Introduction to energy efficiency and life-cycle cost efficient pump and fan systems

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Outline of the presentation

I. About energy and resources

II. About energy efficiency

III. Electric energy consumption in electric motors

IV. Life-cycle costs in pumping and fan systems

V. How to improve energy efficiency in pumping and fan systems

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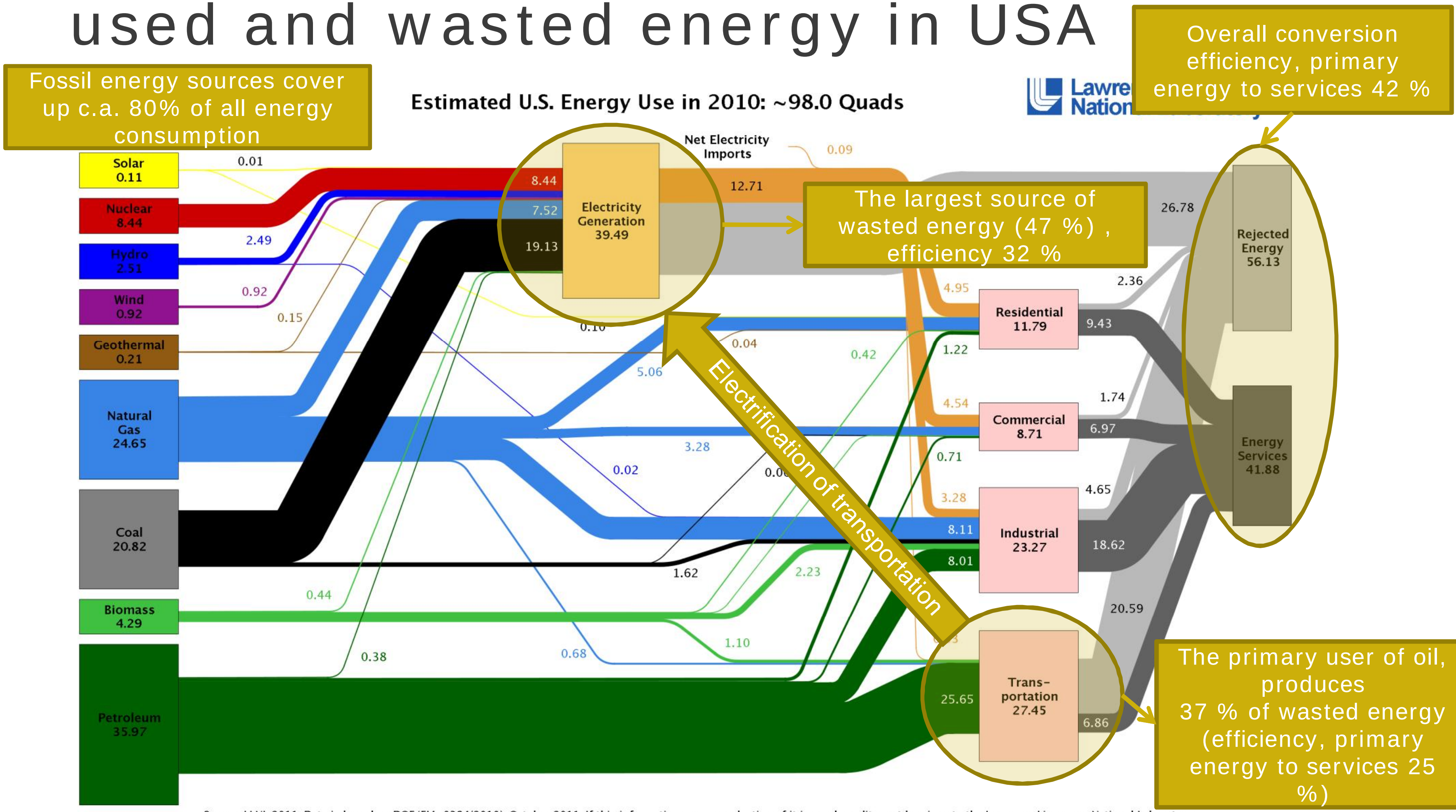
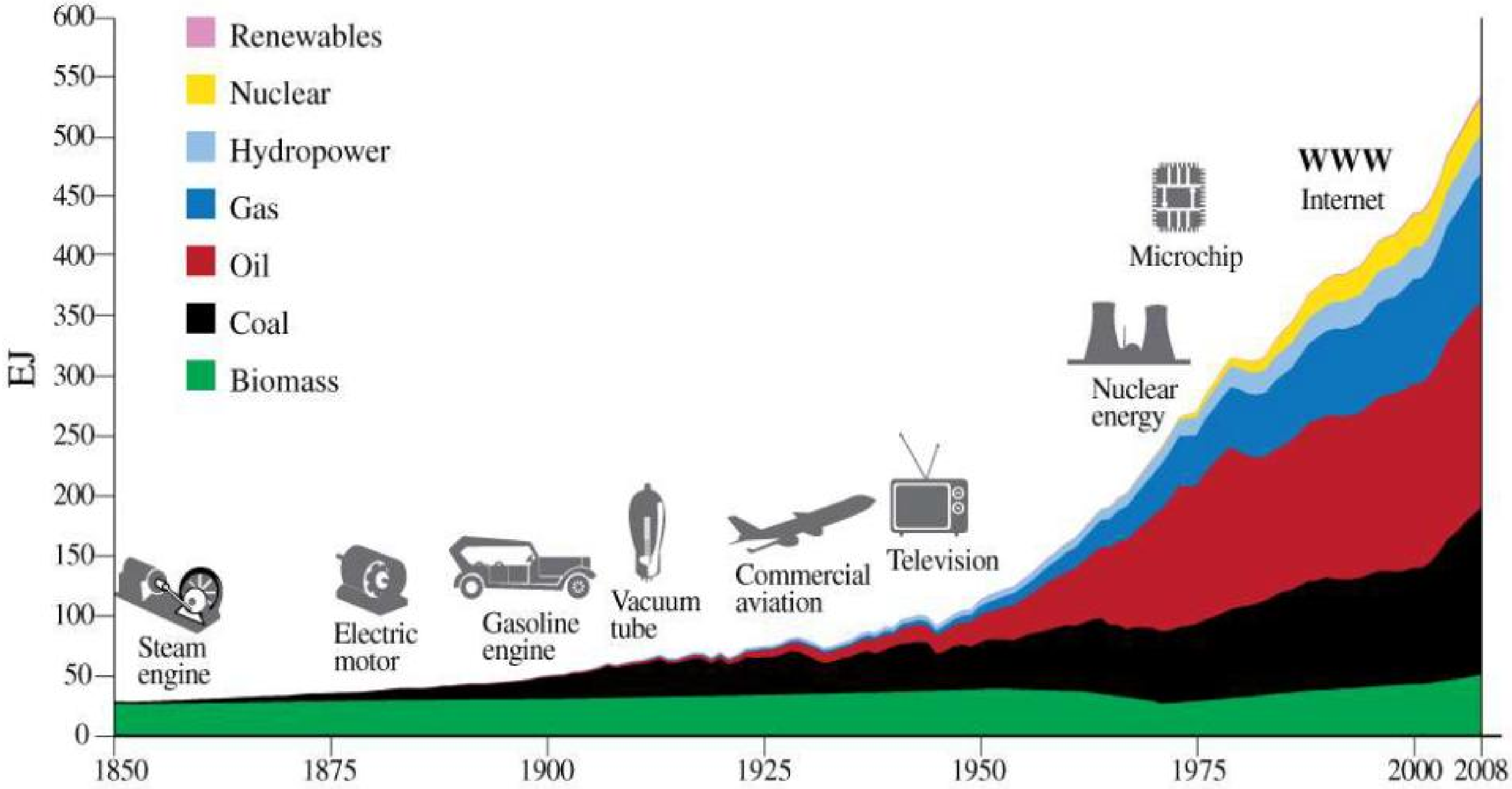
Part I : About energy and resources

The big picture – The flows of produced, used and wasted energy in USA



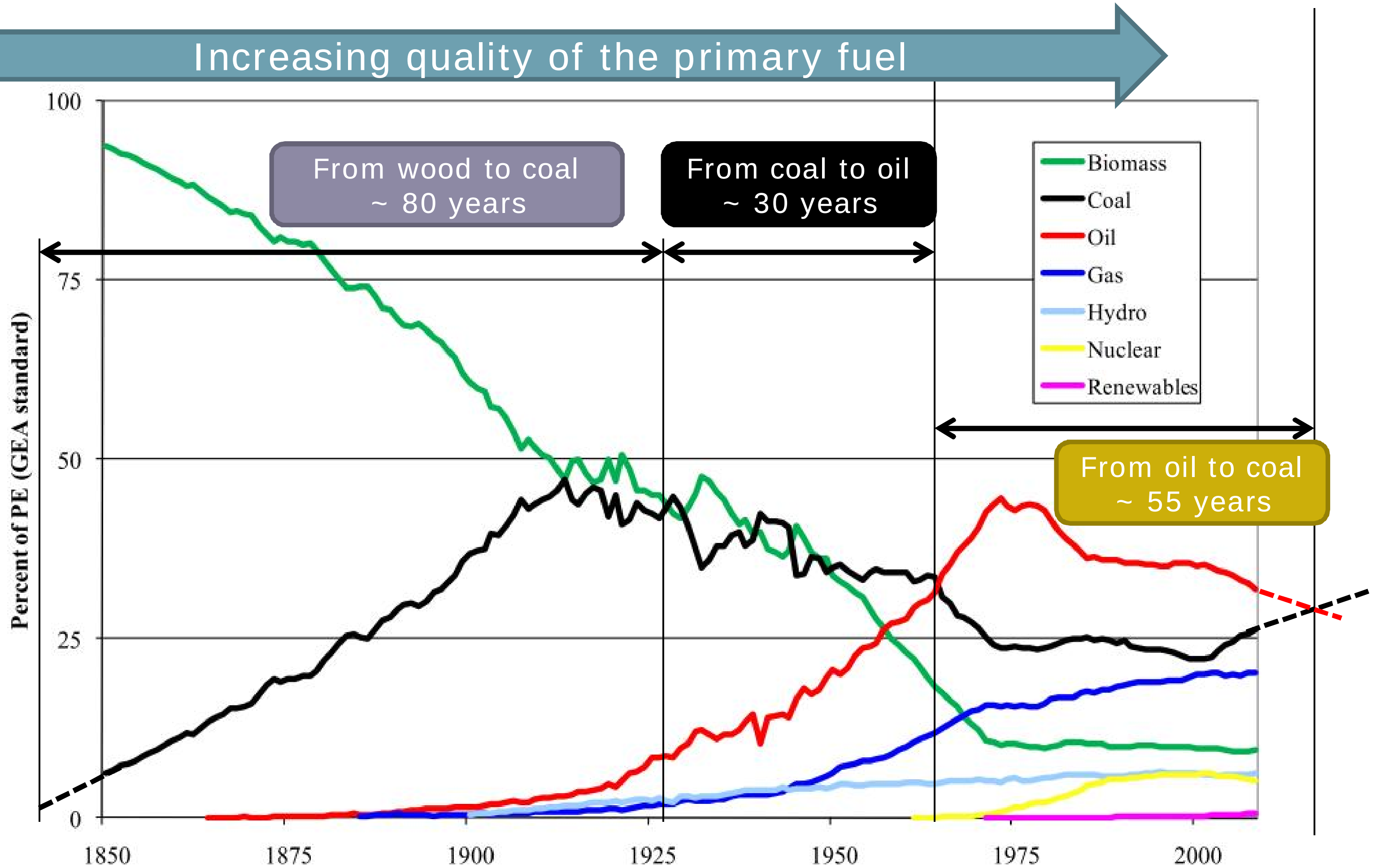
Source: LLNL 2011. Data is based on DOE/EIA-0384(2010), October 2011. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for hydro, wind, solar and geothermal in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." (see EIA report for explanation of change to geothermal in 2010). The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

World primary energy use by fuel 1850-2011



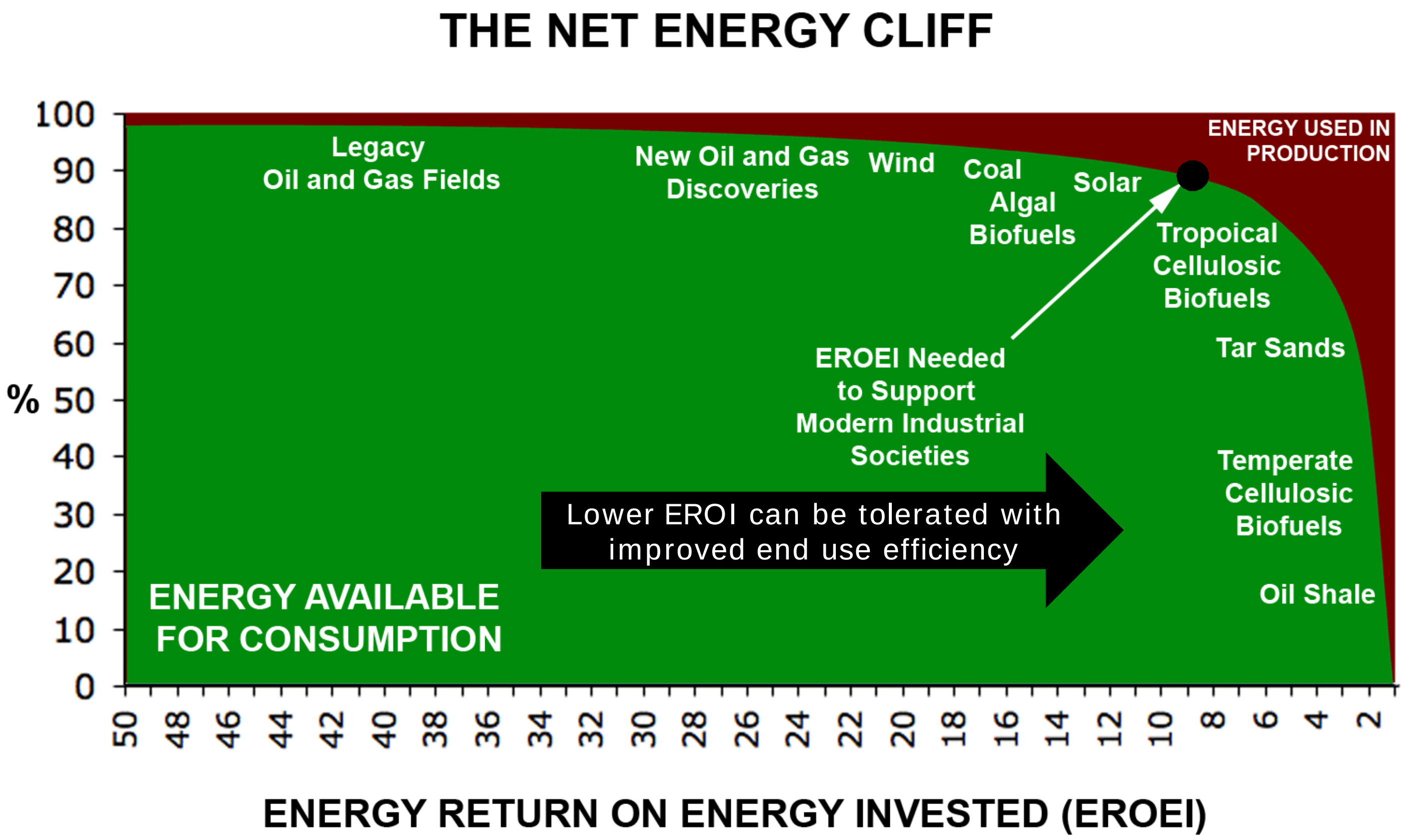
Source: GEA Summary 2011, available at http://www.iiasa.ac.at/Research/ENE/GEA/index.html.accessed 6.8.2012

World energy transitions 1850-2011



Source: GEA Summary 2011, available at http://www.iiasa.ac.at/Research/ENE/GEA/index.html.accessed 6.8.2012

Quality and quantity of energy resources

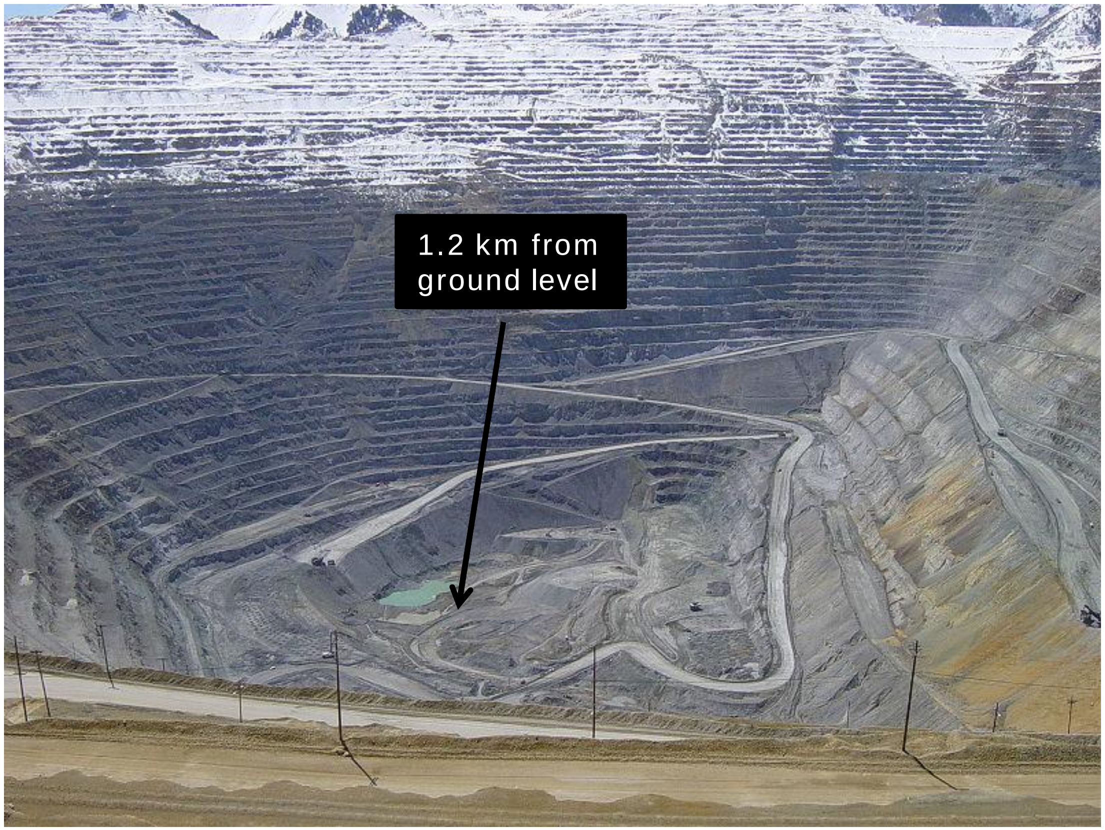


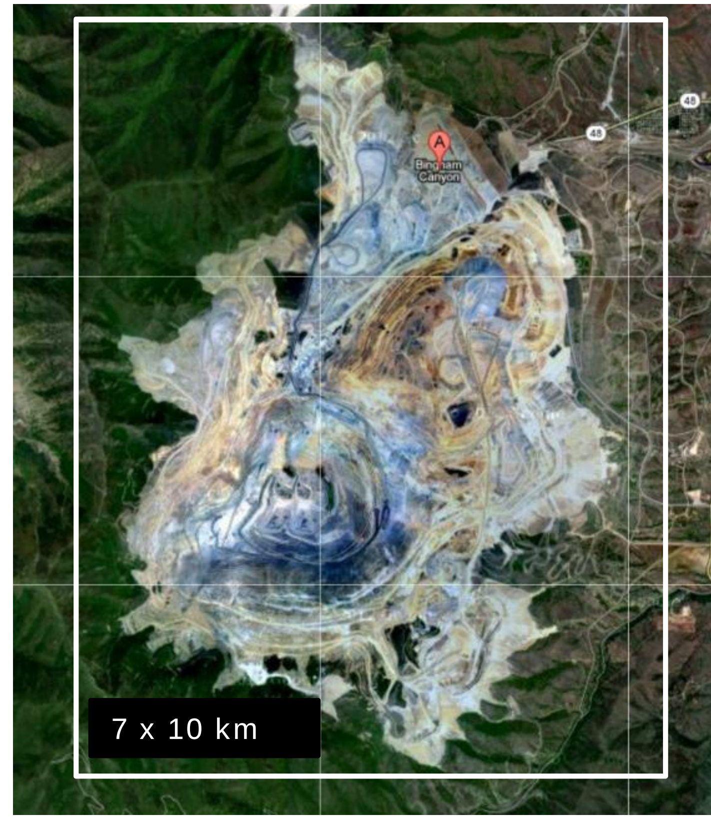
$$\mathrm{EROI} = \frac{E_{\mathrm{out}}}{E_{\mathrm{in}}}$$

Low EROI oil production (EROI ~ 3:1)

Athabasca tar sands, Canada (production 1.5 Mbarrels/day ~ 2 % world use)

Another side - Quality of non-energy resources declines simultaneously



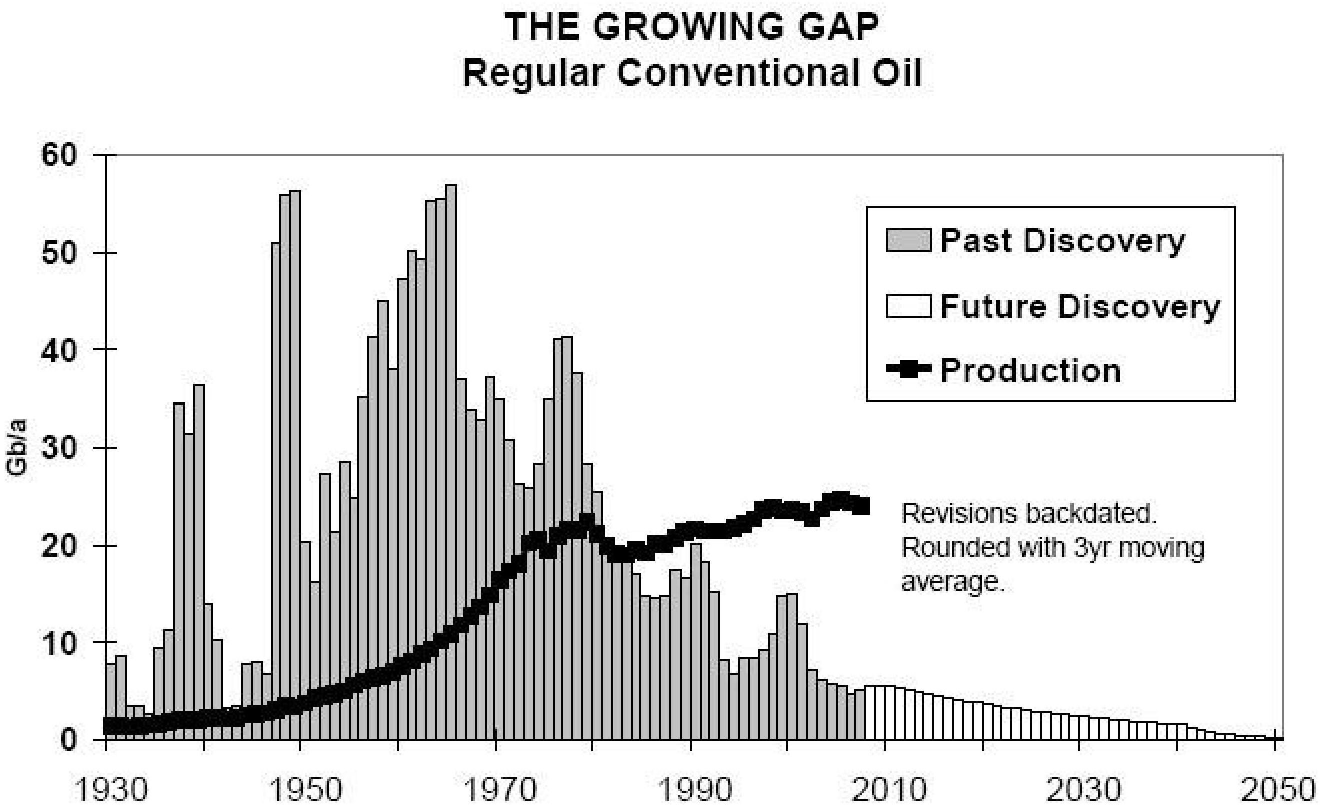


Bingham Canyon, Utah, USA

World's largest open pit copper mine, depth 1.2 km, > 400 000 tons of material removed daily

Copper content of ore 0.6 %, produces about 15 % of yearly copper use of USA

Crude oil discoveries and production



Source: www.theoildrum.com, accessed 30.7.2012

The big picture – Implications

1. The energy efficiency, in general, from primary energy to energy services should be the optimization objective
2. The two most significant sources of waste: electricity generation & transportation
3. Efficiency of primary energy conversion from coal or gas to electricity
   - Limitations by thermodynamics and material technology
   - The utilization of CCS adds the system costs and drops the efficiency of power plants further 20-25%
   - However, large efficiency improvement potential in the utilization of waste heat remains in each step of the energy conversion chain
4. Electricity end-use efficiency
   - Due to energy loss in energy conversion chain each saved Joule in the end use saves from 3-15 Joules of primary energy
   - In the end-use the number of actors increases (e.g. from 1000-10000 power companies to $7*10^9$ end users or maybe $7*10^{10}$ appliances) -> the role of regulations, education, and efficiency services significant
5. In short term the electrification of transportation just moves the consumption from the petroleum to goal and gas (way to combat declining oil availability). Historically, the change of primary energy source, e.g. wood-to-coal, coal-to-oil, has taken 50 years. It can be also assumed with renewables

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Part II: About energy efficiency

Performance of energy transformations - Carnot's efficiency for a heat machine

Carnot's maximum efficiency

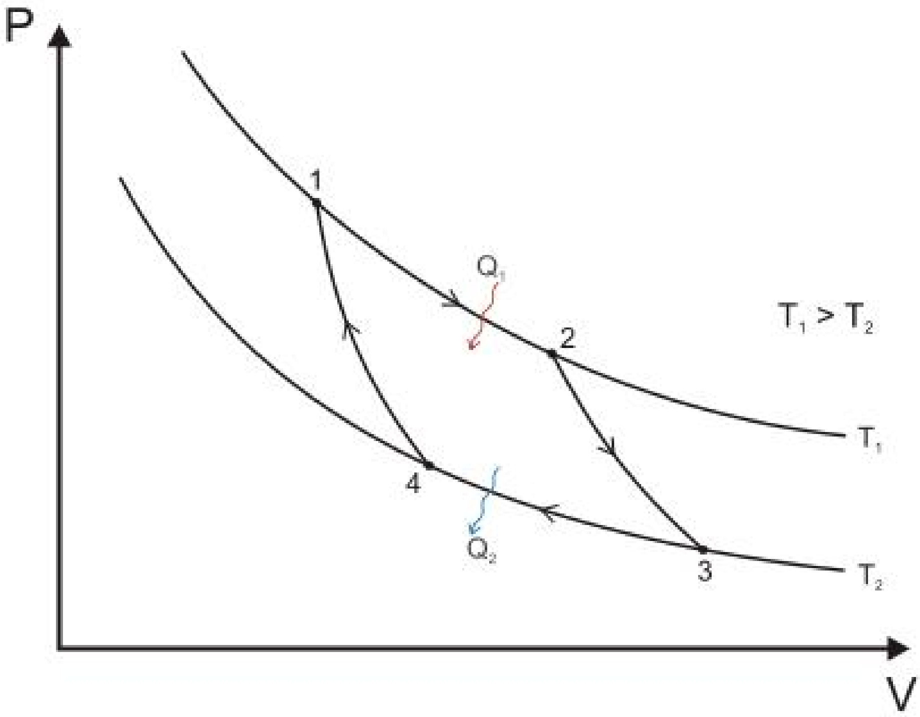
$$\eta_c = 1 - \frac{T_2}{T_1}$$

Efficiency according to the first law of thermodynamics

$$\eta_I = \frac{W_{net}}{Q_1}$$

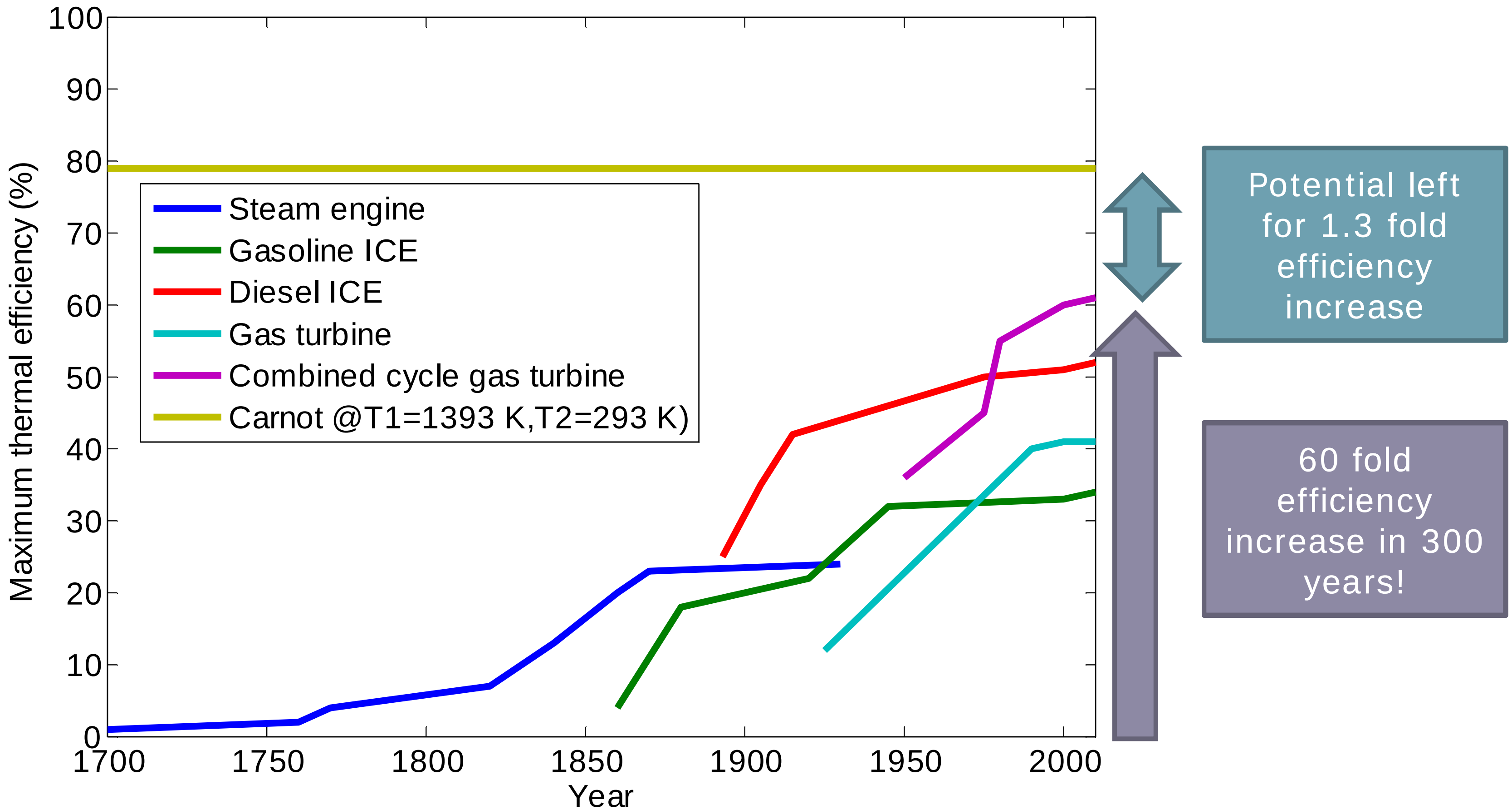
Efficiency according to the second law of thermodynamics

$$\eta_{II} = \frac{\eta_I}{\eta_c}$$



For real systems $\eta_{II} < 1$

Technology evolution – Maximum thermal efficiency of prime movers



"V. Smil, Energy Transitions – History, Requirements and Prospects, 2010, ABC-CLIO LLC" used as a source of information

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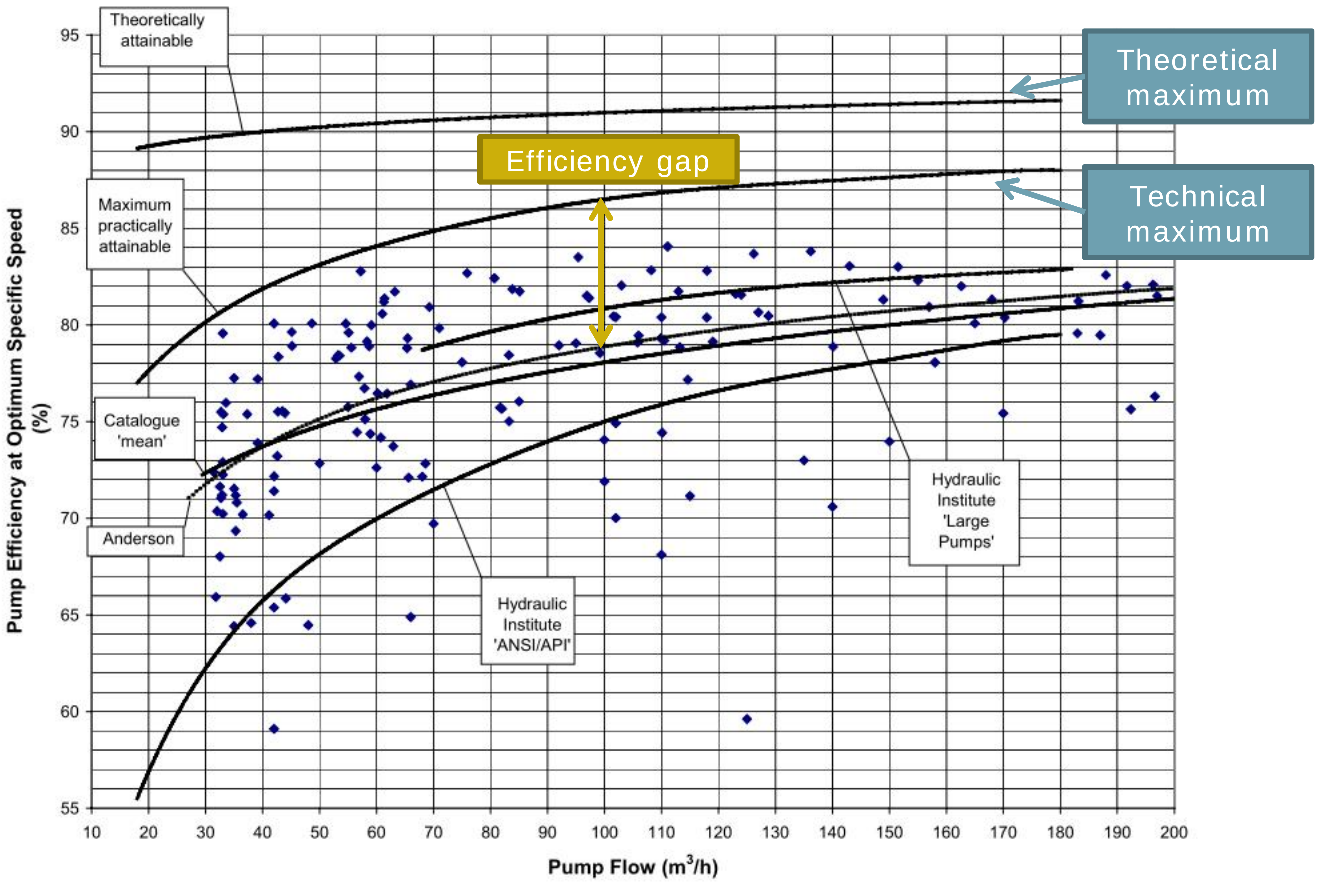
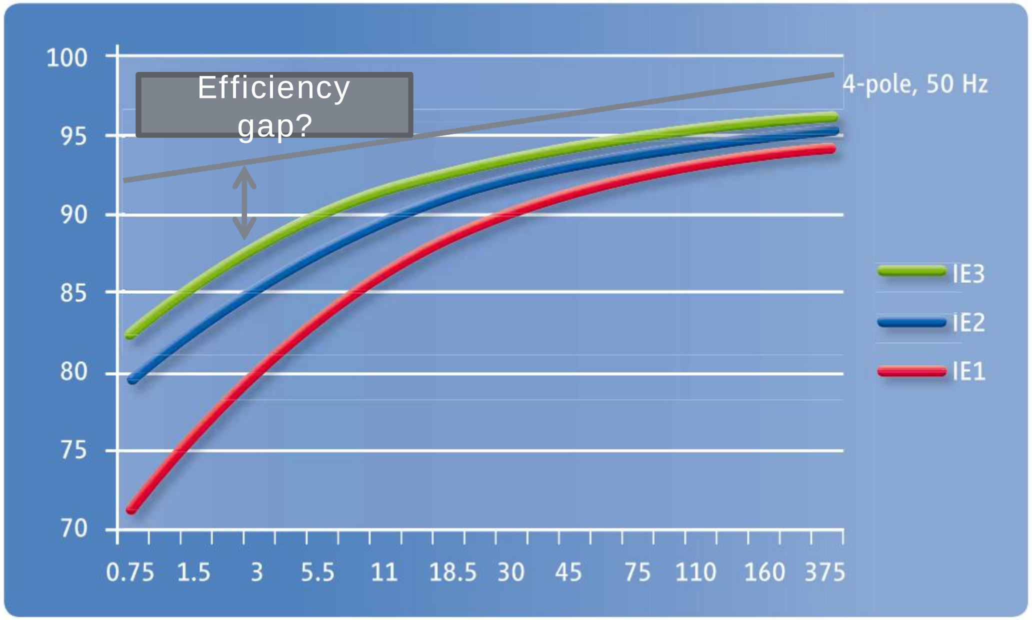
Efficiency of pumps at optimal rotation speed



Source: Study on improving the energy efficiency of pumps, European Commission, 2001.

Standard efficiency level curves for 4-pole 50 Hz low-voltage three-phase motors

Efficiency at nominal operation point (%)



Nominal power (kW)

Source: CEMEP, Electric motors and variable speed drives – Standards and legal requirements for the energy efficiency of low-voltage three phase motors, October 2010.

Productivity of research investments

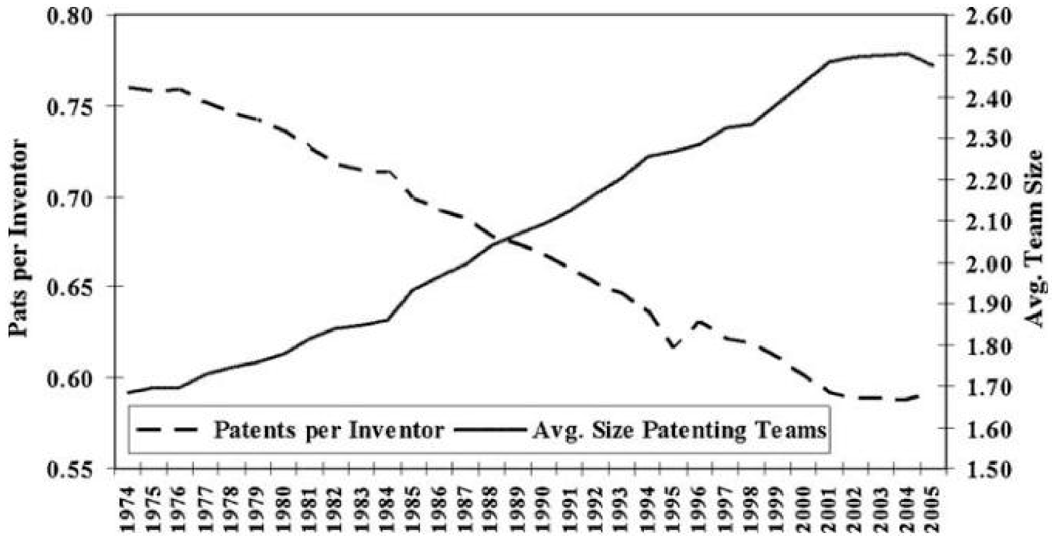


Figure 2 Average size of patenting teams and patents per inventor, 1974–2005

= Cost/patent increasing

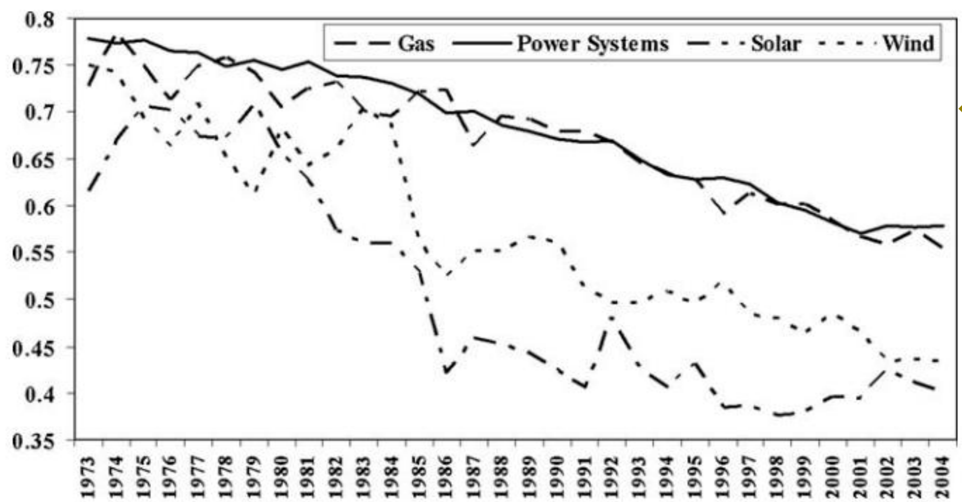


Figure 5 Patents per inventor in energy technologies, 1974–2005

Applies also to the solar and wind power

Source: D. Strumsky, J. Lobo, J. Tainter, Complexity and the Productivity of Innovation, in Systems Research and Behavioral Science, 27, 496-509, 2010

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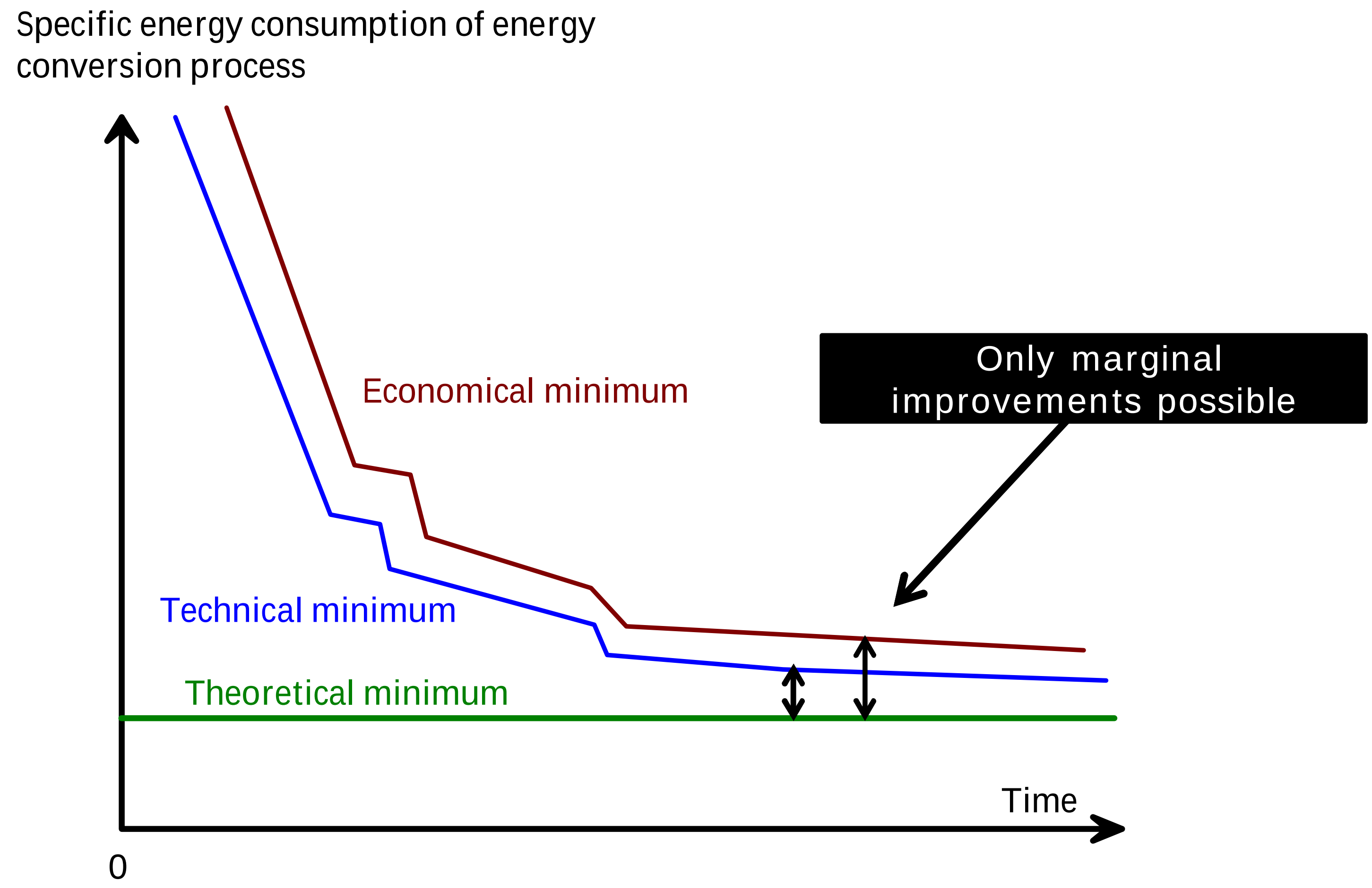
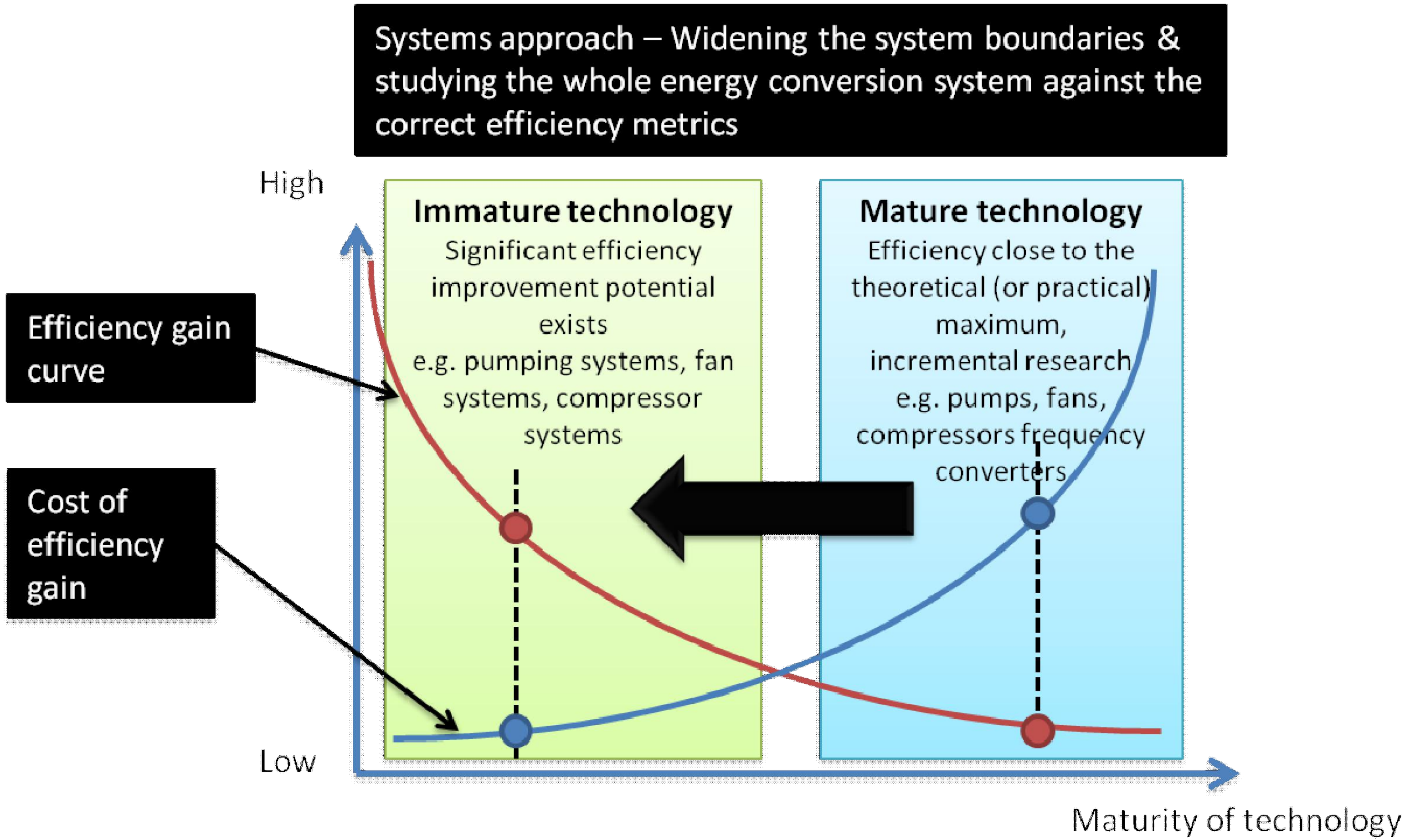
Specific energy "consumption" of an energy conversion process



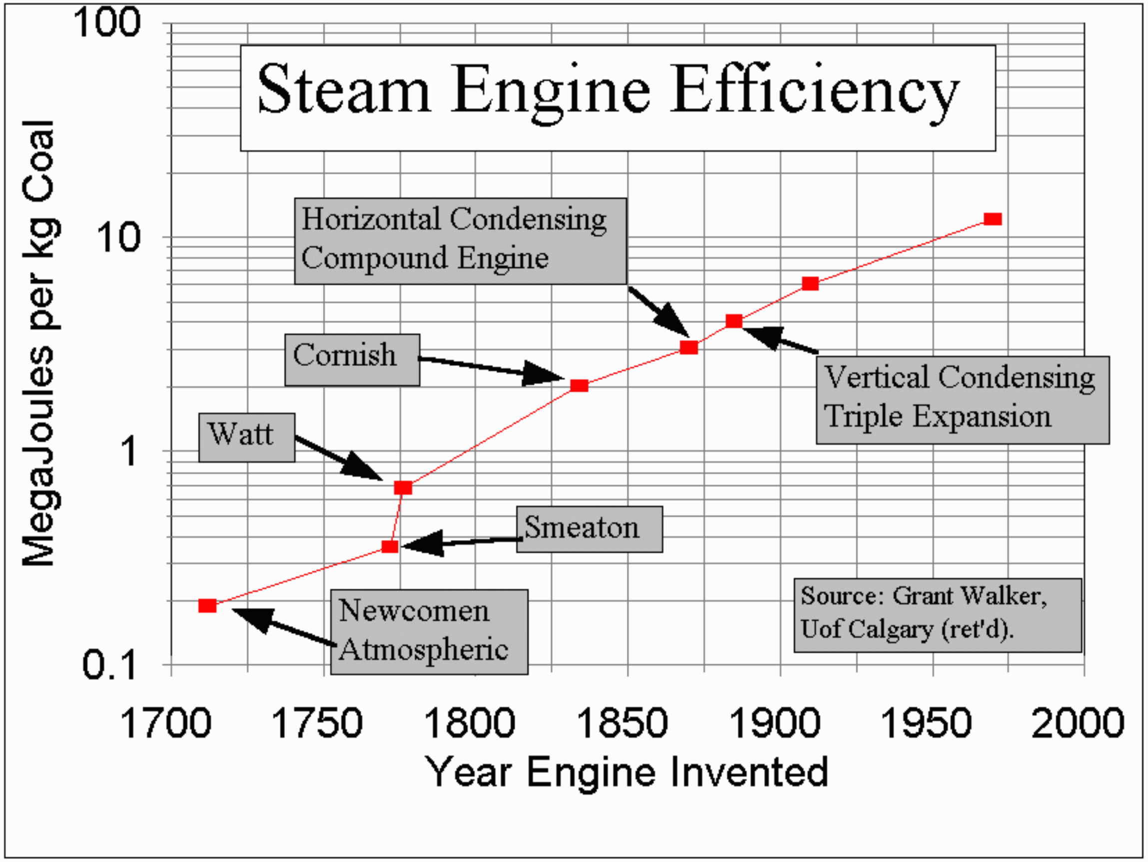
From diminishing returns of R&D in energy efficiency to radical improvements?



Rebound effect in energy efficiency - Background

4 times of work for the same amount of coal

Thomas Newcomen's (1663 – 1729) engine → James Watt's (1736 –1819) engine



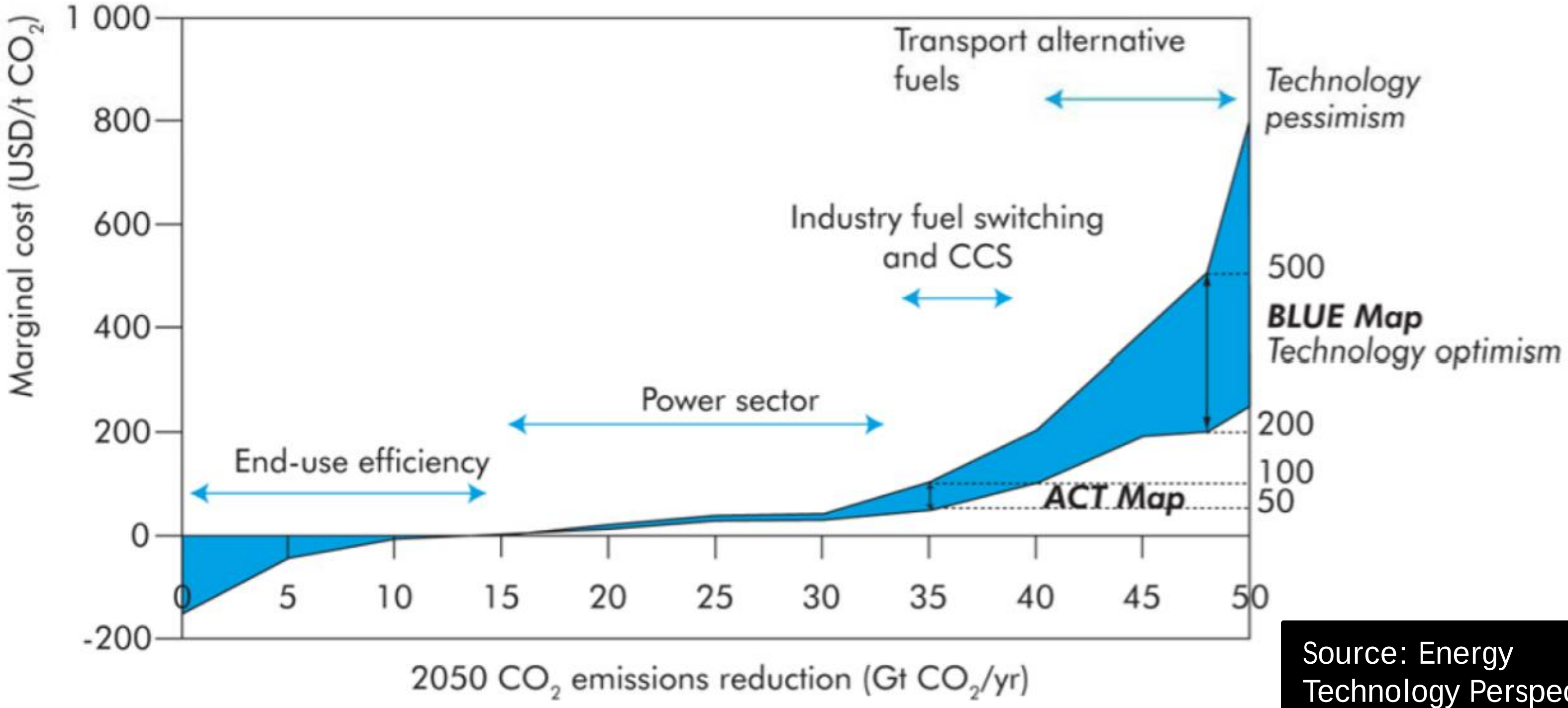
Rebound effect – Jevons' paradox

- In 1865 English economist William Stanley Jevons published a book: *"The Coal Question: An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of our Coal-Mines"*

"When improvements in technology make it possible to use fuel more efficiently, the consumption of to fuel tends to go up, not down"

Figure 1. William Stanley Jevons, [source: wikipedia]

Energy efficiency and CO_2 emissions

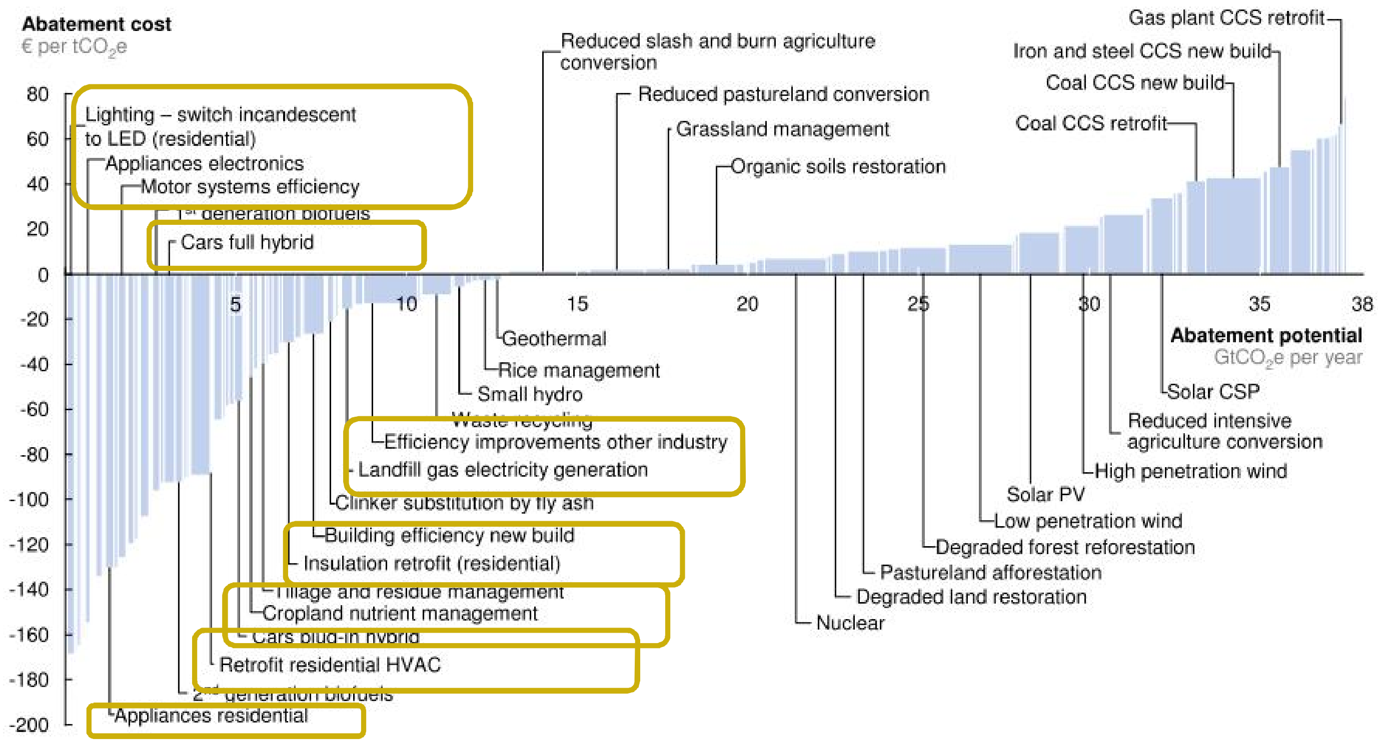


Source: Energy Technology Perspectives 2008, International Energy Agency 2008.

Energy efficiency and CO_2 emissions – more detailed view

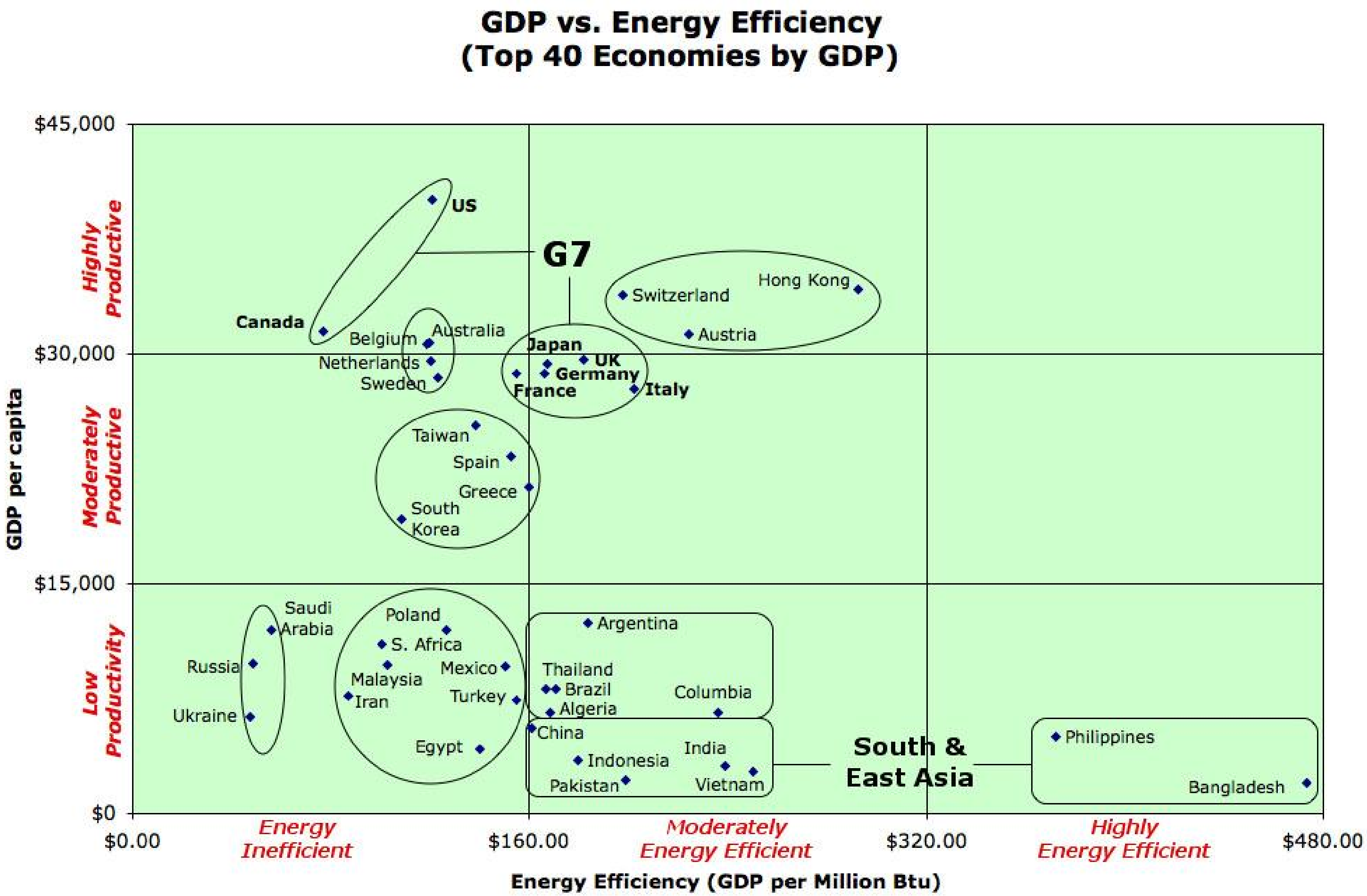
Exhibit 6

V2.1 Global GHG abatement cost curve beyond BAU – 2030



Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €80 per tCO_2e if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.1

GDP vs. Energy Efficiency in Top 40 Economies



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Part III: Electric energy consumption in electric motors

Electrical energy use in electrical motors

In EU area electric motors are responsible for 69 % of total electricity consumption of industry sector and 38 % of services sector

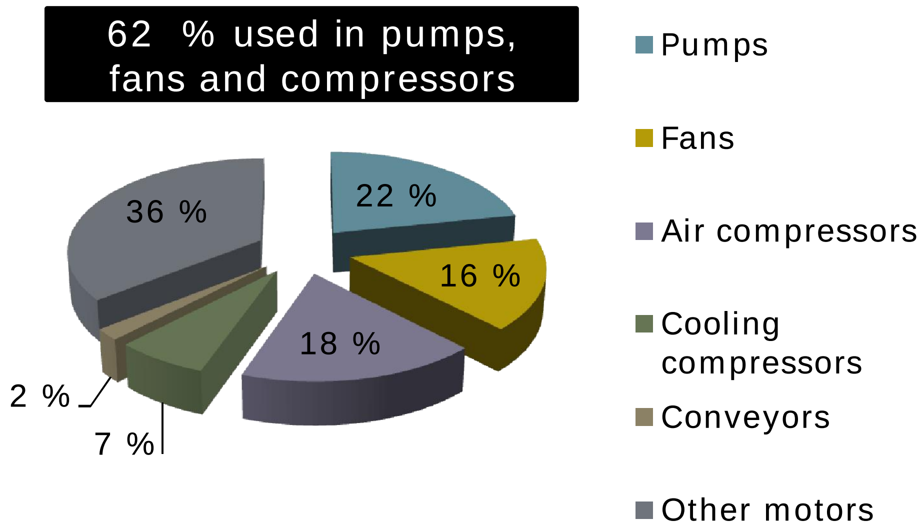


Figure. Share of motor electricity consumption by end-use in industrial sector

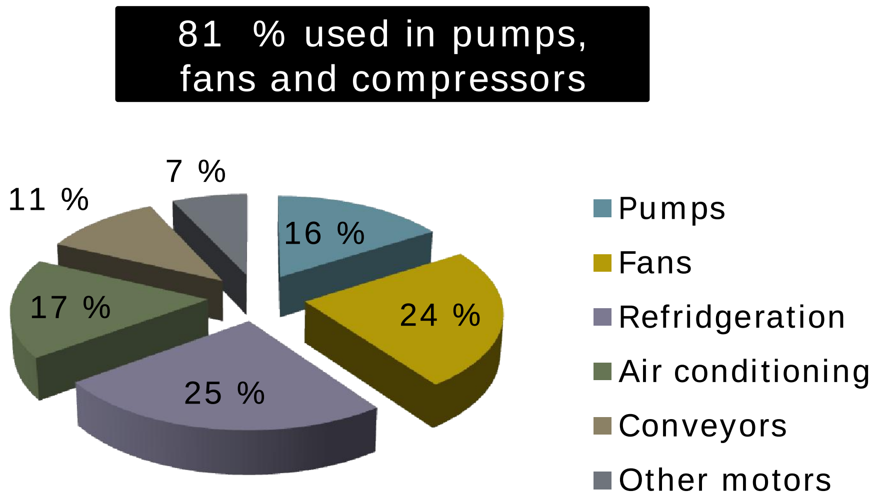


Figure. Share of motor electricity consumption by end-use in services sector

Source: Anibal. T. de Almeida, Paula Fonseca, Hugh Falkner, and Paolo Bertoldi, Market transformation of energy-efficient motor technologies in the EU, in Energy Policy, 31, 2003, pp. 563-575.

The electric energy use of electric motors in industrial sector by power range

In industry P_n > 10 kW motors are responsible for more than 80 % of electrical energy consumption

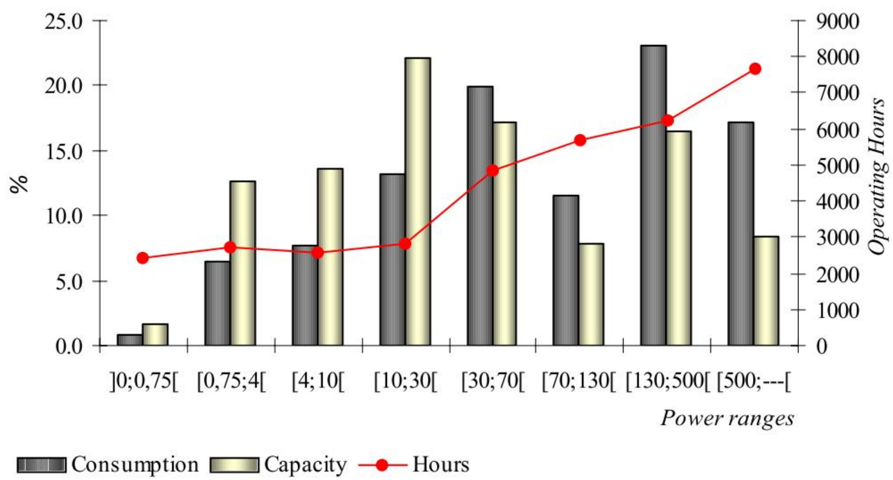


Figure. Installed nameplate capacity, electricity consumption and average operating hours by power range in the industrial sector

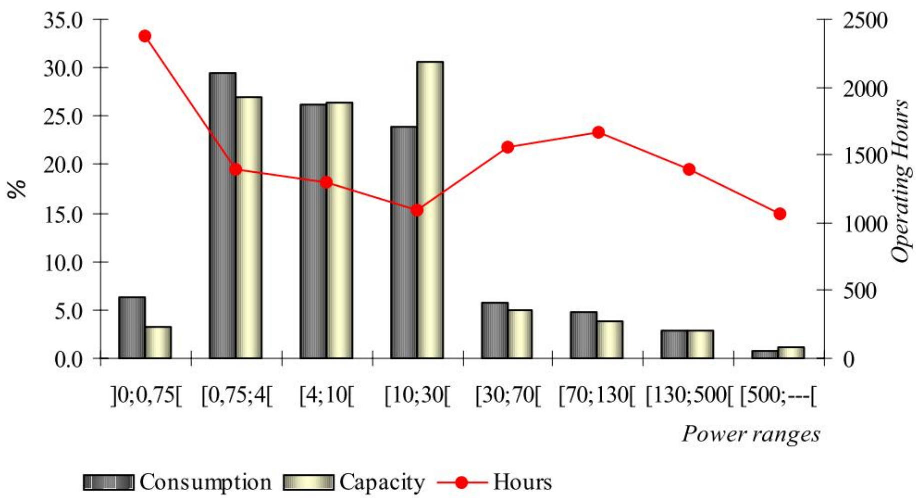
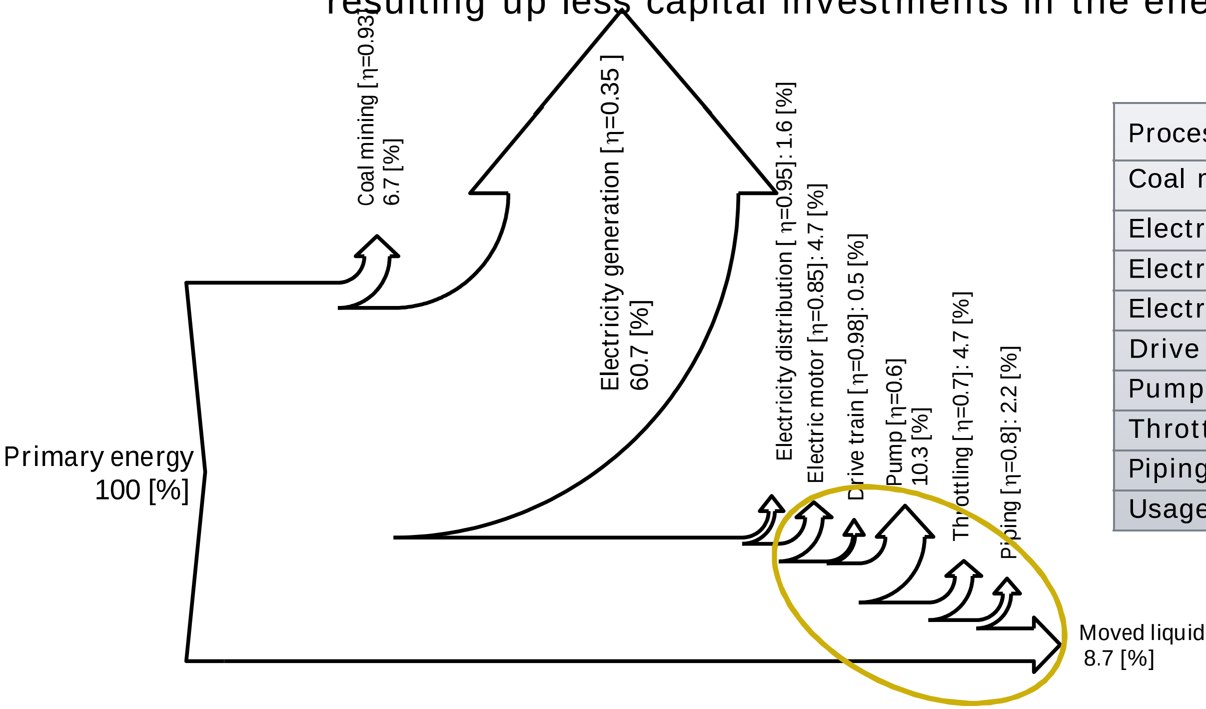


Figure. Installed nameplate capacity, electricity consumption and average operating hours by power range in the services sector

Source: European Commission, Improving the Penetration of Energy-Efficient Motors and Drives, 2000

Energy conversion chain example – Efficiency of liquid pumping

- Due to losses in the energy conversion chain
  - Saved Joule close to the end use location may result up 10 J savings in the primary energy
  - By improving end use efficiency the amount of delivered energy decreases resulting up less capital investments in the energy conversion chain



Process stage	Gain (J/J)
Coal mining	1
Electricity generation	1.1
Electricity distribution	3.1
Electric motor	3.2
Drive train	3.8
Pump	3.9
Throttling	6.5
Piping	9.2
Usage	11.5

$$P_{in} = \frac{P_{out}}{\eta_{Cm}\eta_{Eg}\eta_{Ed}\eta_{Em}\eta_{Dt}\eta_{Pu}\eta_{Th}\eta_{Pi}}$$

Figure. Efficiency of the energy conversion process from the primary energy to the potential and kinetic energy of the moved fluid

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Part IV: Life-cycle-costs in pumping and fan systems

LCC case study – Pulp pump in a paper mill

- Supplies pulp to the paper machine
  - Ahlström ARP 54-400 centrifugal pump
  - 400 kW 6 pole Strömberg induction motor
  - ABB ACS 600 frequency converter
  - Malfunction will cease the paper production (5000 €/h)
  - Calculation period was 10 years
  - Energy price: 55 €/MWh
  - Power requirement 400 kW, 8000 h/a
  - Interest rate: 4 %/a, inflation 1.6 %/a
- Maintenance costs and the amount of possible production losses were estimated by forming the FMECA for the drive on the basis of interviews and maintenance logs

Source: T. Ahonen, J. Ahola, J. Kestilä, R. Tiainen and T. Lindh, "Life-cycle cost analysis of inverter driven pump", in the *Proceedings of Comadem 2007*, 12-15th June, Faro, Portugal, 2007.

LCC Case study – Exhaust blower in a pulp mill

- Responsible for the exhaust of steam from the heat recovery system in a pulp mill
  - Fan: 986rpm, 41.2m^3/s, 1950Pa
  - Motor: 132kW, 986rpm
  - Driven by frequency converter
  - Energy price: 50 €/MWh
  - Power requirement 100 kW, 7000 h/a
  - Interest rate 4%/a, inflaation 1.6 %/a
- Critical for the production
  - The failure of the fan stops the pulp drying fan
  - After eight hours the pulp production has to be stopped
  - Estimated cost of failure is 10k€/h (production losses)
- Calculation time 15 years

Source: Jussi Tamminen, Tero Ahonen, Jero Ahola and Juha Kestilä, " Life Cycle Costs in Industrial Fan Drives – Case Study", in the *Proceedings of BINDT 2010*, Birmingham, UK, 2010

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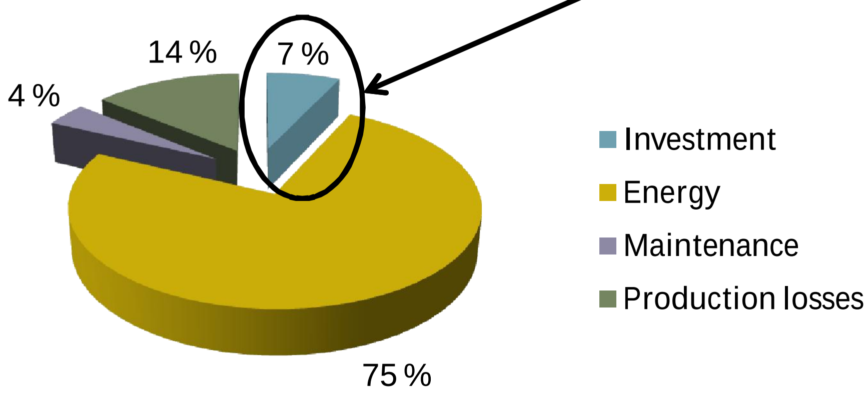
The results of LCC estimations

E.g. 80 % of all LCC costs is bound in the design and investment phase

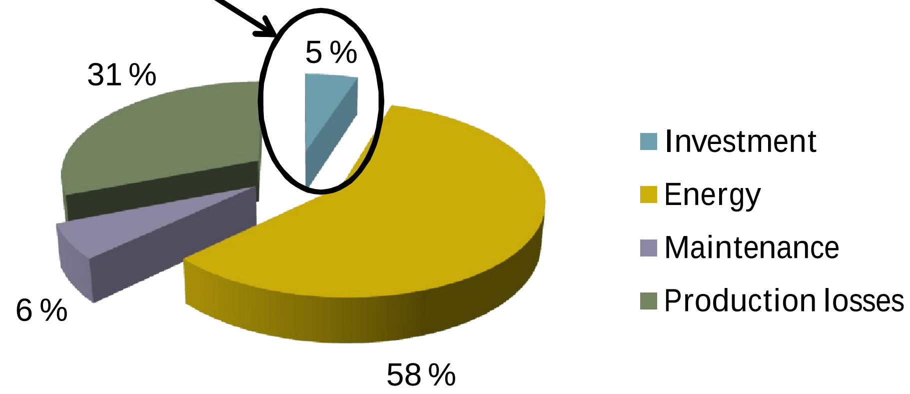
Pulp pump

$P_{e,N}$=400 kW, period = 10 a



Exhaust blower

$P_{e,N}$=132 kW, period = 15 a



Part V: How to improve energy efficiency in pumping and fan systems

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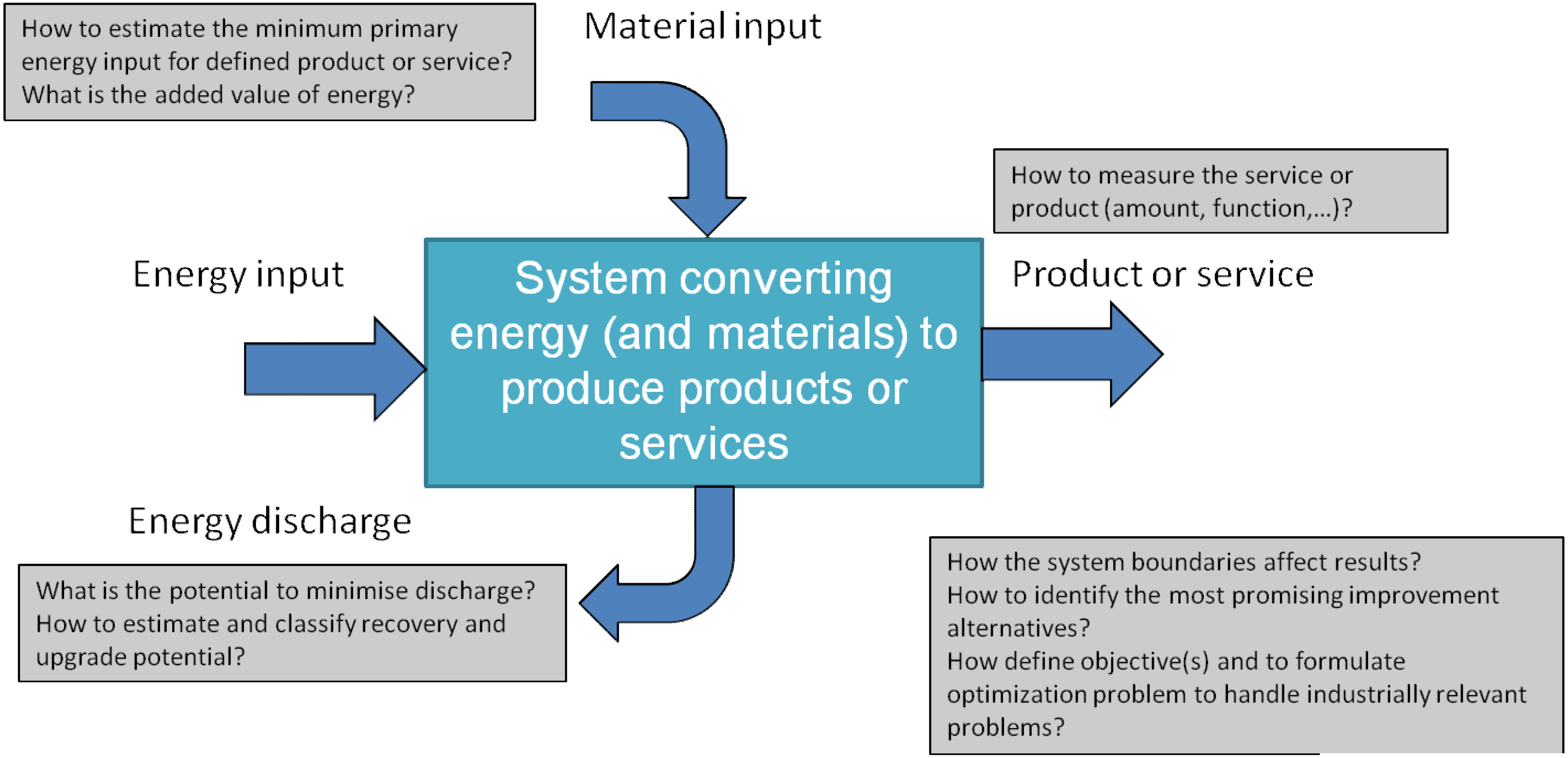
Efficient Energy Use

System energy efficiency analysis and optimization – The main questions



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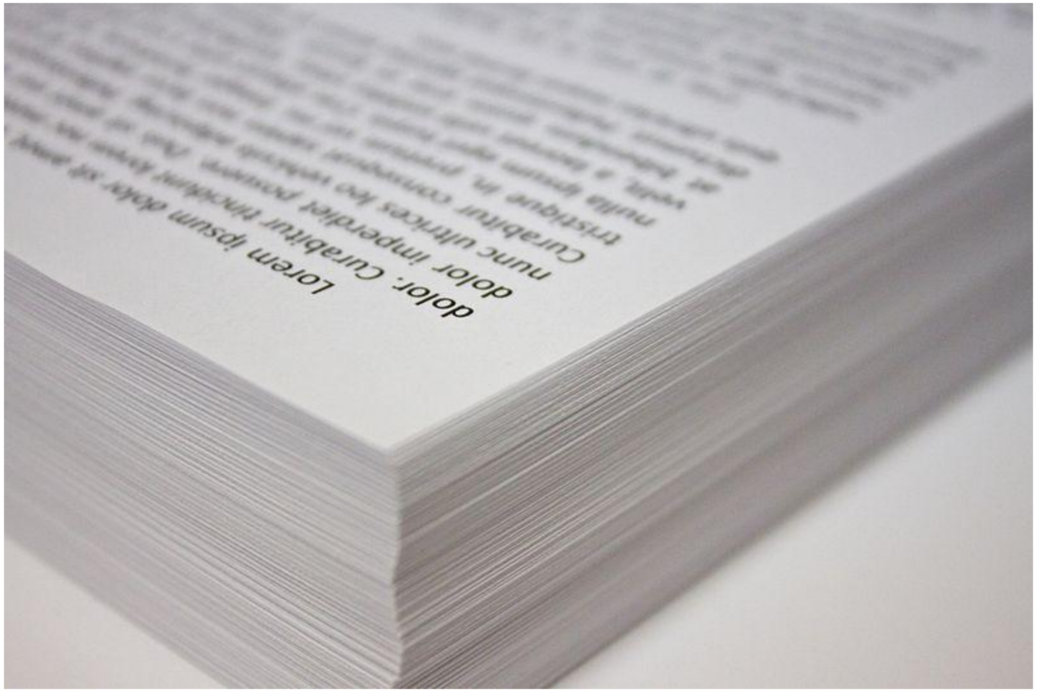
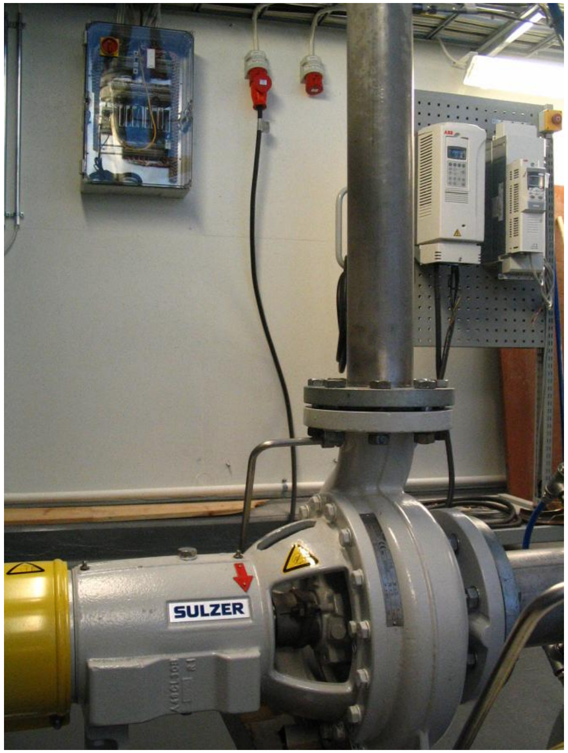
What is the correct energy efficiency metrics for the energy conversion process?

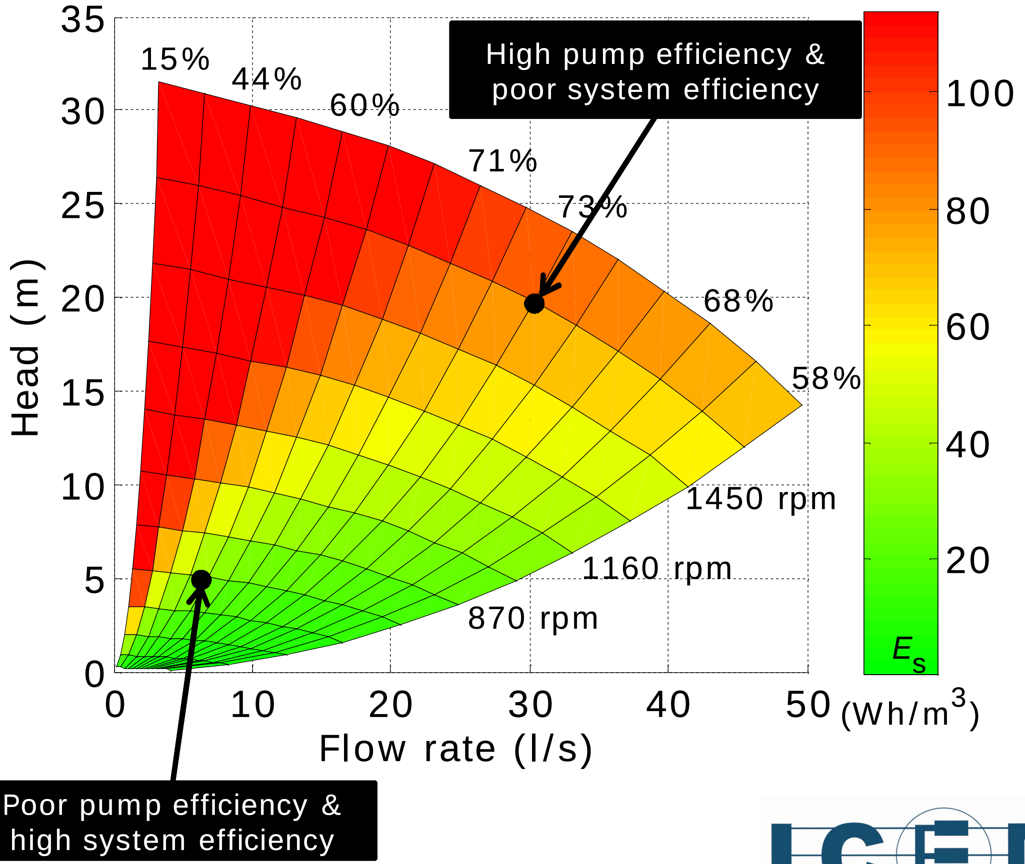
Efficiency of production measured with metrics kWh/t?
However, the main function of paper is to operate as information surface (metrics kWh/m2)



What is the correct energy efficiency metrics for the energy conversion process?

Components of pumping systems are designed with efficiency at nominal point (BEP)
However, the energy efficiency metrics for the user of pumping system is (kWh_e/m3)





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Design and optimization guidelines to energy efficient system

Traditional optimization:

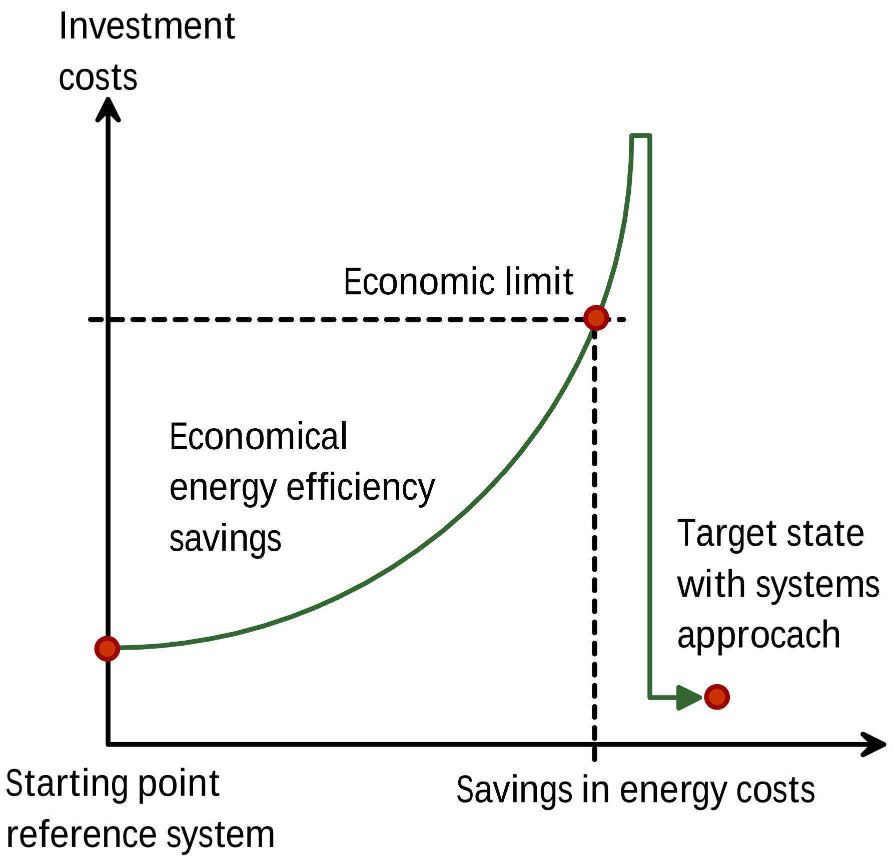
- The efficiency investments are decided on device level (additional cost vs. saved energy)

Widening the system boundaries:

- Over-investment in the end of the energy conversion chain may bring along even more savings elsewhere in the energy chain
- Co-benefit: the system reliability may improve

Examples:

- Over-insulation of building – both heating and cooling system may become un-necessary
- Extremely high efficiency inverters and motors -> no need of active cooling, improved reliability
- Over-dimensioned piping in pumping systems, decreased pump size, motor size and inverter size



Amory Lovins and Rocky Mountain Institute, Reinventing Fire – Bold Business Solutions for the New Energy Era, Chelsea Green Publishing Company, 2011, USA.

Piping is often designed based on beauty and placement of pumps and motors instead of optimization of energy efficiency

Figure: Advanced Energy Efficiency, Lecture 2: Industry (Amory Lovins 2007)

Figure. Old pumping system laboratory in LUT

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Example – The importance of piping design

CASE A: friction loss 100%

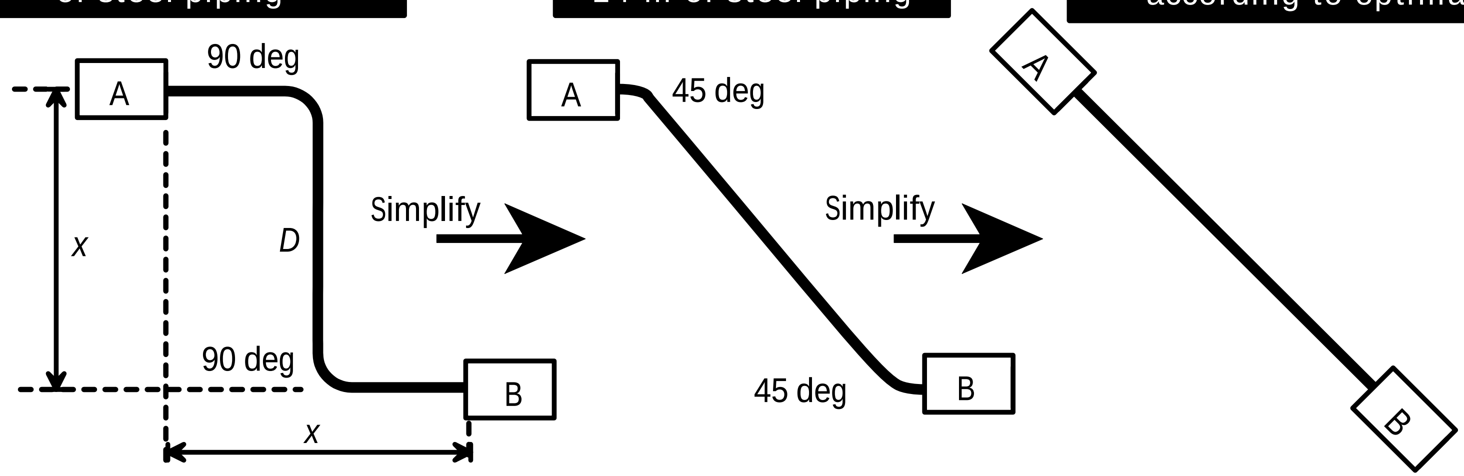
CASE B: friction loss = 60 % from CASE A

CASE C: friction loss 28 % from CASE A

2 * 90 deg bends & 20 m of steel piping

2 * 45 deg bends & 14 m of steel piping

14 m of steel piping, pump placed according to optimal piping



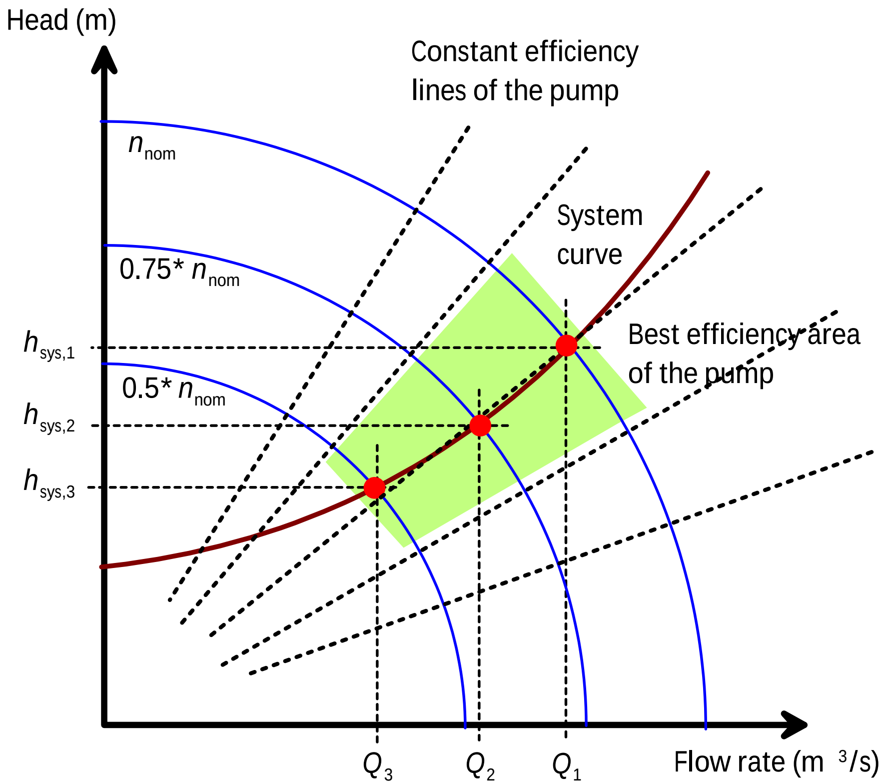
$$h_{\text{dyn, pipe}} = f_{\text{T}} \cdot \frac{v^2}{g} \cdot \frac{L}{D}$$

$$h_{\text{dyn,bends}} = \frac{v^2}{g} \left(\sum_{1}^{n} K_i \right)$$

Parameter values used in example:
x = 10 m, D = 0.5 m, f_T = 0.02 , K_{90} = 30 * f_T,
K_{45} = 16 * f_T

Speed control of a pump - The main tool for the energy savings in pumping systems with centrifugal pumps

QH-curves of a pump: Rotation speed control allows the flow rate or pressure control of a centrifugal pump without adjusting system curve



Required system head an electrical power of the pump

$$h_{sys}(Q_v) = h_{st} + kQ_v$$

$$P_e = \eta_{fc}\eta_{em}\eta_p \rho g h_{sys} Q_v$$

Affinity equations, the effect of rotation speed change to the pump

$$h = \left(\frac{n}{n_n}\right)^2 \cdot h_n$$

$$Q_v = \left(\frac{n}{n_n}\right) \cdot Q_{v,n}$$

$$P = \left(\frac{n}{n_n}\right)^3 \cdot P_n$$

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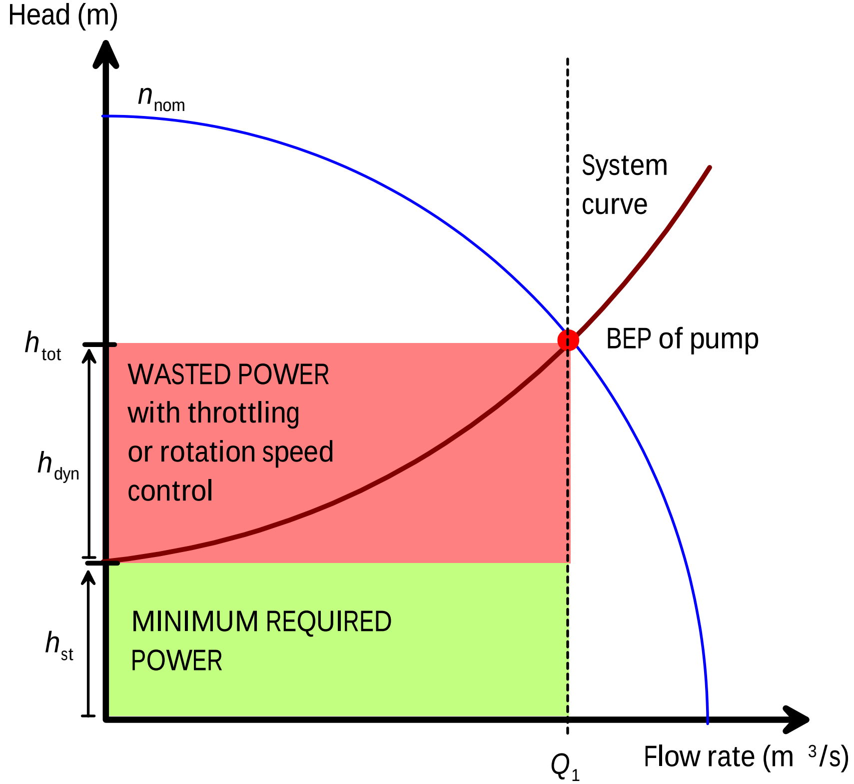
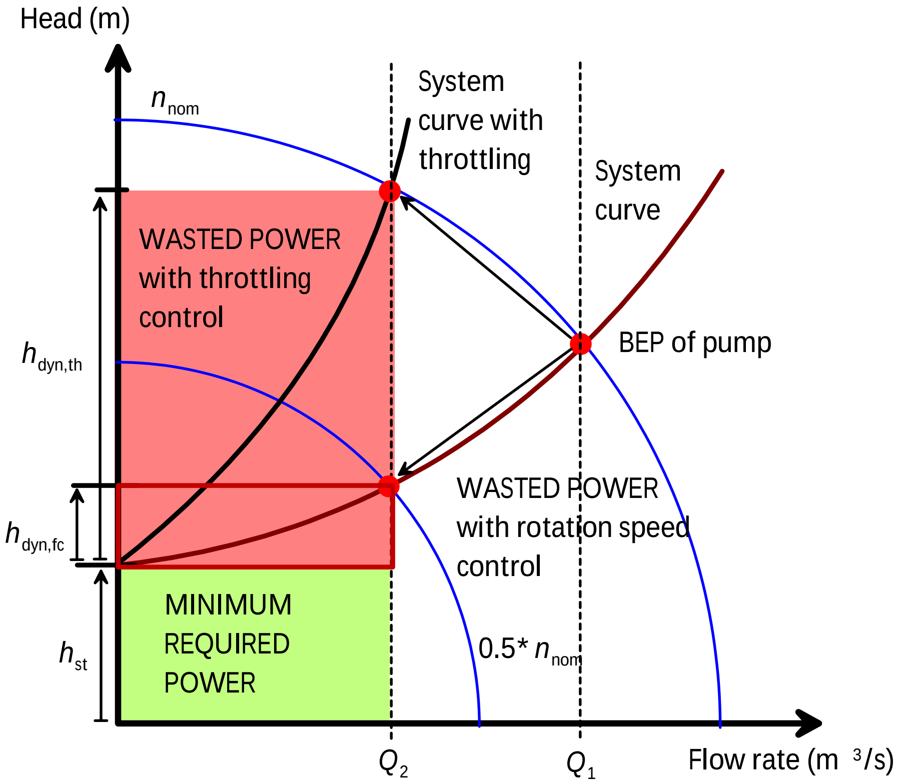
The effect of dynamic head and control method to the energy efficiency of pumping

Case 1: Static operation point, high friction losses in piping



Case 2: Throttling control and rotation speed control with the previous example



The dimensioning is also in a key role in the energy efficiency of the electric motor

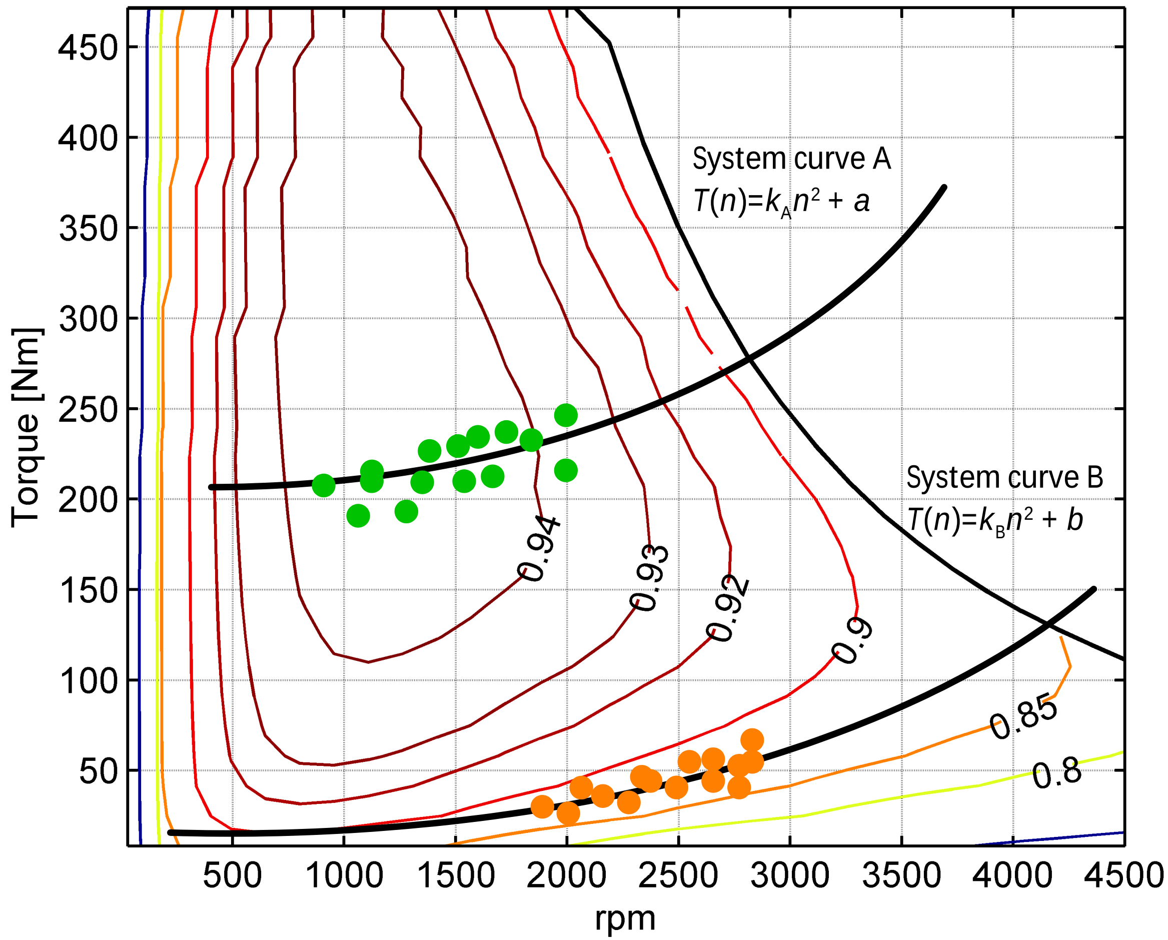


Figure. Efficiency map of an induction motor with two system curves for a pumping process

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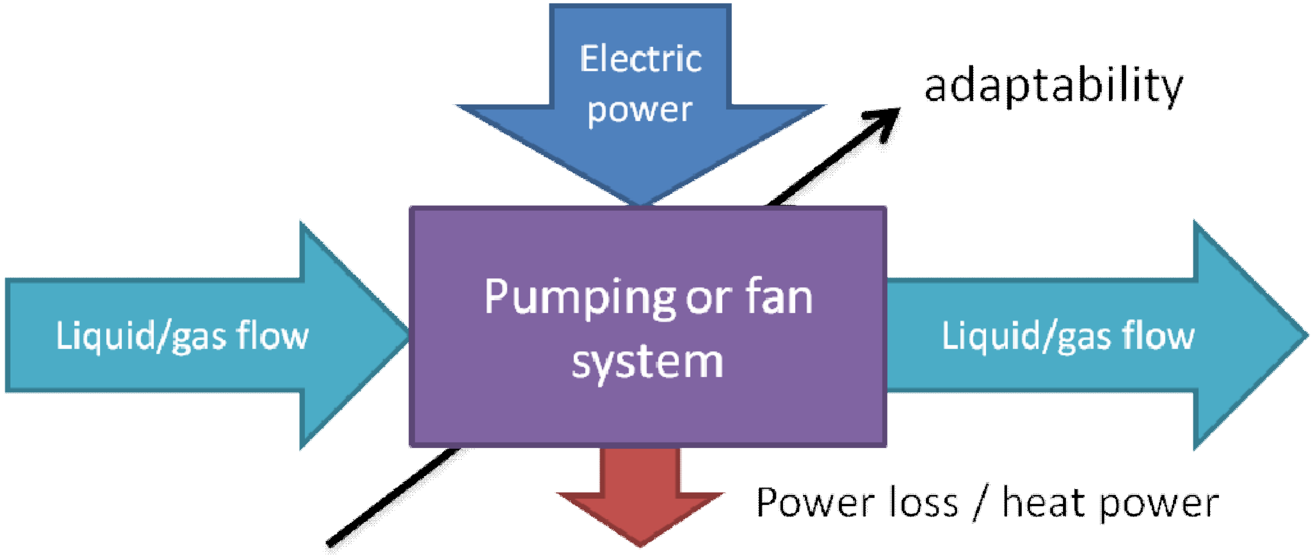
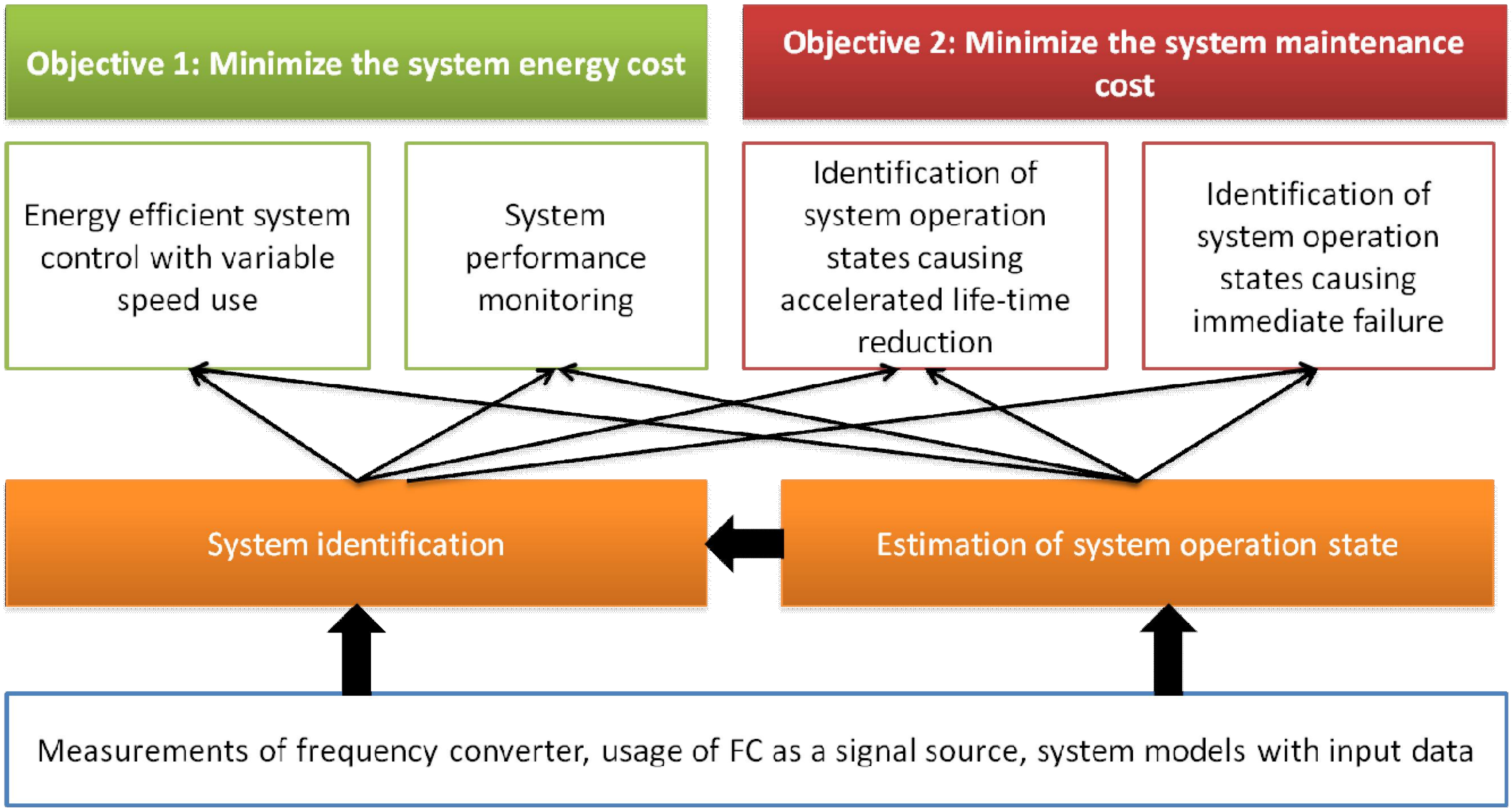
Would it be wise to try to adapt instead of trying to change dimensioning practices?

Only the energy efficiency that comes true is important – High efficiency system components, control methods and algorithms are just tools for this purpose



The role of frequency converter in life-cycle cost efficient pumping and fan systems (system operation phase)



Conclusion

- There are several drivers forcing to improve end use energy efficiency
- The main sources of “wasted primary energy” are the generation of electricity and transportation
- Energy efficiency is the only means mitigating the climate change having the negative cost
- Role of correct metrics in optimization of energy efficiency is essential
- The systems approach makes it possible to improve energy efficiency radically
  - Helps to avoid sub-optimization
  - Requires multi-disciplinary team
- Energy efficiency is not just technology
  - Technology provides means
  - Solutions are required to implement energy savings in practice