Is Green Electricity Sustainable? Evolution of EROIs until 2050

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Contents

The material-energy nexus

- Renewable electricity is much more material-intensive that elec from fossils Vidal (2018); Hertwich et al. (2015)

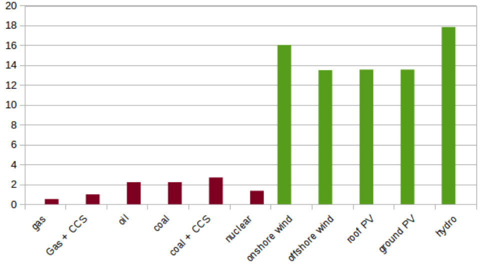


Figure: Copper intensity of different electricity technologies (kg/MWh).

- Mineral extraction and processing is energy-intensive, it uses about 10% of global primary energy (Nuss & Eckelman, 2014)

The relevant concept: EROI

- Energy Returned On Invested: $\text{EROI} = \frac{\text{delivered energy}}{\text{net embodied energy}}$
- An energy system is energetically sustainable if its $\text{EROI} > 1$
- EROI of electricity from renewables lower than that from fossils

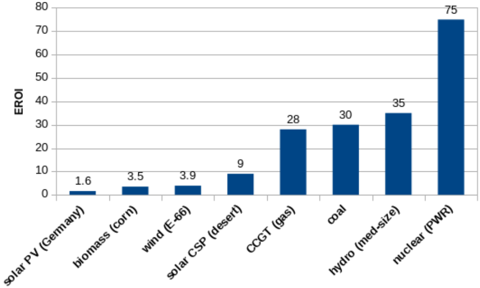


Figure: EROI estimates of electricity technos, from Weißbach et al. (2013), where supplementary capacity and storage required for the deployment of these technos is accounted for.

EROI is not an intrinsic property

- if plants currently used to build solar panels (PV) employed renewable electricity instead electricity from coal as their sources of energy => EROI of PV would decrease
- i.e. the EROI of a technology is not intrinsic, it depends on the chain of production / whole economic system (King, 2014)

$\Longrightarrow$ Is decarbonized electricity energetically sustainable? Or will the EROIs of some technos fall below 1? Tverberg (2017), Jancovici (2018)

$\Longrightarrow$ I compute the evolution of EROIs until 2050, relative to different scenarios.

Does size of EROI matter?

« Think of a society dependent upon one resource: its domestic oil. If the EROI for this oil was 1.1:1 then one could pump the oil out of the ground and look at it. If it were 1.2:1 you could also refine it and look at it, 1.3:1 also distribute it to where you want to use it but all you could do is look at it. Hall et al. [7] examined the EROI required to actually run a truck and found that if the energy included was enough to build and maintain the truck and the roads and bridges required to use it (i.e., depreciation), one would need at least a 3:1 EROI at the wellhead. Now if you wanted to put something in the truck, say some grain, and deliver it that would require an EROI of, say, 5:1 to grow the grain. If you wanted to include depreciation on the oil field worker, the refinery worker, the truck driver and the farmer you would need an EROI of say 7 or 8:1 to support the families. If the children were to be educated you would need perhaps 9 or 10:1, have health care 12:1, have arts in their lifemaybe 14:1 and so on.»

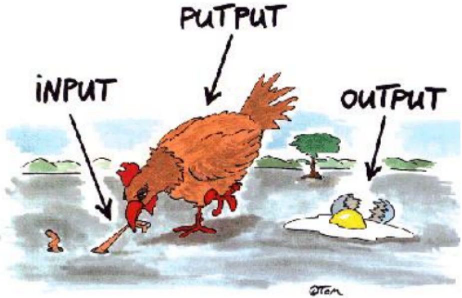
Hall (2011).

Strong underlying assumptions: factors used at full capacity, no future progress.

Still, this argument should not be neglected, and some authors draw a link between affluence of a society and its EROI: (Hall et al., 2009; Lambert & Lambert, 2011; Lambert et al., 2014; Fizaine & Court, 2016).

Input-Output Analysis

- IO analysis was developed by Leontief, a “Nobel” in economics (e.g. Leontief, 1986)
- Now, in the US, input-output analysis is mostly conducted in departments of Industrial Ecology
- Still a useful tool for economists: Life Cycle Analysis relies on the same framework, IO tables used in trade (GTAP)



Definitions

The element $a_{i,j}$ of the technology matrix A represents the quantity of input i required to produce one unit of output j.

$$A = (a_{\text{in, out}}) = \begin{pmatrix} a_{1,1} & \cdots & a_{1,n} \\ \vdots & \ddots & \vdots \\ a_{n,1} & \cdots & a_{n,n} \end{pmatrix} \leftarrow \text{inputs}$$

$$\downarrow$$

outputs

$$A = \begin{pmatrix} 0 & 0 & 1 \\ m_e & m_m & 0 \\ E_e & E_m & 0 \end{pmatrix} = \begin{array}{c} \begin{pmatrix} 0 & 0 & 1 \\ m_e & 0.2 & 0 \\ 0.1 & 0.5 & 0 \end{pmatrix} \end{array} \begin{array}{c} \text{energy techno.} \\ \text{materials} \\ \text{energy} \end{array}$$

EROI formula

The embodied inputs x required for a final demand y can be calculated using the well known formula (Leontief 1986; Eurostat 2008; Miller & Blair 2009):

$$x\left(y\right) = \left(I_n - A\right)^{-1} \cdot y.$$

$$\begin{aligned} \text{EROI} &= \frac{\text{delivered energy}}{\text{net embodied energy}} \\ &= \frac{1}{\mathbb{1}_E^T \cdot \left(\left(I_n - A\right)^{-1} \cdot \mathbb{1}_E - \mathbb{1}_E\right)}. \end{aligned}$$

EROI and material intensity

$$\text{EROI} = \frac{(1 - E_e)(m_m - 1) + E_m m_e}{E_e(m_m - 1) - E_m m_e}$$
$$= \frac{0.72 - 0.5 m_e}{0.08 + 0.5 m_e}$$

EROI decreases with the material intensity of the energy technology, because extracting and processing material requires energy

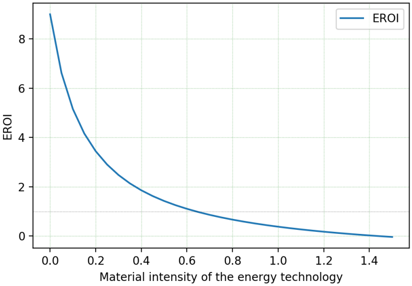


Figure: EROI in the simple model in function of the material intensity m_e of the energy technology.

$$A = \begin{pmatrix} 0 & 0 & 0 & p \\ 0 & 0 & 0 & 1-p \\ m_{PV} & m_g & m_m & 0 \\ E_{PV} & E_g & E_m & 0 \end{pmatrix}$$

$$= \begin{array}{cc} \begin{pmatrix} 0 & 0 & 0 & p \\ 0 & 0 & 0 & 1-p \\ 0.7 & 0.1 & 0.2 & 0 \\ 0.1 & 0.1 & 0.5 & 0 \end{pmatrix} & \begin{array}{c} \text{PV} \\ \text{gas} \\ \text{materials} \\ \text{energy} \end{array} \end{array}$$

EROI and material intensity

$$\mathrm{EROI}_{sytem} = \frac{0.67 - 0.3p}{0.13 + 0.3p}$$

$$\mathrm{EROI}_{PV} = 1.558 - 0.698p$$

$$\mathrm{EROI}_{gas} = 5.154 - 2.308p$$

The higher the share of PV in the mix, the lower the EROI of both technologies: this comes from the higher material intensity of PV For highest penetration of PV, the EROI falls below unity

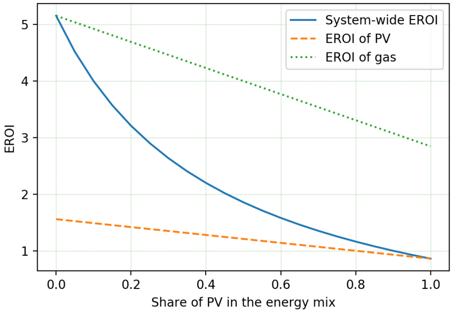


Figure: EROIs in the two-technology model in function of the share p of PV in the energy mix.

Previous studies

- This argument was first made by King (2014)
- King (2014) provided a numerical application, where incidentally the EROI fell below 1 in a 100% renewable mix (see Table)
- did not comment on this result, because the computations had a purely illustrative purpose, were not supposed to be accurate

% Grid that is fossil electricity (α)	$NEER_{sys}$ fossil electricity	$NEER_{sys}$ renewable electricity	$NEER_{sys}$ grid electricity
99%	2.85	1.89	2.33
50%	1.67	1.18	1.02
10%	1.23	0.89	0.63
1%	1.16	0.84	0.57

Figure: Table 4 in (King, 2014). NEER is the EROI concept defined afterwards.

- No other study on the dependency of EROI to the mix

Data

- Exiobase: Multi-Regional Input-Output Tables (200 sectors, incl. 56 energy sectors, 48 regions, hundreds of impacts)
- ecoinvent: Life Cycle Inventory (15,000 processes) (Wood et al., 2014)
- IEA BaseLine (BAU) and Blue Map (+2°C) scenarios: energy mix for 9 regions until 2050 (ETP 2017)
- THEMIS: hybrid MRIOT combining Exiobase (background), ecoinvent and other data (foreground) (Gibon et al., 2015)
- "Greenpeace"'s scenarios (developed at DLR using model REMix, Teske et al., 2015)

Using an IO approach, I should find lower estimates that the literature relying on LCA

Different notions of EROIs

- Brandt & Dale 2011; Murphy et al. 2011 clarify the different concepts and try to harmonize terminology
- Most relevant notion in our case: Gross Energy Ratio...
- ... called Net External Energy Ratio by King (2014)

- The GER measures the ratio of energy delivered over energy embodied in inputs net of the energy of the fuels used in the process
- In this paper, we use secondary energies instead of the more common primary energy: both approaches are equally valid

Formula for GER

$$\text{supply}_t = E^S \cdot y_t = \text{demand}_t \cdot \mathbb{1}_t$$

$$\text{net secondary embodied}_t = E^S \odot \mathbb{1}_{\text{secondary}} \cdot \left((I - A)^{-1} \cdot y_t - y_t \right)$$

$$\text{fuel input}_t = E^S \odot \mathbb{1}_{\text{secondary fuel}} \cdot A \cdot y_t$$

$$GER_t^{2nd} = \frac{\text{supply}_t}{\text{net secondary embodied}_t - \text{fuel input}_t}$$

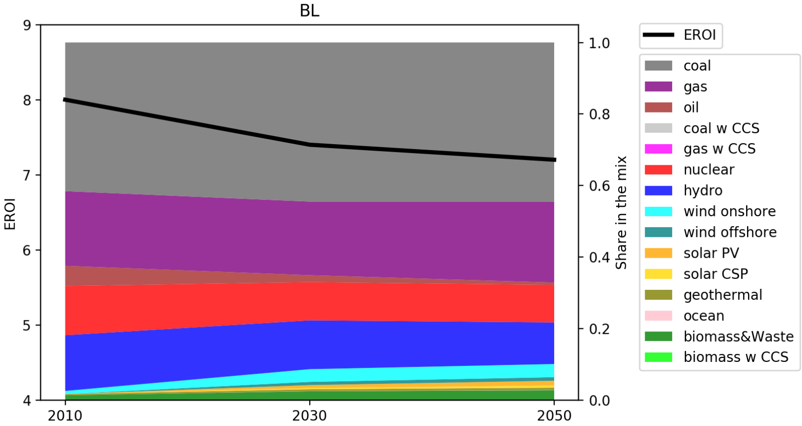
Other elements

- Embedding Greenpeace mixes in matrix sec:Quality-adjusted-Results see method
- Murphy et al. (2011) recommend to present quality-adjusted EROIs along simple EROIs. Electricity is thus given a higher weight for its higher quality, when aggregating energy, e.g. embodied energy: sec:Quality-adjusted-Results see results

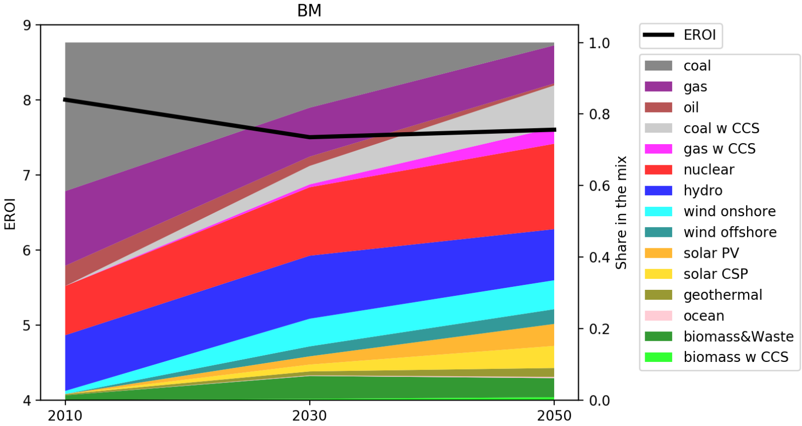
$$\text{embodied}_t^{\text{qual. adj.}} = E^S \odot (2.6 \cdot \mathbb{1}_{\text{elec}} + \mathbb{1}_{\text{heat}}) \cdot (I - A)^{-1} \cdot y_t$$

- No need to account for the growth of some sectors, as THEMIS IOT are as if the economy were at a steady-state
- Correction of the data was necessary for solar CSP because of inconsistencies: I imputed *OECD North America* values to all regions

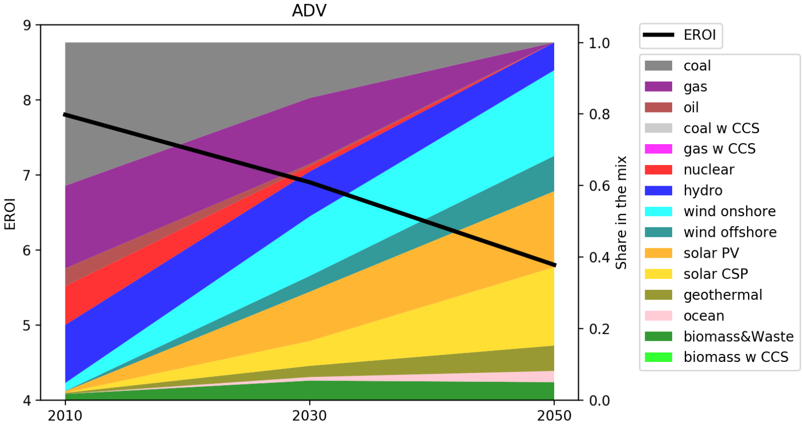
Baseline (BAU, IEA)



Blue Map (+2°C, IEA)



Advanced Energy [R]evolution (100% renewable)



Baseline (BAU, IEA)

Year	2010		2030		2050	
Variable	EROI	mix	EROI	mix	EROI	mix
biomass w CCS	–	0	–	0	–	0
biomass&Waste	11.3	0.01	6.2	0.02	5.8	0.03
ocean	5.5	0	2.4	0	2.9	0
geothermal	5.3	0	5.1	0.01	5	0.01
solar CSP	21.5	0	8.8	0	9.1	0.01
solar PV	9.2	0	7.4	0.01	7.1	0.01
wind offshore	9.3	0	10.9	0.01	10.5	0.01
wind onshore	9.4	0.01	9.2	0.04	8	0.04
hydro	13.1	0.16	11.8	0.14	11.8	0.12
nuclear	10.4	0.14	7.2	0.11	7	0.1
gas w CCS	–	0	–	0	7.4	0
coal w CCS	–	0	–	0	6.1	0
oil	8.2	0.06	9.5	0.02	9.6	0.01
gas	13.7	0.21	14.8	0.21	14.6	0.23
coal	12.6	0.42	11.3	0.45	11.3	0.45
Total (PWh/a)	**8**	19.76	**7.4**	34.29	**7.2**	45.97

Blue Map (+2°C, IEA)

Year	2010		2030		2050	
Variable	EROI	mix	EROI	mix	EROI	mix
biomass w CCS	–	0	4.6	0	4	0.01
biomass&Waste	11.3	0.01	5.5	0.06	5.2	0.05
ocean	5.5	0	3.7	0	5.8	0
geothermal	5.3	0	5.2	0.01	5.4	0.02
solar CSP	21.5	0	8.2	0.02	7.9	0.06
solar PV	9.2	0	6.3	0.02	6	0.06
wind offshore	9.3	0	7.6	0.03	6.2	0.04
wind onshore	9.4	0.01	7	0.08	7.3	0.08
hydro	13.1	0.16	12.7	0.18	13.1	0.14
nuclear	10.4	0.14	7.3	0.19	7.4	0.24
gas w CCS	–	0	7.9	0.01	9.1	0.05
coal w CCS	–	0	7.1	0.05	7.1	0.12
oil	8.2	0.06	9.4	0.03	7.3	0.01
gas	13.7	0.21	17.1	0.14	19.6	0.11
coal	12.6	0.42	11.4	0.18	12.4	0.01
Total (PWh/a)	**8**	19.76	**7.5**	28.01	**7.6**	40.22

Advanced Energy [R]evolution (100% renewable)

Year	2010		2030		2050	
Variable	EROI	mix	EROI	mix	EROI	mix
biomass w CCS	–	0	–	0	–	0
biomass&Waste	11.3	0.01	5.2	0.05	4.6	0.05
ocean	5.5	0	4.8	0.01	4.9	0.03
geothermal	5.3	0	3.8	0.03	3.9	0.07
solar CSP	21.5	0	9.2	0.07	7.8	0.22
solar PV	9.2	0	5.4	0.14	4.7	0.21
wind offshore	9.3	0	6.5	0.04	6.4	0.1
wind onshore	9.4	0.01	7.1	0.17	5.8	0.24
hydro	13.1	0.16	11	0.13	10.9	0.08
nuclear	10.4	0.14	8.3	0.02	–	0
gas w CCS	–	0	–	0	–	0
coal w CCS	–	0	–	0	–	0
oil	8.2	0.06	9.9	0.01	–	0
gas	13.7	0.21	16.4	0.18	–	0
coal	12.6	0.42	10.3	0.16	11.5	0
Total (PWh/a)	**8**	19.76	**6.9**	36.74	**5.8**	64.04

- The EROIs of renewables should decrease, as anticipated
- However they remain largely above 1, suggesting that renewables are truly sustainable
- The system-wide EROI is currently 8.0; it decreases slightly until 7.4 ± 0.2 in 2030 and 2050 in both THEMIS scenarios.
- The decrease is a little more pronounced in the Greenpeace scenario: at 6.9 in 2030 and 5.8 in 2050
- First and crude attempt: room for improvement, e.g. including the transportation system. However, technical progress is notoriously difficult to predict, so we will never know future EROIs for sure

- King & Hall (2011) show empirically and theoretically that EROI is inversely related to price:

$$p = \frac{\$_{\text{out}}}{\$_{\text{investment}}} \frac{\$_{\text{investment}}}{E_{\text{in}}} \frac{E_{\text{in}}}{E_{\text{out}}} = \frac{\text{MROI}}{\text{EROI}} \frac{\$_{\text{investment}}}{E_{\text{in}}}$$

- Heun & de Wit (2012) find an equivalent formula, calling MROI the markup m, considering cost per gross output $c = \frac{\$_{\text{investment}}}{E_{\text{out}}+E_{\text{in}}}$ and using their own notion of EROI: $\text{EROI}^H = \frac{E_{\text{out}}+E_{\text{in}}}{E_{\text{in}}} = \text{EROI} + 1$:

$$p = \frac{m}{\text{EROI}^H - 1} \frac{\$_{\text{investment}}}{E_{\text{out}} + E_{\text{in}}} \frac{E_{\text{out}} + E_{\text{in}}}{E_{\text{in}}} = \frac{m \cdot c}{1 - 1/\text{EROI}^H}$$

- Problem: all variables move together. Indeed, their empirical estimation yields

$$p = a \cdot \text{EROI}^{-1.4}$$

Definitions

- Herendeen (2015) introduces value-added a matrix form in a 2*2 model: I extend his result in dimension n

$$p = v \cdot (I - A)^{-1}$$

- The energy mobilized by technology t to deliver one unit of energy, i.e. energy intensity: $\varepsilon_t = \mathbb{1}_E^T \cdot (I - A)^{-1} \cdot \mathbb{1}_t$

$$\text{EROI}_t = \frac{\mathbb{1}_E^T \cdot \mathbb{1}_t}{\mathbb{1}_E^T \cdot \left((I - A)^{-1} - I \right) \cdot \mathbb{1}_t} = \frac{1}{\varepsilon_t - 1}$$

- p is function of A's coefs, each coef of A can be expressed as a function of EROI. Composing the two, we obtain that price is inversely related to EROI
- But the relation is not unique (as it depends on the coefficient of A chosen to make the connection), and the other parameters in the relation are not constant...

Demonstration

Lemma

Let A be an invertible matrix and let x be a coefficient of A. Then,
(i) the determinant of A is a linear function of x, denoted D^A;
(ii) each coefficient (i,j) of the adjugate of A is a linear function of x, denoted $P^A_{i,j}$;
(iii) each coefficient (i,j) of A^{-1} is a rational function in x of degree 1, which writes: $\left(A^{-1}\right)_{i,j} = \frac{P^A_{i,j}(x)}{D^A(x)}$.

Proof.

(i) Using Leibniz formula: $\det(A) = \sum_{\sigma \in S_n} \operatorname{sgn}(\sigma) \prod_{i=1}^{n} a_{i,\sigma(i)}$
(ii) Each coefficient of the adjugate of A is a linear combination of minors of A (themselves determinants), hence is linear.
(iii) Using (i), (ii) and Laplace expansion of A: $A^{-1} = \frac{\operatorname{adj}(A)}{\det(A)}$. $\square$

Theoretical result

Theorem

(Generalization of Herendeen, 2015) Assuming that all coefficients of the transformation matrix A are constant except one, noted $x = a_{i_0,j_0}$, *and that EROI varies with x; the price of t can be expressed as a linear function of its energy intensity* $\varepsilon_t = 1 + \frac{1}{EROI_t}$, *so that:*

$$\exists! \, (\alpha, \beta) \in \mathbb{R}^2, \; p_t = \frac{\alpha}{EROI_t} + \beta$$

Proof

- Defining $R(x) := D^{I-A}(\delta_{i_0,j_0} - x)$, lemma 1 yields

$$\left((I-A)^{-1}\right)_{e,t} = \frac{P_{e,t}^{I-A}(\delta_{i_0,j_0} - x)}{R(x)}$$

- $Q(x) := \sum_{e\in E} P_{e,t}^{I-A}(\delta_{i_0,j_0} - x)$,
  $P(x) := \sum_{i=1}^{n} v_i P_{i,t}^{I-A}(\delta_{i_0,j_0} - x)$ and $R(x)$ are all linear, so:

$$\exists!\,(\alpha,\gamma)\,, \quad P(x) = \alpha Q(x) + \gamma R(x)$$

- $\varepsilon_t = \sum_{e\in E}\left((I-A)^{-1}\right)_{e,t} = \frac{Q(x)}{R(x)}$
- $p_t = \sum_{i=1}^{n} v_i \left((I-A)^{-1}\right)_{i,t} = \sum_{i=1}^{n} v_i \frac{P_{i,t}^{I-A}(\delta_{i_0,j_0}-x)}{R(x)}$
- $\left.\begin{aligned} p_t &= \frac{P(x)}{R(x)} \\ Q(x) &= \varepsilon_t R(x) \end{aligned}\right\} p_t = \frac{\alpha Q(x) + \gamma R(x)}{R(x)} = \alpha\varepsilon_t + \gamma$ $\square$

A Negative Result

- We cannot obtain a better result, i.e. a formula that still holds when letting more than one coefficient vary
- Even letting all coefficients vary, p can be expressed as:

$$p_t = \frac{\tilde{v}}{\text{EROI}_t} + r$$

- But r, $\tilde{v}$ and EROI_t all depend on the coefficients of A, and vary together when A changes
- Relation between EROI and price so fragile that we cannot even conclude there is a decreasing relation
- No simple relation either with energy expenditures nor GDP. Hence, caution with statements as in Fizaine & Court (2016) that there is a minimum viable EROI

- Using, $p = v \cdot (I - A)^{-1}$, we can predict future prices

Table: Predicted average global price of electricity (in €/MWh)

year	2010	2050		
scenario	all	BL	BM	ADV
price	27	28	30	32

- But caution with such estimates: IO is best suited for physical analysis, as it does not model general equilibrium effects nor behaviors

- Empirical relation $p = b \cdot \text{EROI}^{-0.6}$ (N=2111, $R^2 = 0.6$)

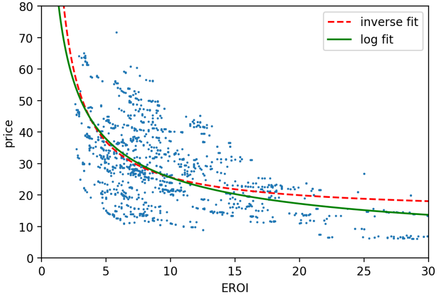
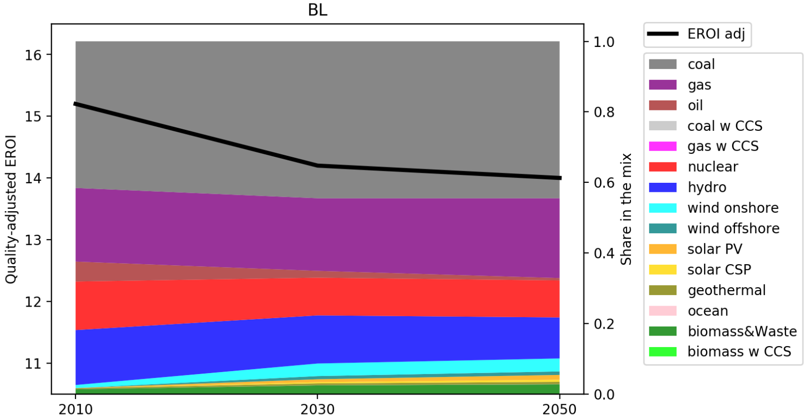


Figure: Regressions p = EROI using all scenario estimates

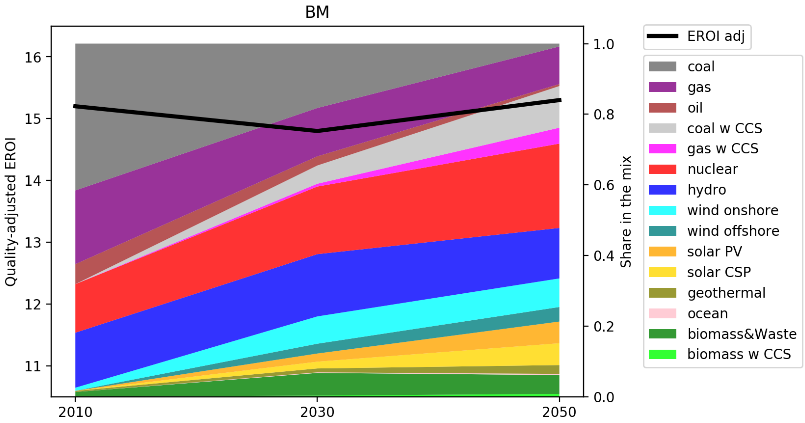
Conclusion

- First attempt at estimating future EROIs in a decarbonized electricity system
- System-wide EROI of the power sector should not vary much until 2050, albeit a noticeable decrease, from 8 to 7, or even 6 in the case of a scenario with 100% renewable
- As EROI $\gg 1$, our results restore confidence about the energetic sustainability of renewable electricity, which was questioned theoretically
- Lower EROI doesn't necessary imply increasing prices

Baseline (BAU, IEA)



Blue Map (+2°C, IEA)



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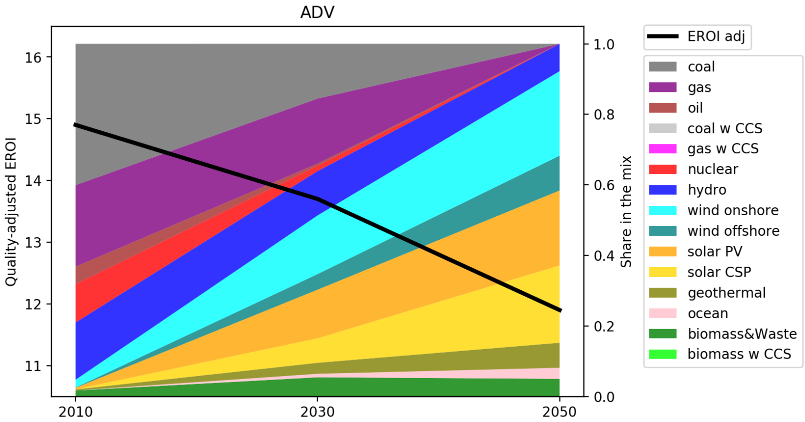

go back

Conclusion

- A: submatrix with electricity rows => D: conversion to energy unit => E (E_{is} electricity from i required for s output)
- $=> B = M \cdot E, \; B = \begin{pmatrix} B_1 \\ \vdots \\ B_R \end{pmatrix}, \quad B_r = \begin{pmatrix} E_r^{tot} \\ \vdots \\ E_r^{tot} \end{pmatrix}$
- multiply row $i = i\,(r, t)$ of B with shares of t in regional mix => $\tilde{E}$: conversion => $\tilde{D}$ go back