Energy intensitites, EROI (energy returned on invested), for electric energy sources

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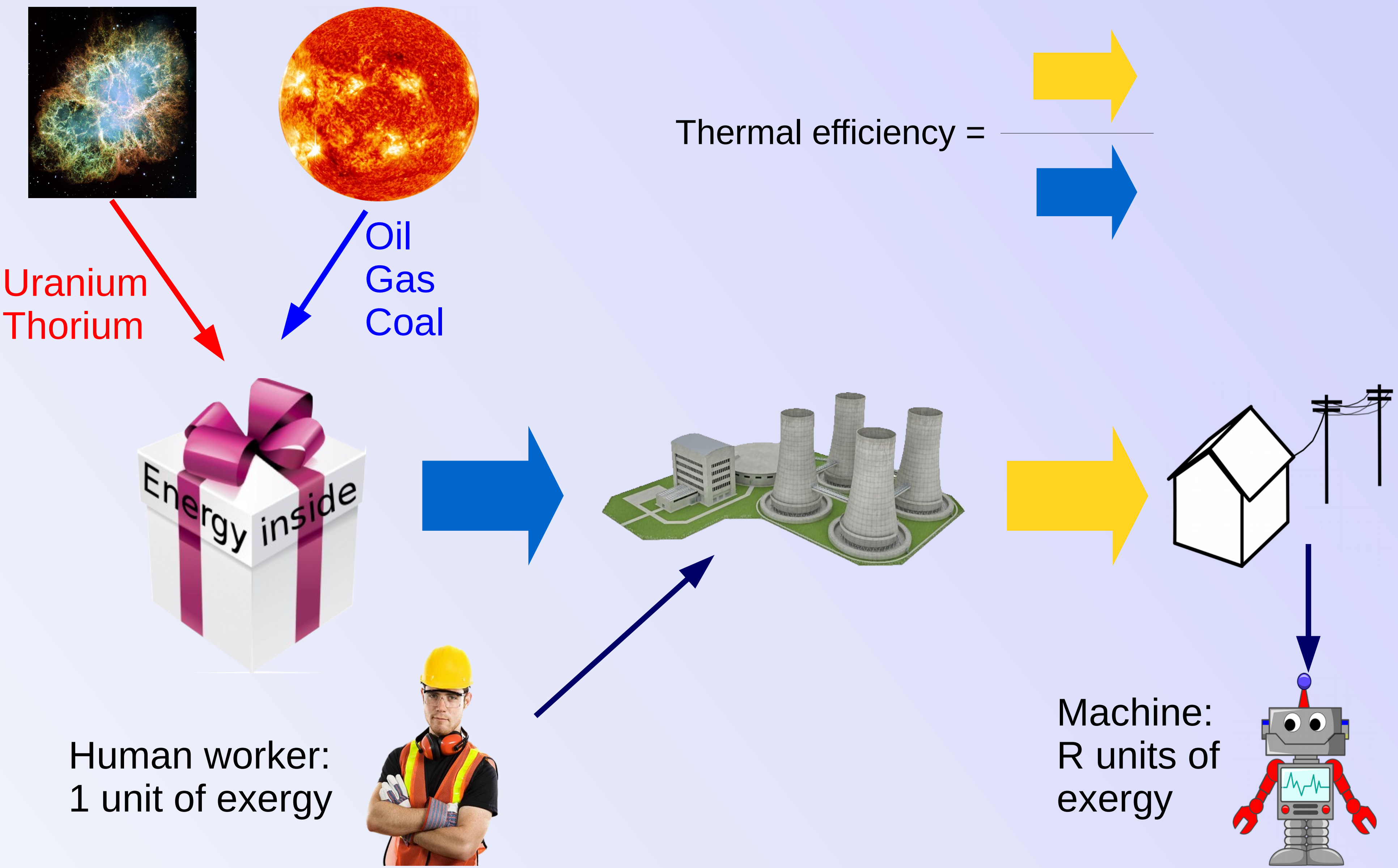
Exergy and Efficiency



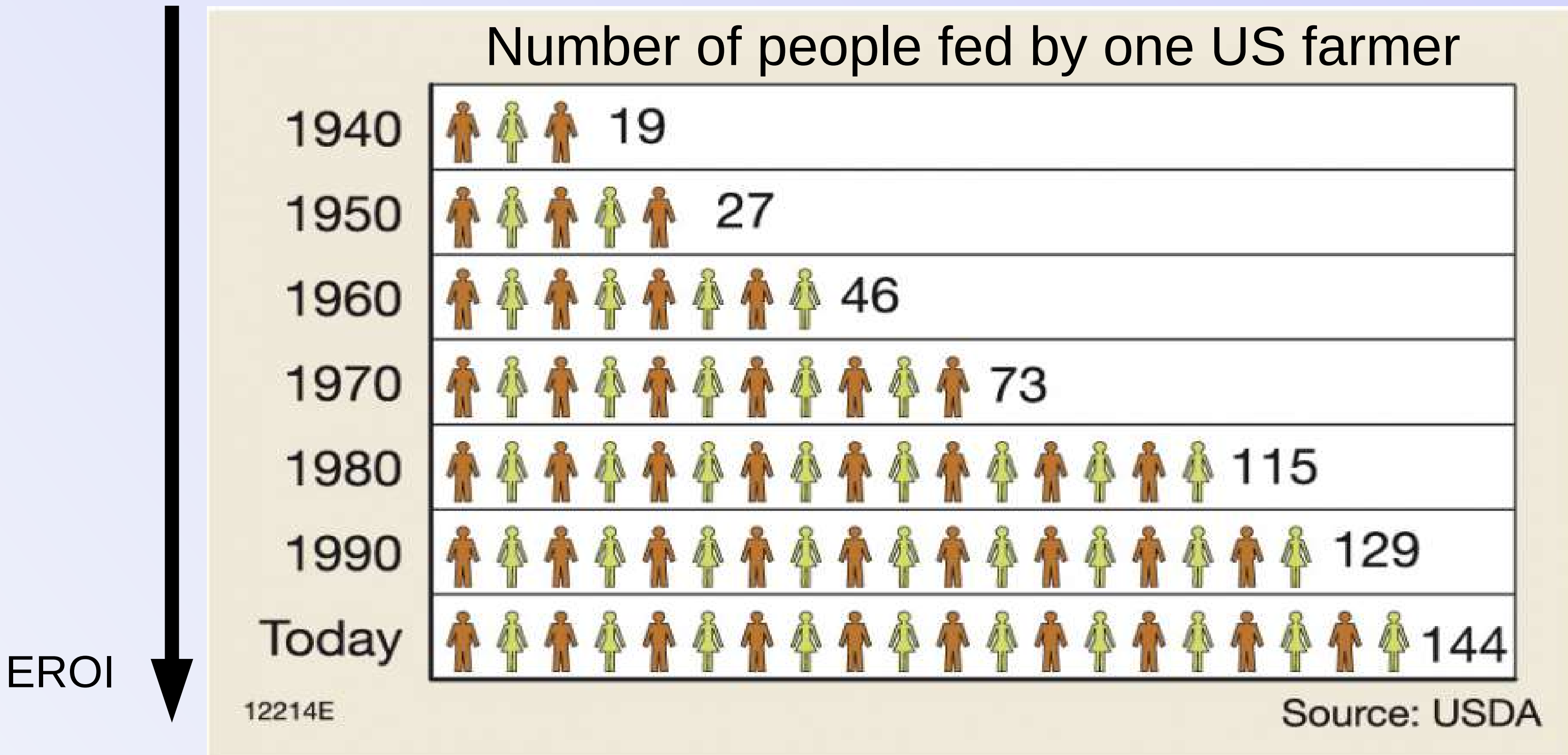
Impact of EROI Increase on Human Civilization

They produce sufficient food for themselves and at best a few other people.

Impact of EROI Increase on Human Civilization

The combine harvester, driven by a heat engine, accomplishes as much as hundreds of pre-industrial peasants.

Impact of EROI Increase on Human Civilization



The increase of sated people / farmer is even greater than the EROI rise (single digit → ~ 30). Enhancing usable exergy often triggers avalanches of innovations – here, artificial fertilizers, pesticides, genetic engineering, etc. Thus, the impact on civilization can actually overtake the EROI.

Motivation

- Problem: Comparing influence of power generation systems on national economics
- Goal of analysis: Physical quantity for a power plant's economic efficiency – EROI as a multiplicator for economically relevant and valuable work

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

- Exergy: All energies have to be exergies (= Part of energy that can do mechanical/usable work). Main contributor to economy (product refining) → output of thermodynamic machines has to be analyzed
- Methodology criteria: comparability, EROI invariant against non-physical issues
- Uniformity: Same conditions for all techniques (safety and environmental standards, reliable output) required for comparability

Methodology I

- Strict exergy concept: Heat output of power plant ignored. Exergy versatile for all processes (also heating)
- No output weighting: Do not weight the electrical output – otherwise it is no EROI anymore.
- No input weighting: Weighting factors are market factors (price for electricity ~ 3x price for heat) with physical background (efficiency of turbines $\eta \sim 1/3$) that might change.
- Transparency: Separate listing of exergy and heat input. So it can be easily compared with EROIs calculated by other methodologies.

As our Google table:

https://docs.google.com/spreadsheets/d/1lBK3pntKdd3bo8oAAvjnpQvYaLZp1G-ieuS5GA5NGV4

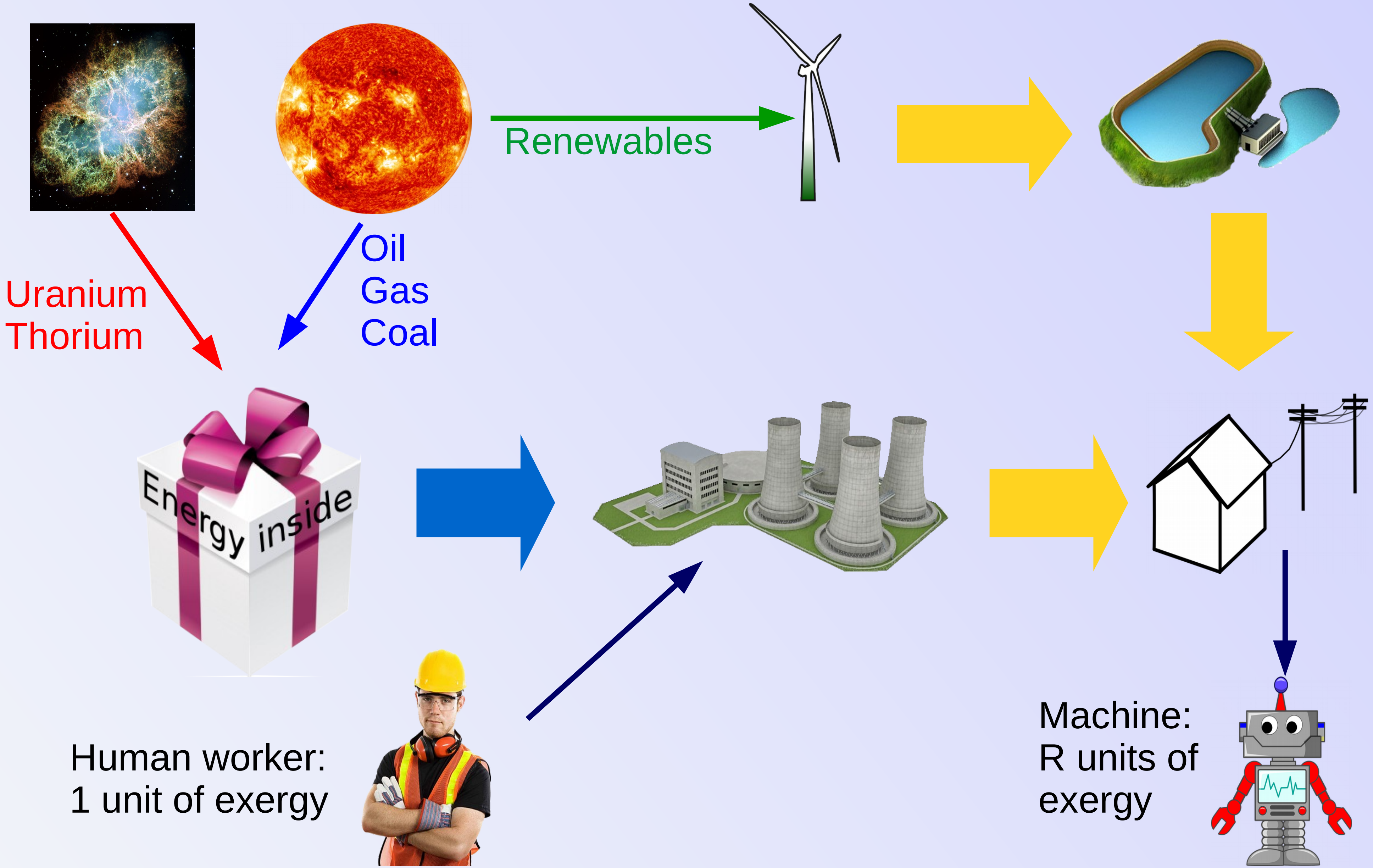
…or easier

http://tinyurl.com/z7329lh

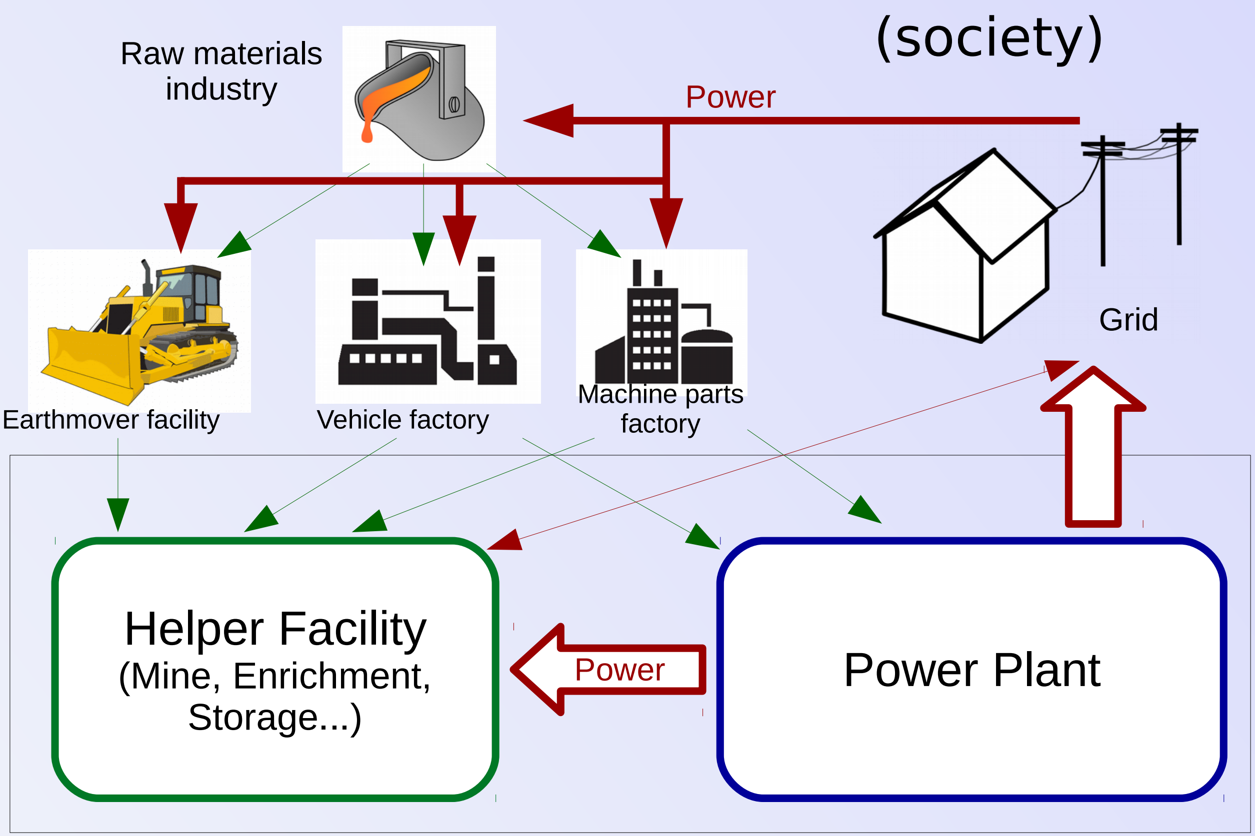
Methodology II

- Realistic: For EROI determination realistic societal exergy flows have to be considered, not theoretically achievable ones
- No non-physical efforts: Other inputs that directly or indirectly contain non-physical efforts (labor, interest,...) are ignored (see Issues) → arbitrary quantities
- Completeness: All energy needs (fuel supply, construction and decommission, operation, volatility countermeasures,...) have to be included
- Recycling: Only state-of-art material mix is considered, not exclusively recyled materials (as sometimes done by other EROI studies), worst case: Full recycling → zero input.
- No fuel energy content: Humans do not put the energy into the fuel, they just extract/refine it. Otherwise you end up with the thermodynamic efficiency η (easier to obtain from the turbine manual)

From Fuel to Exergy



Methodology – System borders



Example:
Energy demand $E_{in,2}$ of on-site pump operation

Method 1:

$$EROI = \frac{E_{out}}{E_{in,1} + E_{in,2}}$$

Method 2:

$$EROI = \frac{E_{out} - E_{in,2}}{E_{in,1}}$$

Buffering for inherent volatile techniques included
Real societal exergy/energy flows evaluated

Which one is correct?
→ „Investor's point of view"

Methodological Issues

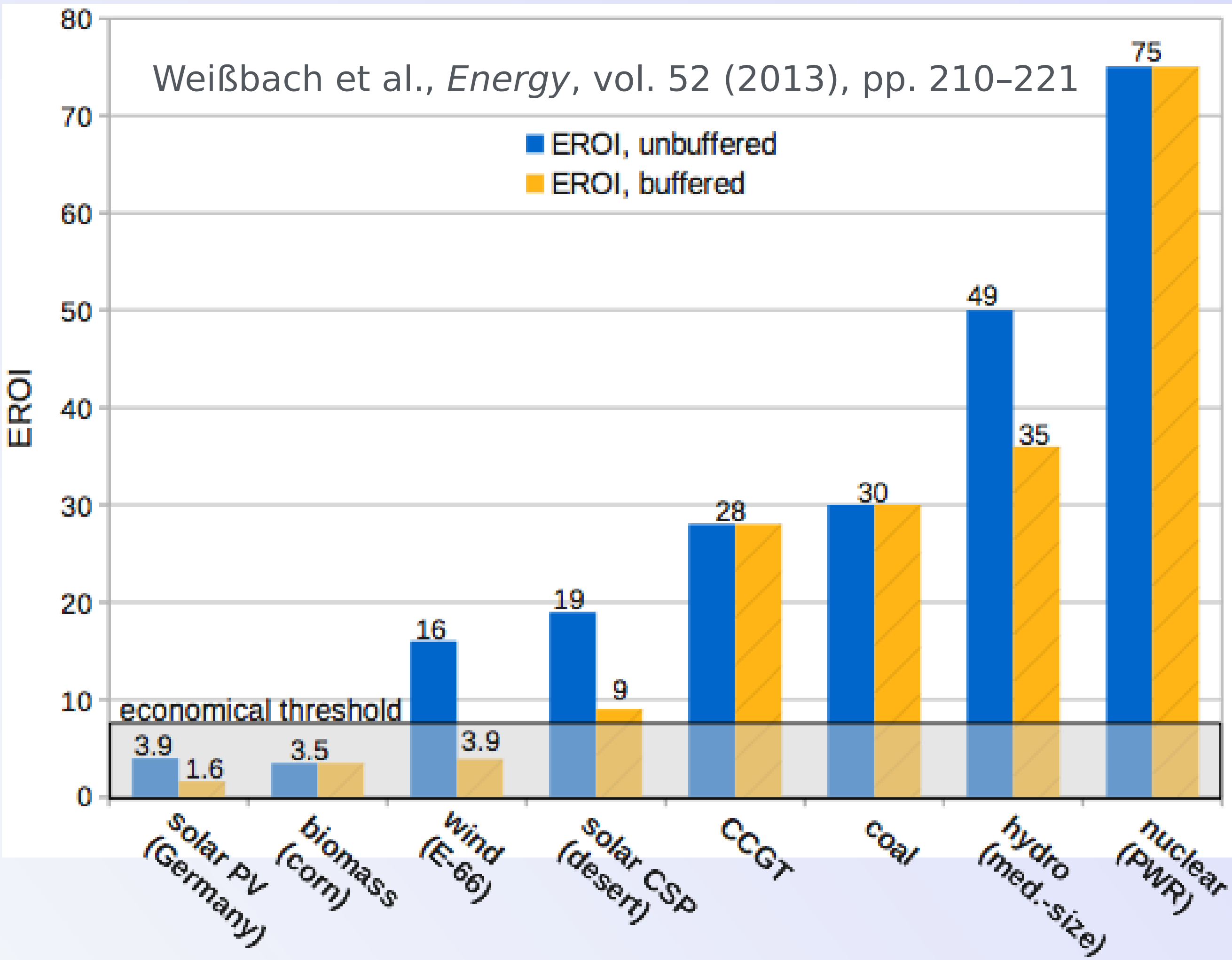
- Energy inputs without weighting hampers comparability of techniques since exergy contributions can be quite different (see transparency)
- Resource range is not reflected in the EROI (assuming a range larger than the plant's lifetime) but rather in the EROI *history* → scarcity lowers EROI.
- Other non-physical inputs (labor, interests,...) depend heavily on societal and political issues – ignored, although monetary relevant
- Using reasonable plant load with respective lifetime and maintenance

Result

EROI invariant against societal structure, but depends on actual industrial technology and location (Germany chosen for this analysis)

EROI Results

	Author 1	Author 2	Our work
Solar PV	**~2.5** (Prieto/Hall)	**>20** (Raugei)	**3.9***
Nuclear	**~2.2** (Leeuwen)	**~1** (Tyner)	**75**



*unbuffered

Raugei:
Output weighting x 3

Prieto:
Labor etc.

Leeuwen:
Old data, top-down

Tyner:
Top-down, outdated costs

Pump-storage hydro assumed for buffering – not implementable at such scales for Germany

Results and Comparison

Raugei

2.3 —(no buffering)→ 4.0 —(insolation x 1.7)→ ~7 —(output weighting x3)→ ~20

Leeuwen

75 —(lifetime reduction to 40 y)→ 50 —(enrichment/extraction far overestimated)→ ~5 —(additional top-down analysis)→ 2.2

Nuclear example

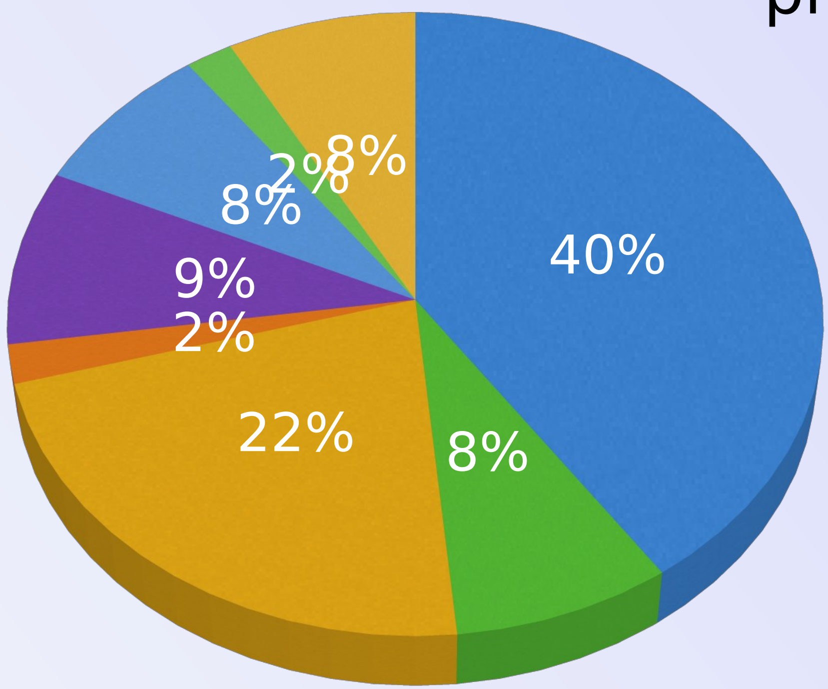
Installed capacity (net)	1,340 MW
Full-load hours	8,000
Lifetime	60 a
Output	2,315,000 TJ
Construction energy demand	4,050 TJ, thereof 35% electrical
Decommissioning energy demand	1,150 TJ, thereof 40% electrical
Maintenance energy demand	6,900 TJ, thereof 68% electrical
Fuel related energy demand	18,800 TJ (9,650 TJ), thereof 68% (40%) electrical
Sum energy demand	30,900 TJ (21,750 TJ), thereof 60% (50%) electrical
EROI	75 (105)

Is this EROI good?

	Coal		Nuclear (PWR)
EROI	30	x 2,5	75
Energy content	Hydrocarbon atom: 2 eV	x 100 mil.	Uranium nucleus: 200.000.000 eV

The expensive nuclear fuel cycle

Contributions to the energy demand in the nuclear power production



Source: Vattenfall, EPD Forsmark 2009/10

	100% Diffusion		17 % Diffusion + Centrifuge (today)		100 % Centrifuge		100 % LASER
EROI:	29	→	75	→	105	→	115

Solar PV example

Extensive analysis by P. Prieto (Les Houches, 2016) – a mixed top-down analysis

http://science-and-energy.org/wp-content/uploads/2016/03/20160307-Des-Houches-Case-Study-for-Solar-PV.pdf

Fraction of output used for	Prieto (2016)	Weißbach (2013	Comments
Manufacturing	12%	21%	difference corresponds to insolation
Installation, transports	3.5%	4.1%	Prieto: mostly top-down
Backup fraction	4%	18%	Prieto: top-down (CCGT backup), Weißbach: Pump hydro
direct/indirect labor	5.5%	0%	Prieto: 90 MWh/year per worker (primary energy)
Operation / maintenance	7.7%	0%	Prieto: top-down, Weißbach: no energy data known
surveillance, taxes, fees, insurance, PR	3.5%	0%	Prieto: top-down, money-to-energy conversion 2 kWh/euro
losses, production overcapacities, grid fraction	8% (3.5% grid-related)	0.8% (grid connection only)	Prieto: top-down, fraction of whole grid included
EROI, buffered	**2 – 3** accidently similar	**2.3**	Poly-Si, field, Prieto 1730, Weißbach 1000 full-load hours per year

Methodologies in other works

- Including primary energy (heating value) of fossile fuels in inputs
- Weighting energy quality (factor 1.5...2)
- Subtract complete inventories of recycleable materials, regardless if used, ignoring recycling energy demand, often done for renewables (factor 1.2...1.5)
- Conventional plants: Converting monetary costs into energy costs, top-down analysis (factor 2...10)
- Indirect/unphysical costs (labor,...) issue: human energy costs depend on wealth which is intended to be the consequence of EROI (factor <2)
- EROI of fuels only: Not appropriate answer to physical-economic question since no exergy output is analyzed (equivalent to output weighting)
- Renewables: no buffering taken into account to eliminate unpredictable volatility (factor 2...5)
- Large lifetime and full-load hours variance (factor 2 on average)

→ Methodological EROI variance up to a factor of 20 (renewables) and of >50 (conventional)

ToDo List

- Inventory databases should provide exergy contributions
- Publications should apply output weighting uniformly for comparison reasons (otherwise it is no EROI but replacement factor)
- Never use fuel inventories for (physical) EROI.
- No lifetime and load cheating
- Use state-of-art technology (e.g. Leeuwen)
- Inclusion of output buffering is mandatory for volatiles (PV, wind)
- EROI evaluation should mention location (if dependent on, e.g. PV, CSP, wind)
- Take care of the origin of data - do not just „take“ the EROI of a publication

Summary

Highest potential for energy saving can be found on producer’s side, not on consumer’s side.
Thus deployment of highly efficient (high EROI) power plants

Thank you

How we used storage

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

Energy demand of storage system per time and per capacity (size)

$$q := \frac{E_{in,StorSys}}{T_{storSys} \times C_{Storsys}}$$

Additional energy demand for power plant

$$E_{Storage} = E_{out} \times q \times t_{storage}$$

...plus over-capacity

$$E_{in,Buffering} = f_{Overcapacity} E_{in} + E_{Storage}$$