	42,5	16155 (13400)	3974
Nuclear	62,2	41,1	9528	6528
Wind	11,5	7,6	5420+	2122
Solar	~0	~0	79	800
CHP-industrial	5,9	3,9	1375	4291
CHP-district heat	6,9	4,6	3681	1874
Peak and reserve GT, steam condens	0,5	0,33	3311	151
Total	**151,2**	**100**	**39549**	

Future Swedish Power System Studied

Nearly 100% renewable, about 20 GW overcapacity

(Source: Prof. Lennart Söder, KTH-Elektro)

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Power Source	TWh	Share %	MW-max	Operating Hours
Hydro	65,7	45,1	12951	5037
Nuclear	0	0	0	0
Wind	46,8	32,1	15633	2994
Solar	11,6	8,0	9148	1268
CHP-Industrial	6,4	4,4	1240	5160
CHP-distr. heat	13,9	9,5	4127	2736
Peak and reserve	1,3	0,9	5081	256
Total	**139,9**	**100**	**48180**	