Energy-Return-On-Investment (EROI):

The accessibility of energy and its link with economic growth

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BEIS Workshop on EROI, 30 June 2017

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Energy and the economy

- Societies are based on the transformation of natural resources into final goods that provide useful services (food supply, protection, entertainment, etc.).
- Energy is needed to perform such changes from raw material to useful infrastructures and goods.
- Humans cannot produce energy, they can only collect it from the environment.
- It takes energy to extract primary energy from the environment (coal, oil, gas, uranium, solar flows) and refined it into final forms (liquid fuels, heat, electricity).

Definition of the EROI

- The EROI is the ratio of the quantity of energy delivered by a given process to the quantity of energy consumed in that same process.
- The EROI is a measure of the accessibility of an energy resource.
- The higher the EROI, the greater the amount of net energy delivered to society in order to support activities other than energy extraction.

$$EROI = \frac{Energy\ output}{Energy\ input}. \quad (1)$$

$$Net\ energy = Energy\ output\ - Energy\ Input. \quad (2)$$

$$Net\ energy = Energy\ output\ * \frac{EROI - 1}{EROI}. \quad (3)$$

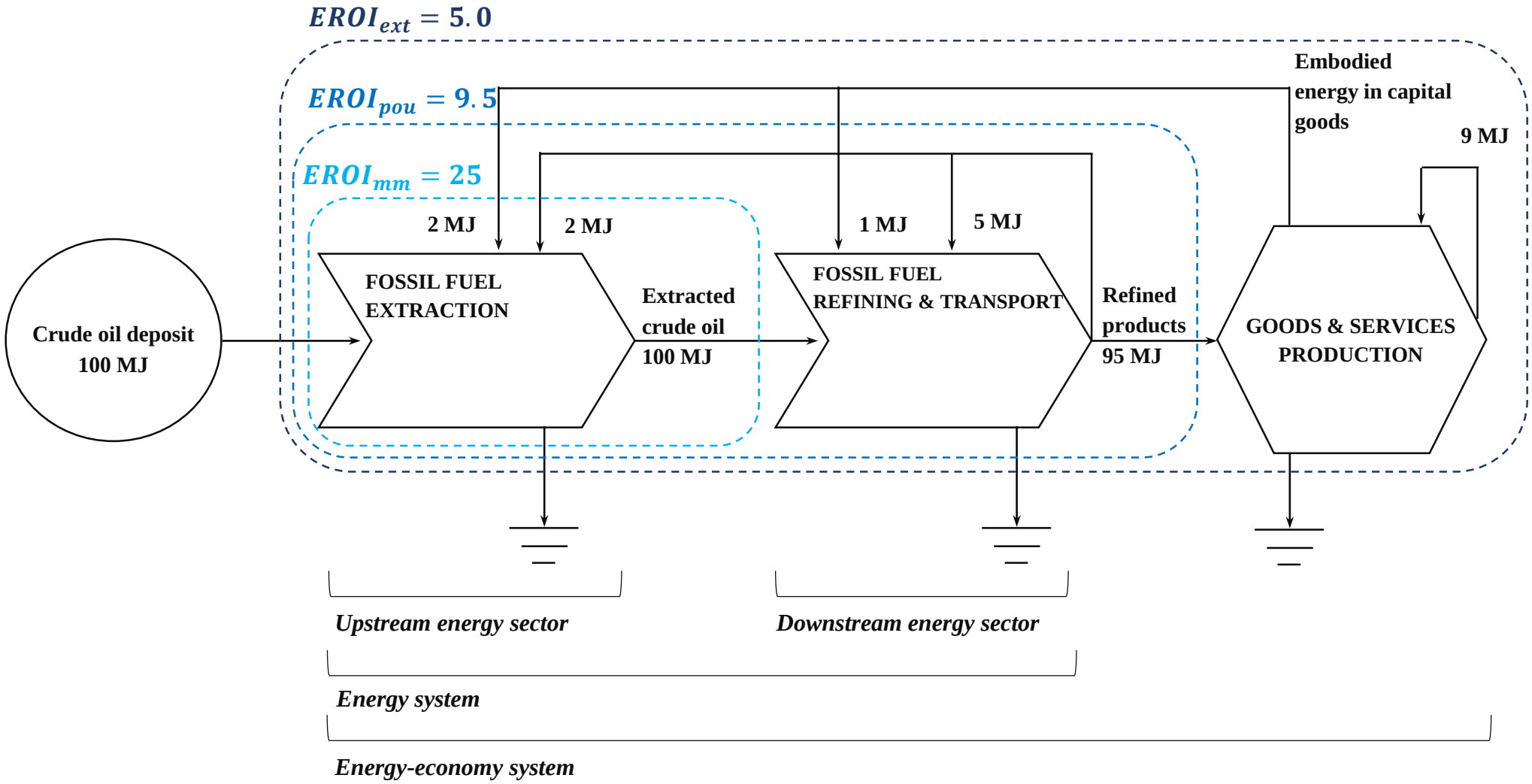
EROI boundaries: « mm », « pou », and « ext »

$$EROI_{mm} = \frac{Primary\ energy\ produced\ at\ the\ mine - mouth}{Energy\ required\ to\ find\ and\ produce\ that\ energy}. \quad (4)$$

$$EROI_{pou} = \frac{Final\ energy\ delivered\ at\ the\ point\ of\ use}{Energy\ required\ to\ get\ and\ deliver\ that\ energy}. \quad (5)$$

$$EROI_{ext} = \frac{Useful\ energy\ enjoyed\ as\ a\ service}{Energy\ required\ to\ get, deliver, and\ use\ that\ energy}. \quad (6)$$

EROI boundaries: an example



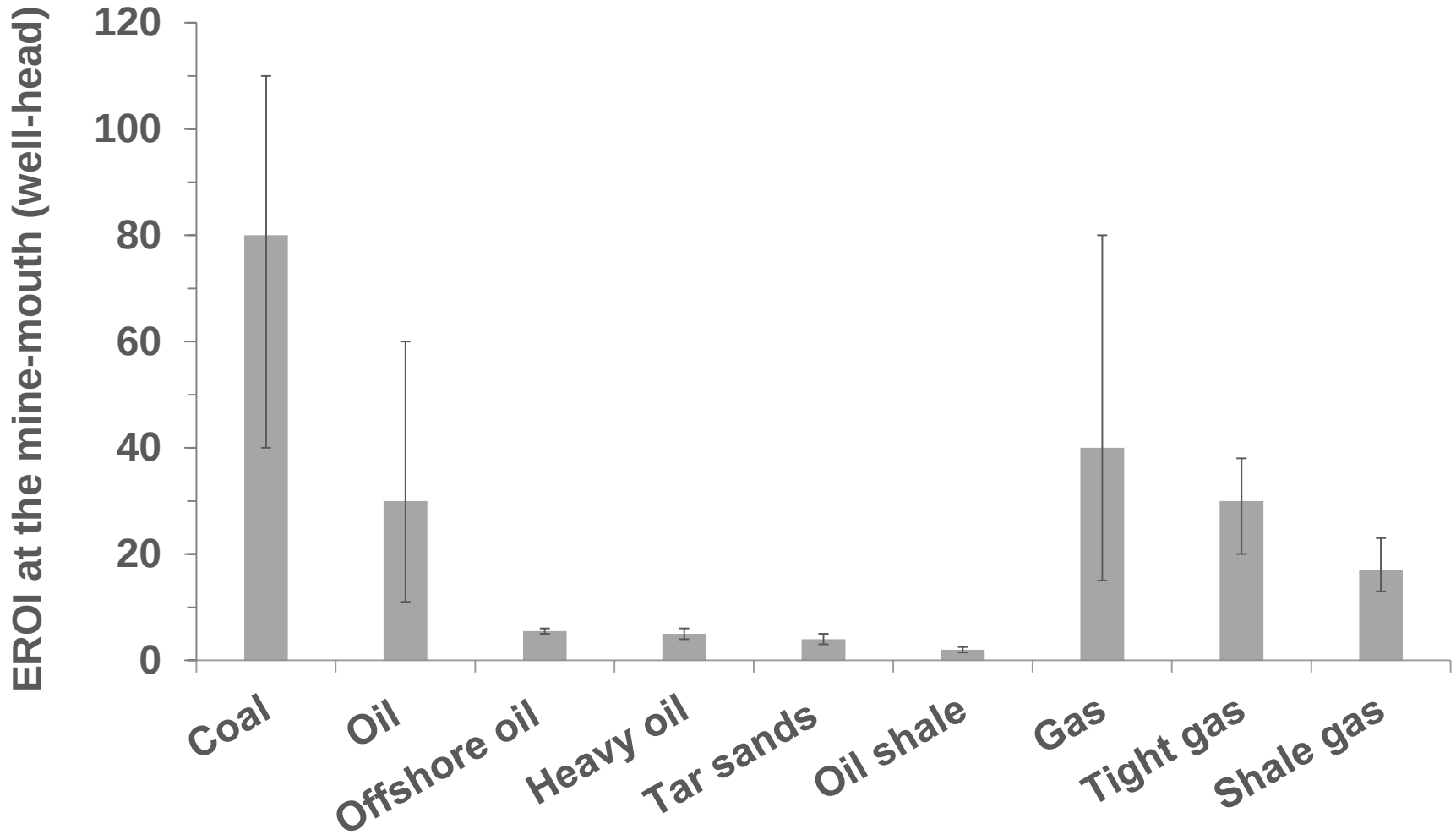
Methodology summary: a two-dimensional boundary

	Boundary for energy Inputs	**Boundary for energy Outputs**		
		1. Extraction (mm)	2. Processing (pou)	3. End-use (ext)
1	Internal energy	$EROI_{1,int}$	$EROI_{2,int}$	$EROI_{3,int}$
2	Direct external energy	$EROI_{1,dir}$	$EROI_{2,dir}$	$EROI_{3,dir}$
3	Indirect energy embodied in material inputs	$EROI_{1,ind}$	$EROI_{2,ind}$	$EROI_{3,ind}$
4	Indirect energy embodied in labor	$EROI_{1,lab}$	$EROI_{2,lab}$	$EROI_{3,lab}$
5	Auxiliary services and environmental externalities	$EROI_{1,aux}$	$EROI_{2,aux}$	$EROI_{3,aux}$

- $EROI_{1,ind}$ is also called $EROI_{stnd}$ for « standard ».

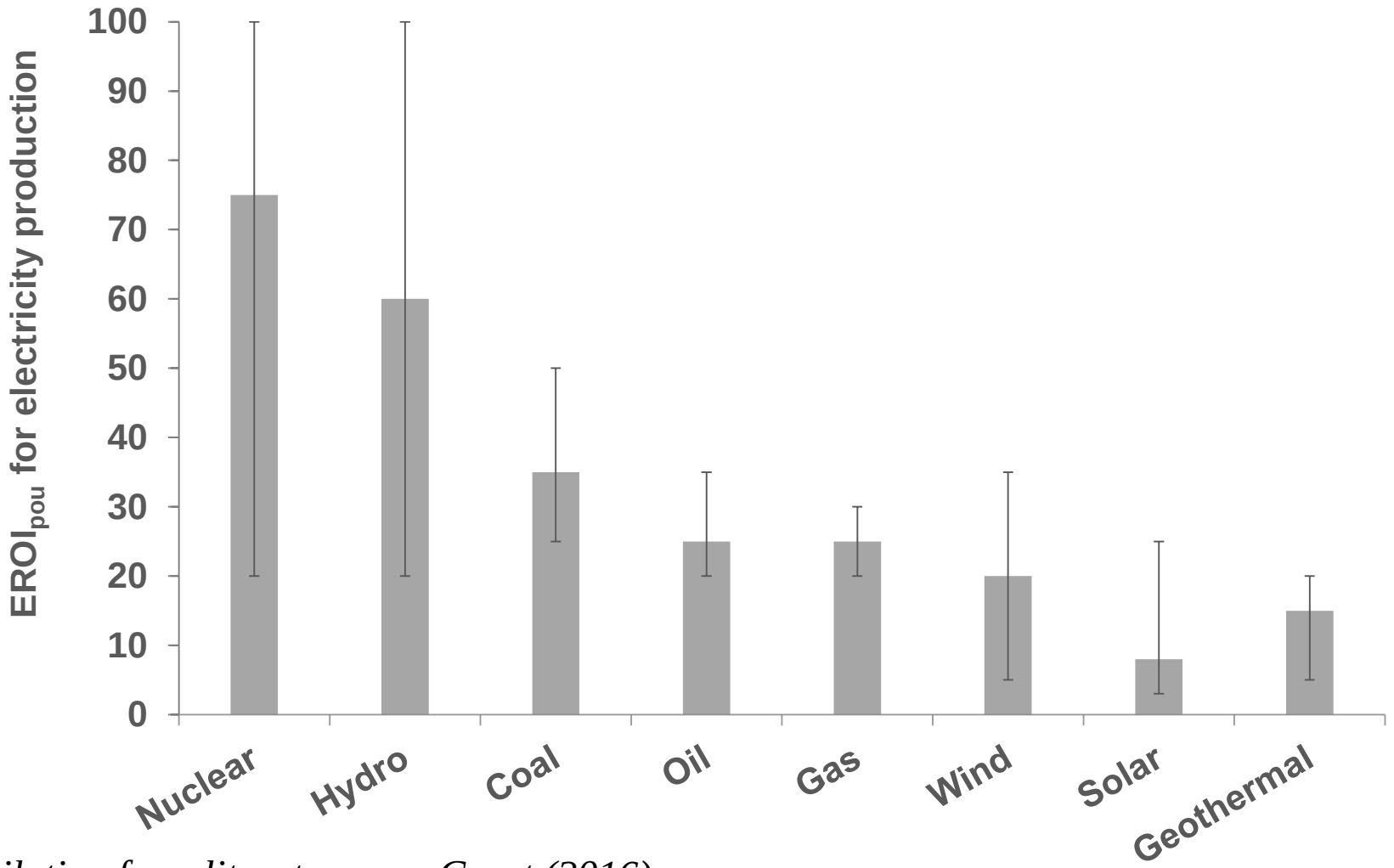
Source: Murphy et al. (2011).

EROI values for fossil fuels at the mine-mouth (« mm »)



Source: author compilation from literature, see Court (2016).

EROI values for electricity at the point of use (« pou »)



Source: author compilation from literature, see Court (2016).

Order of magnitudes

- Pre-industrial energy systems based on solar energy had EROIs around 10-20.
- Conventional fossil energies have higher EROIs around 40-80.
  - **Switch from biomass (low energy density) with low EROI, to fossil energies (high energy density) with high EROIs, seems to be a key factor to enable a regime of sustained high economic growth.**
- EROIs of conventional fossil fuels seem to be decreasing in recent decades.
- Non conventionnal fossil fuels and modern renewable energies have, for now, lower EROIs around 5-20.
  - **Crucial to take into account a third dimension: *time*.**

EROI as a function of the exploited resource ratio

- For a given energy resource, the EROI represents the struggle between technological progress and physical depletion.
- Exploited resource ratio, $\rho \in [0,1]$:
  - Non renewable: cumulated production divided by Ultimately Recoverable Resources (URR).

$$\rho_{non\ renewable,t} = \frac{Cumulated\ production_t}{URR}. \quad (7)$$

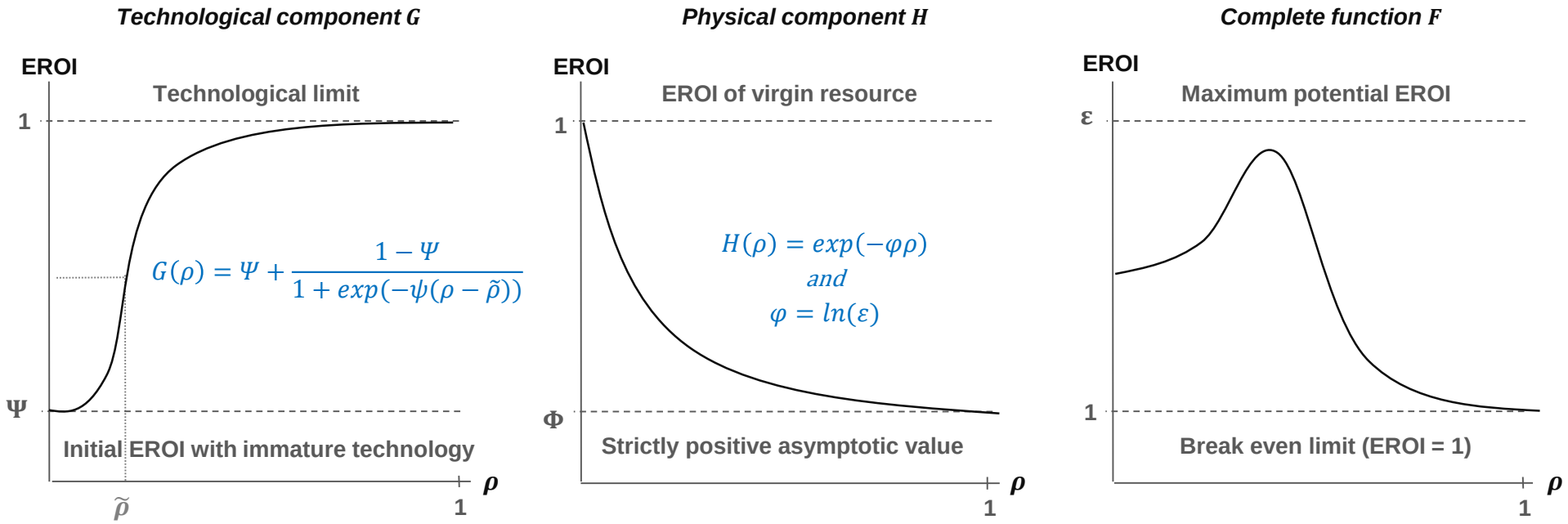
  - Renewable: annual production divided by par Technical Potential (TP).

$$\rho_{renewable,t} = \frac{Annual\ production_t}{TP}. \quad (8)$$

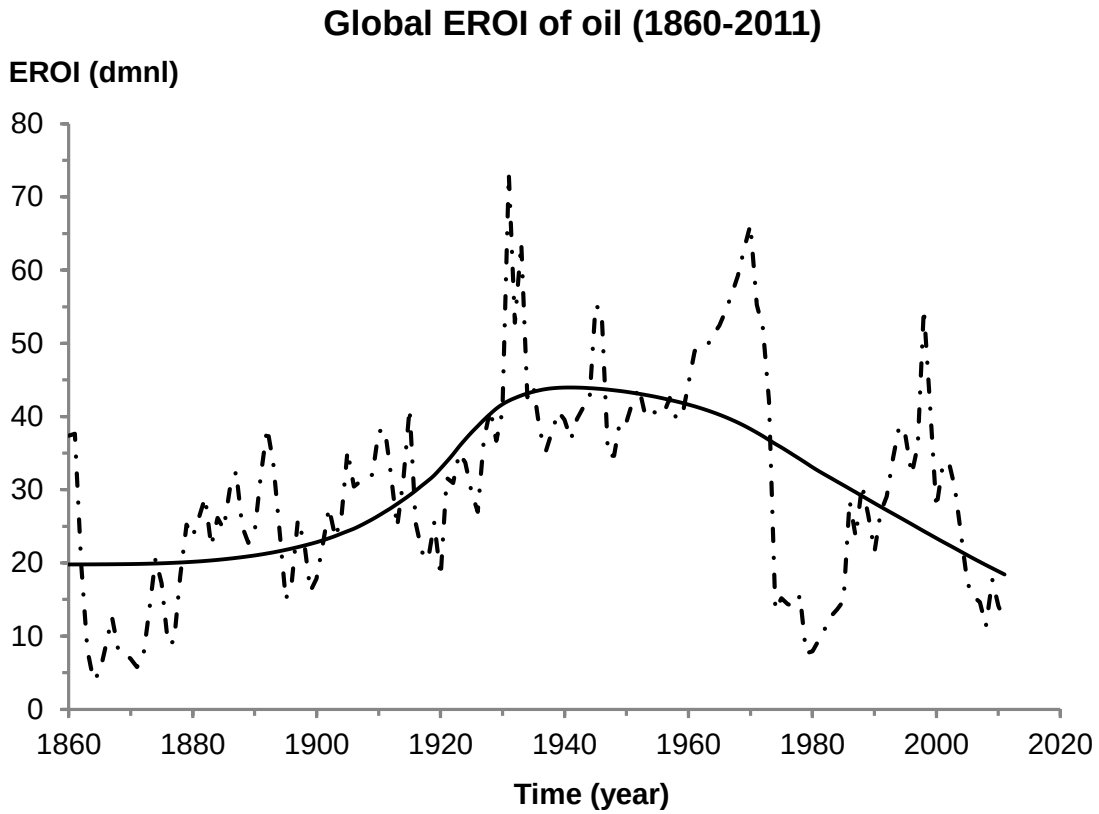
Theoretical model of the EROI

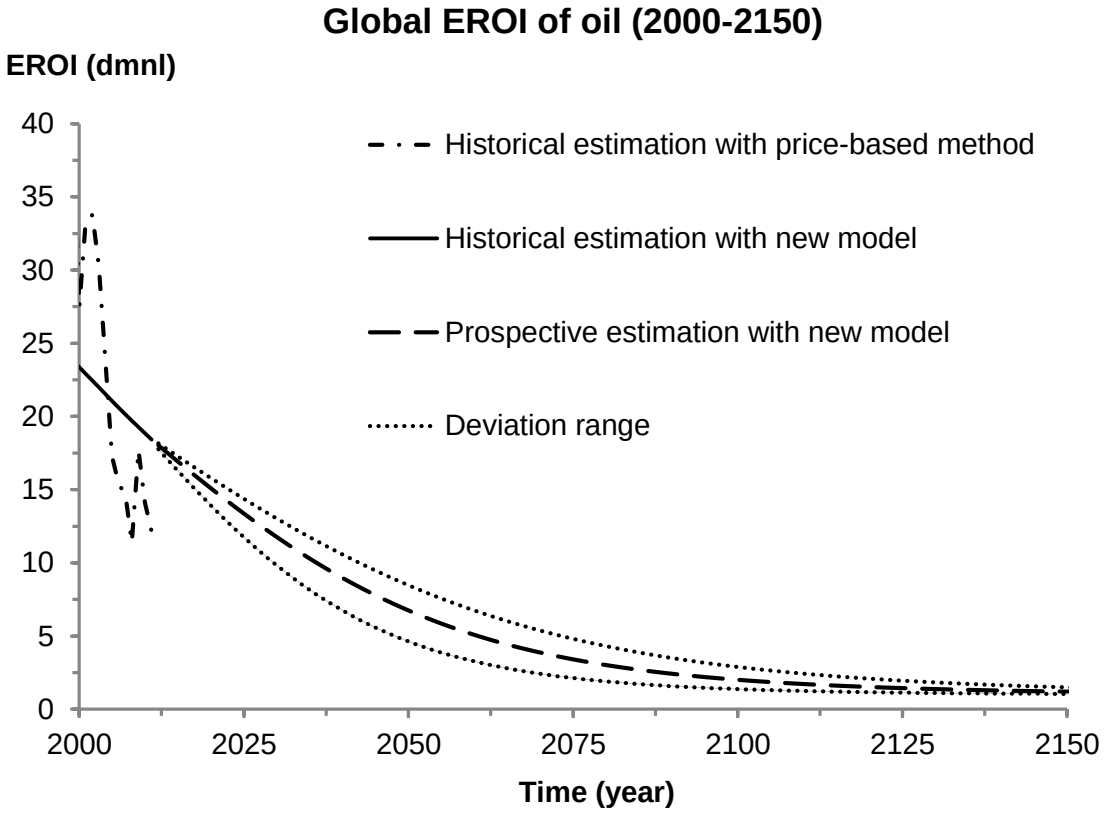
- The exploited resource ratio $\rho \in [0,1]$ is a proxy measure of both:
  - ➢ experience, i.e. technological learning,
  - ➢ physical depletion of the resource.
- So we can define:

$$EROI(\rho) = \varepsilon\, F(\rho) = \varepsilon G(\rho) H(\rho). \qquad (9)$$



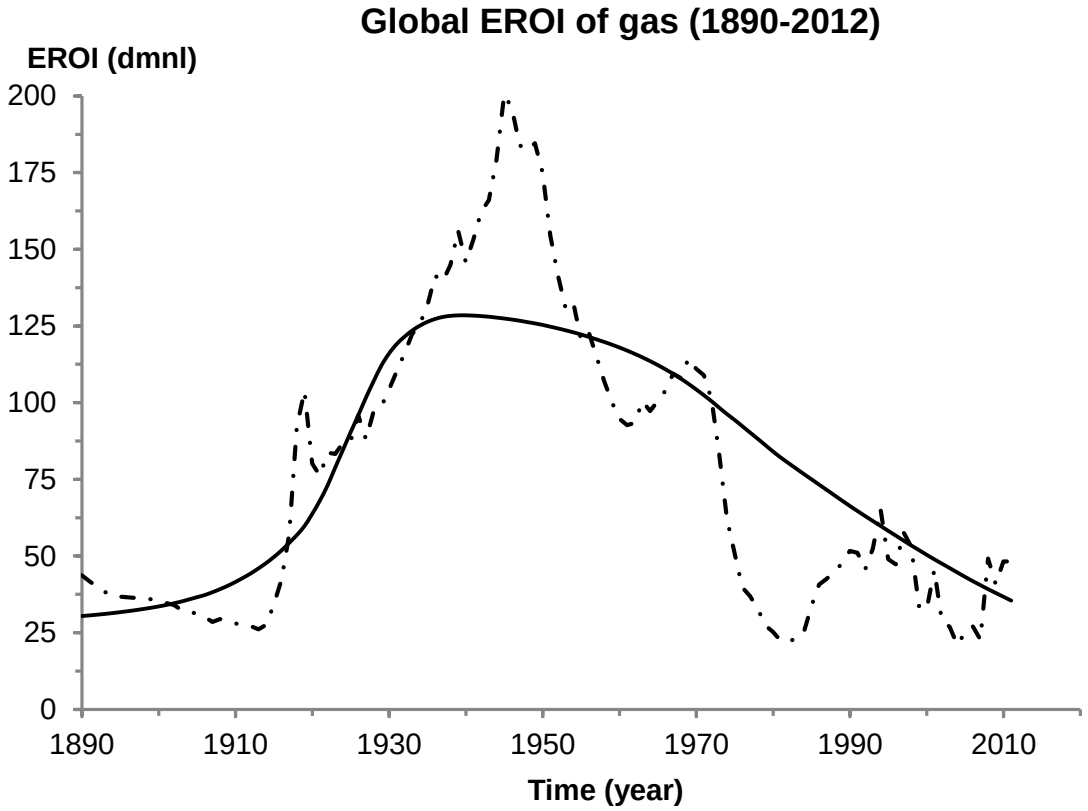
Implication 1: Maximum EROI of global oil already reached

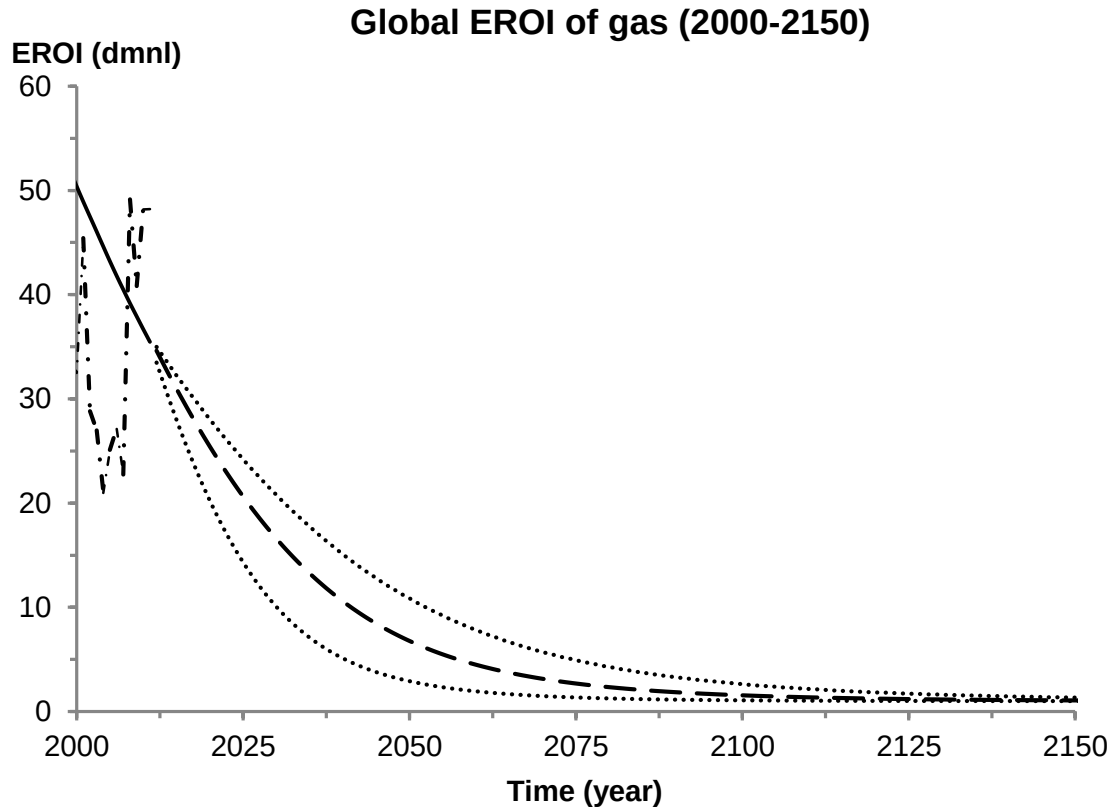




Source: Court & Fizaine (2017).

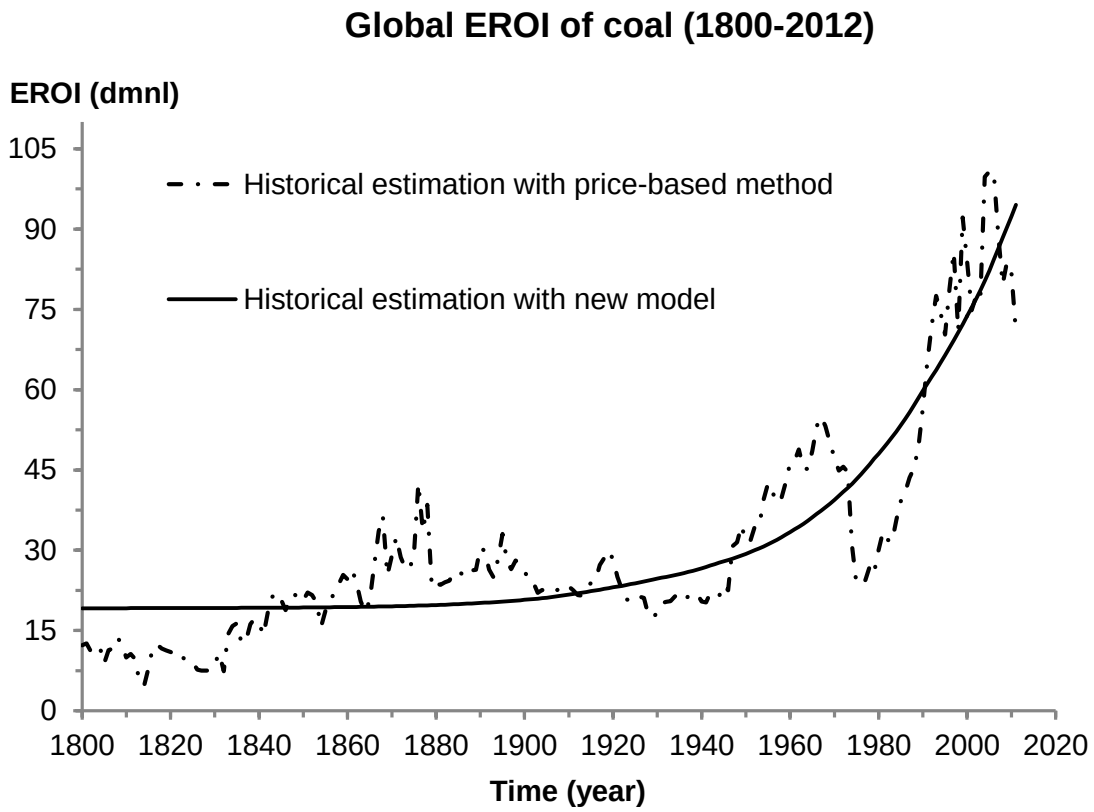
Implication 2: Maximum EROI of global gas already reached

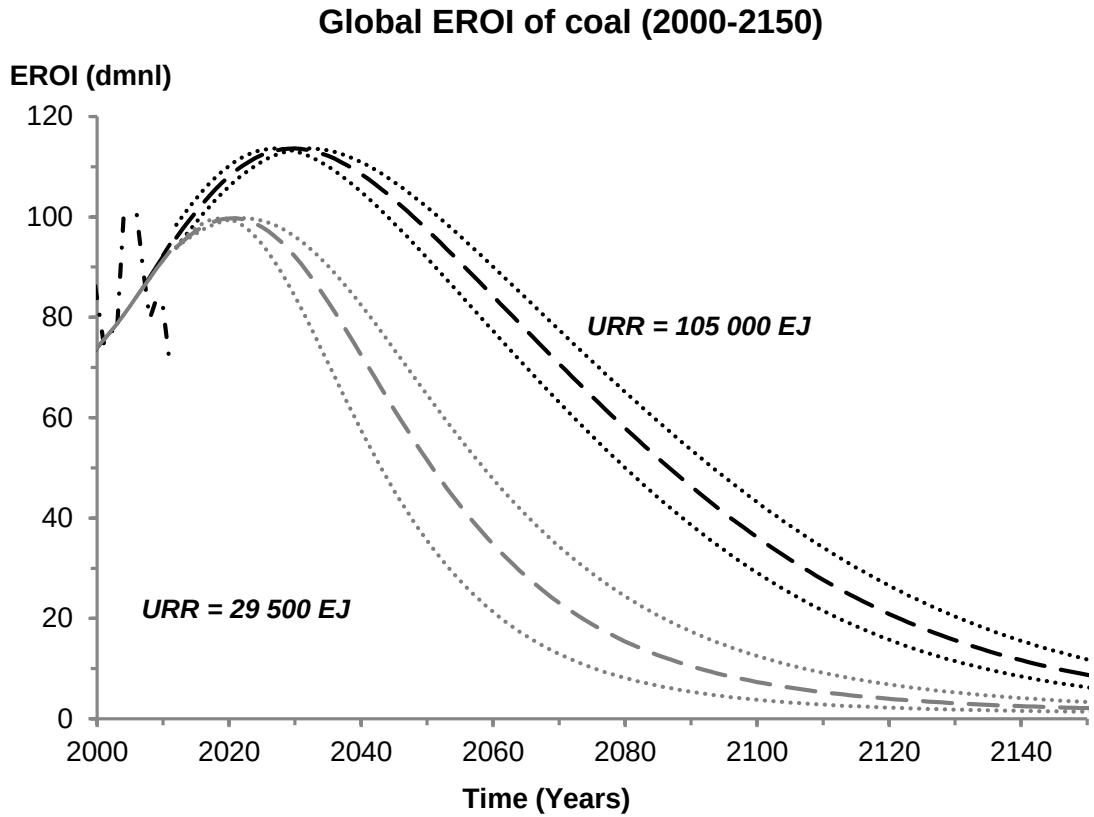




Source: Court & Fizaine (2017).

Implication 3: Maximum EROI of global coal not yet reached





Source: Court & Fizaine (2017).

Implication 4: EROI of modern renewables are probably increasing

- No way to confirm that in our article.
- Recent studies on PV are consistent with this idea:
  - Meta-analysis from Bhandari et al. (2015): « The mean harmonized EROI varied from 8.7 to 34.2 ».
  - Leccisi et al. (2016): « quality-adjusted energy return on investment ($EROI_{PE\text{-}eq}$) values ranging from over 60 to ~10 ».
- Negative side: storage at grid-level is **not** included in such studies.
- Positive side:
  - Last barrel of oil will have an EROI equal or below 1.
  - Last installed wind turbine will have an EROI of 1 but the global wind farm will have an EROI above one.

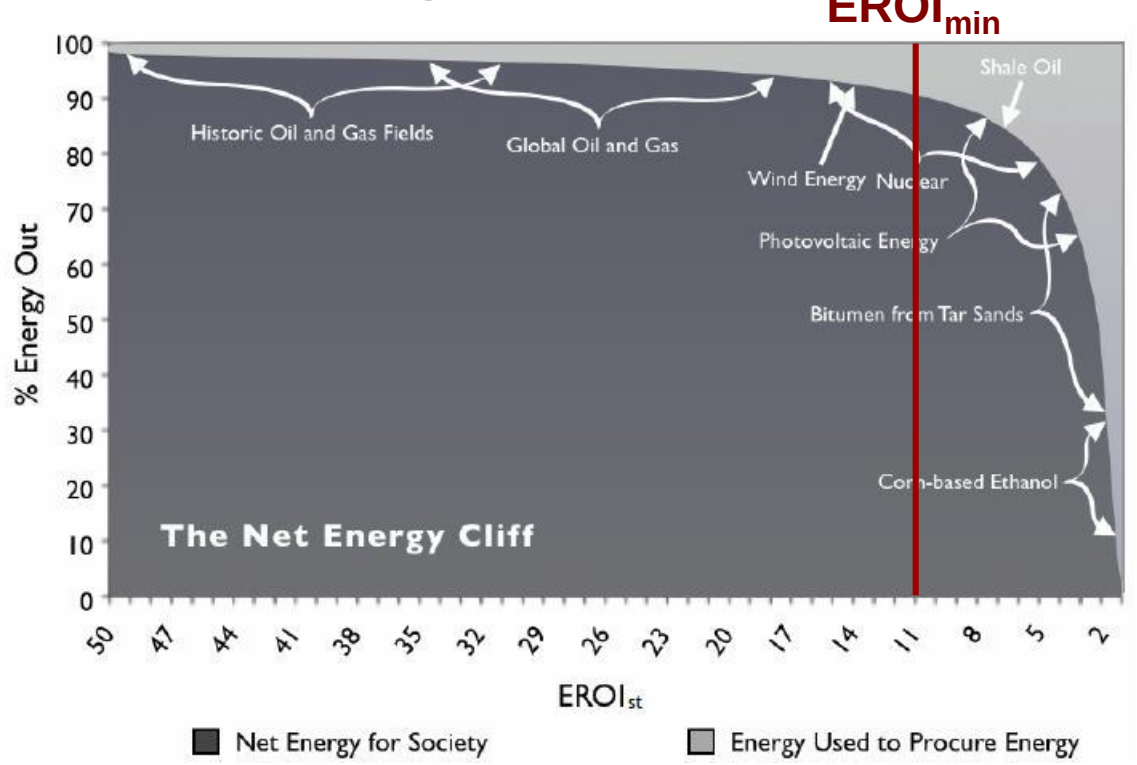
What is the minimum EROI that a society must have?

- Depends on:
  - society's complexity,
  - society's energy intensity.
- Hall et al. (2009) postulate that a minimum EROI of 12-14 is probably needed to have growth in moder economies.
- With an indirect approach based on energy expenditures, Fizaine & Court (2016) show that the US economy requires a primary energy system with an EROI above 11 in order to enjoy a positive rate of growth.

Decreasing EROIs for oil and gas have already impacted the economy ?

- Average rate of growth of GWP of 2.7%/year between 1950-75, compared to 1.8%/year between 1975-2010.
  - ➢Energetic determinism not only through EROI but also the efficiency of primary-to-useful exergy conversion (see forthcoming article).

- Moreover, be carefull with the non-linearity between EROI and net energy:
  - ➢Consequences of a 50% EROI decrease from 15 to 7.5 are not proportional to a 50% decrease from 30 to 15.



Source of graphic: Lambert et al. (2013).

Conclusion

- EROI represents the evolving struggle between technological progress and physical depletion to get energy from the environment.
- EROI of oil and gas will most likely continue to decrease in the future.
- EROI of coal should be maximum in a few decades and decrease after that.
- Currently, modern renewables have lower EROI than fossil fuels but progress is expected.
- Uncertainty remains on the compatibility between a full renewable mix including high storage capacities and the minimum EROI of 11 required to have growth in a modern economy.

Thank you for your attention.

References

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