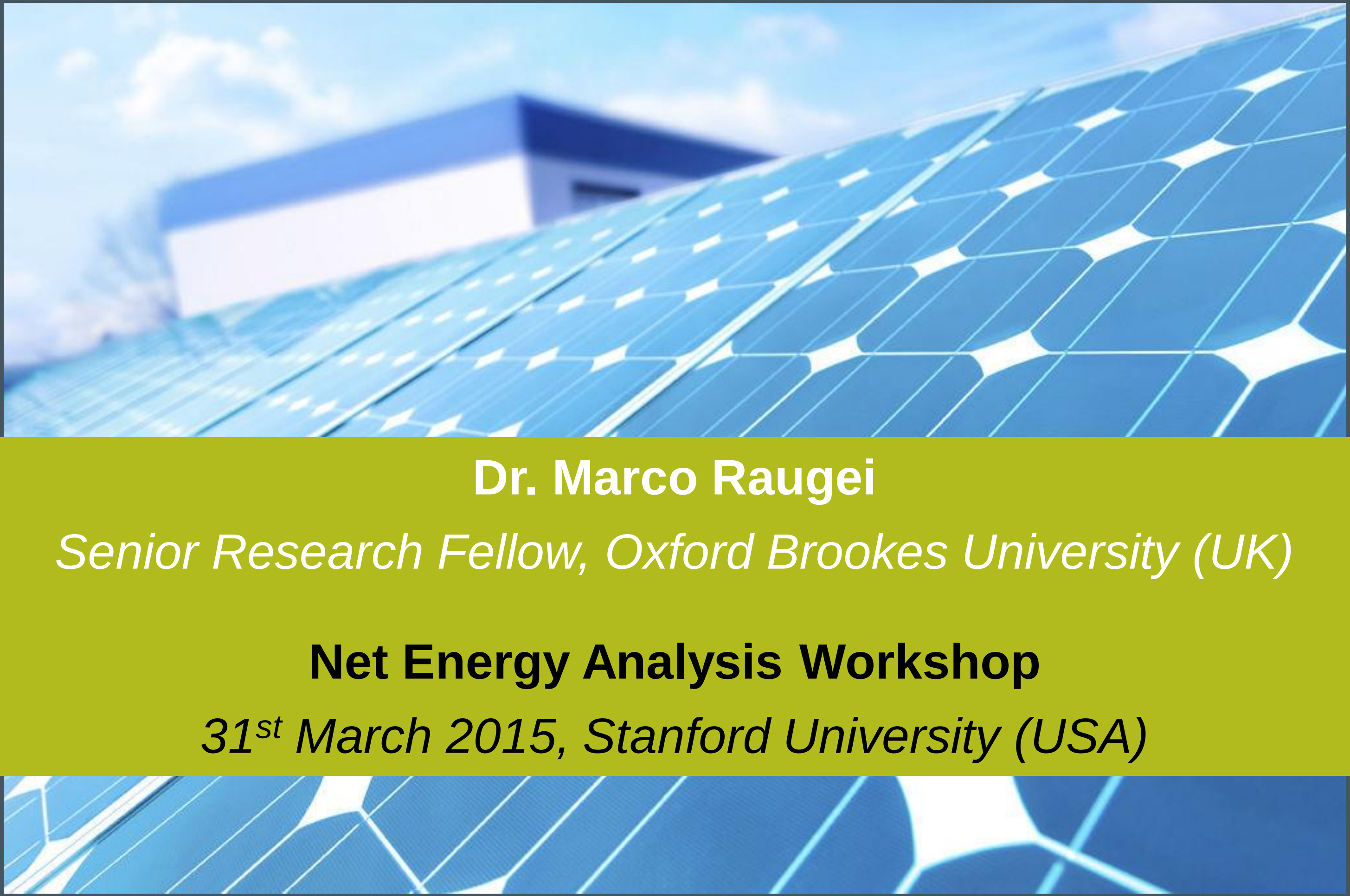
Net Energy Analysis of Photovoltaics: the whys and wherefores… and the potential pitfalls



Dr. Marco Raugei

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Net Energy Analysis Workshop

31st March 2015, Stanford University (USA)

Structure of the presentation

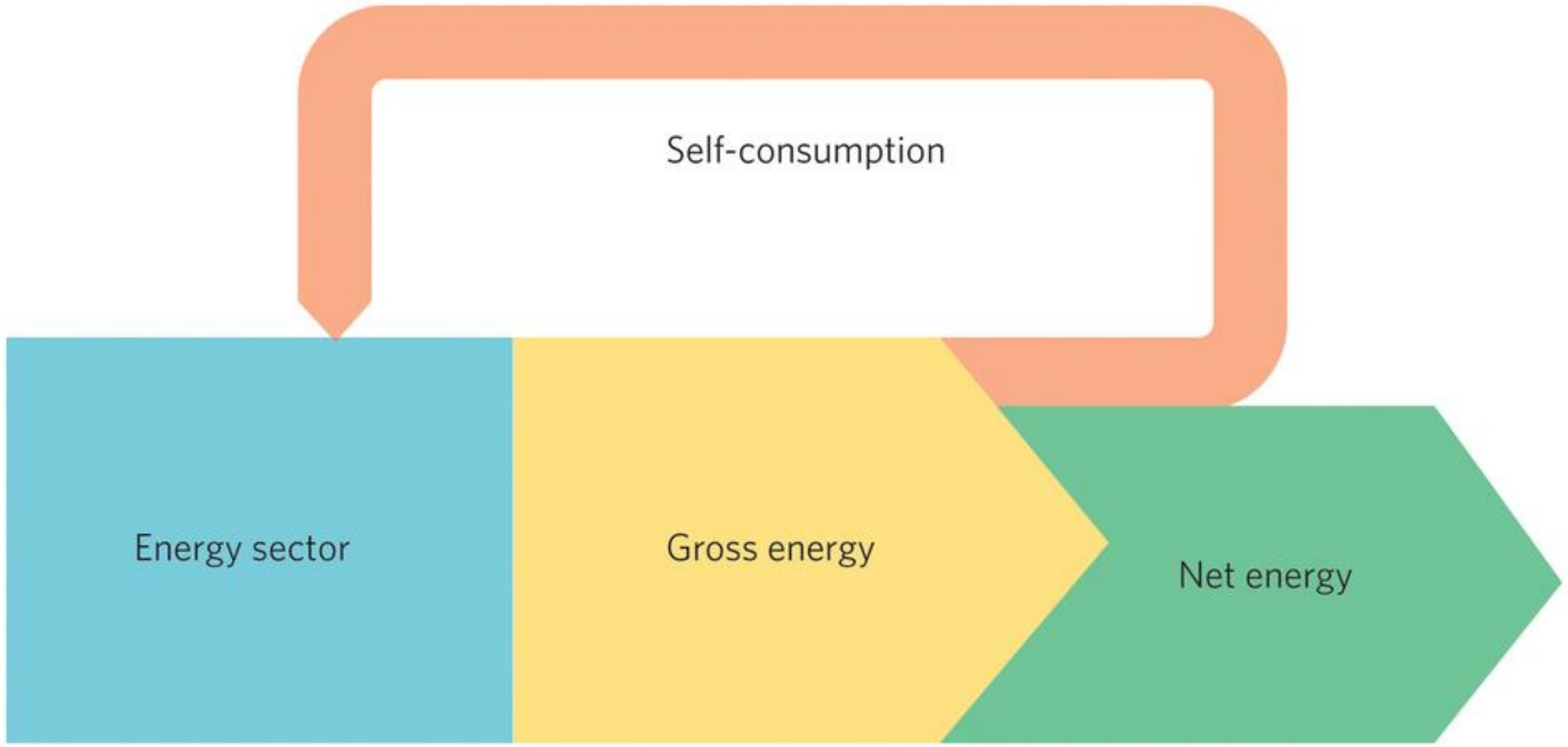
1. Overall aim of NEA of PV
2. NEA and LCA: different (and complementary) approaches
3. The problem with “typical” EROI balloon / bar charts
4. Potential issues with NEA of thermal *vs*. PV electricity
5. E.g. NEA of coal and PV electricity
6. Steady-state *vs*. dynamic analyses
7. The WISE-PV project

Overall aim

To inform energy policy on the energy performance of photovoltaic systems…

…in the context of the crowded arena of competing energy alternatives

Toolkits (1): Net Energy Analysis



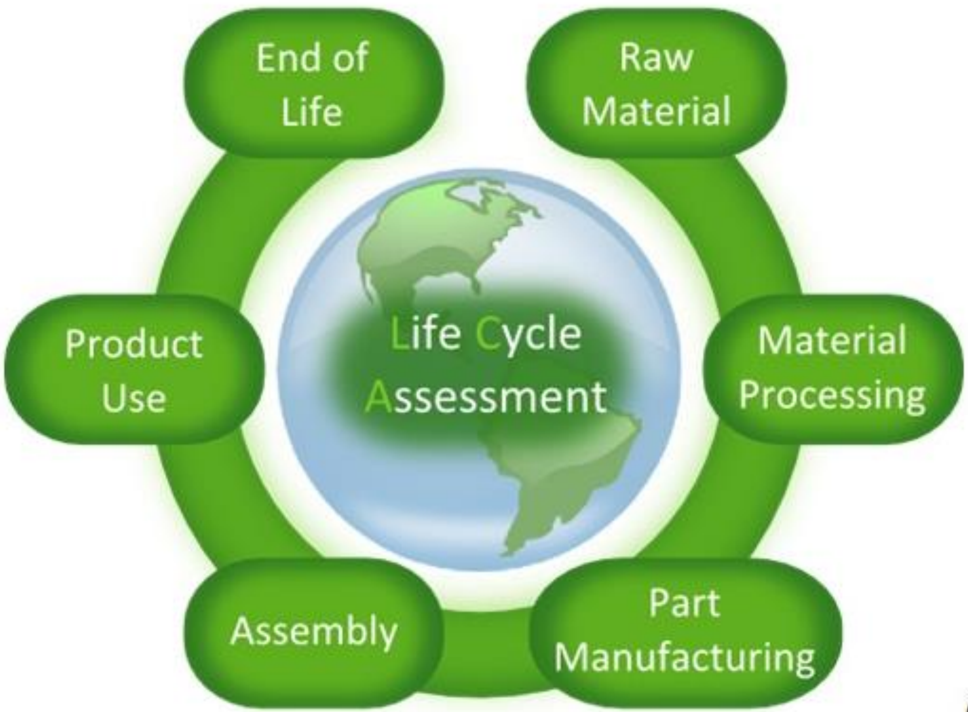
Source: Dale et al., 2014. *Nature Climate Change* **4**:524-527

Toolkits (1): Net Energy Analysis

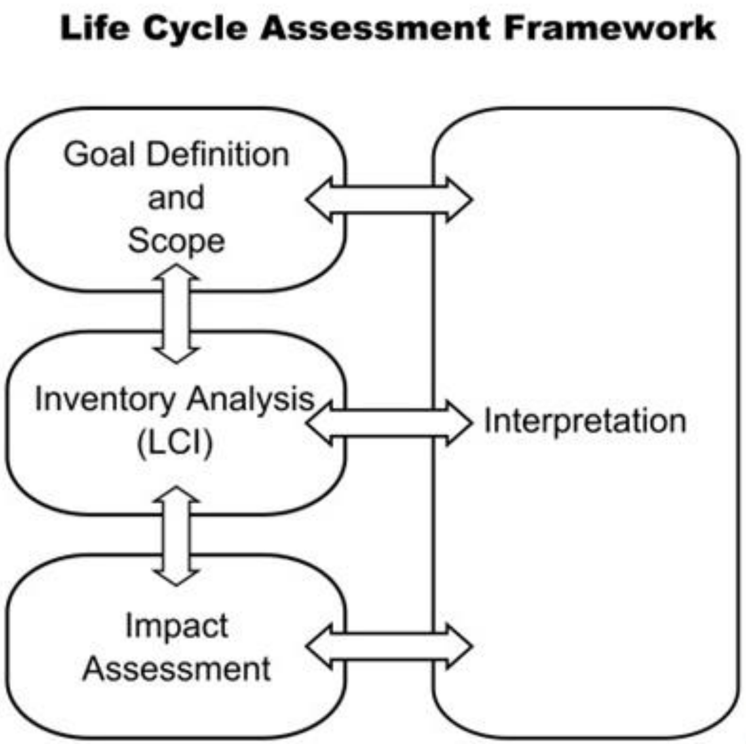
- NEA seeks to understand how effective a system is at exploiting primary energy sources and upgrading environmental stocks and flows into usable energy carriers (*"bang for the buck"*)
- NEA is not equipped to say anything about the long-term sustainability of an energy technology, since:

  1. the actual amounts of primary energy stocks and flows that are directly extracted, delivered and transformed into the 'returned' energy carriers are not included in the calculation of the EROI;
  2. it does not differentiate between renewable and non-renewable primary energy sources.

Toolkits (2): Life Cycle Assessment



(a)



(b)

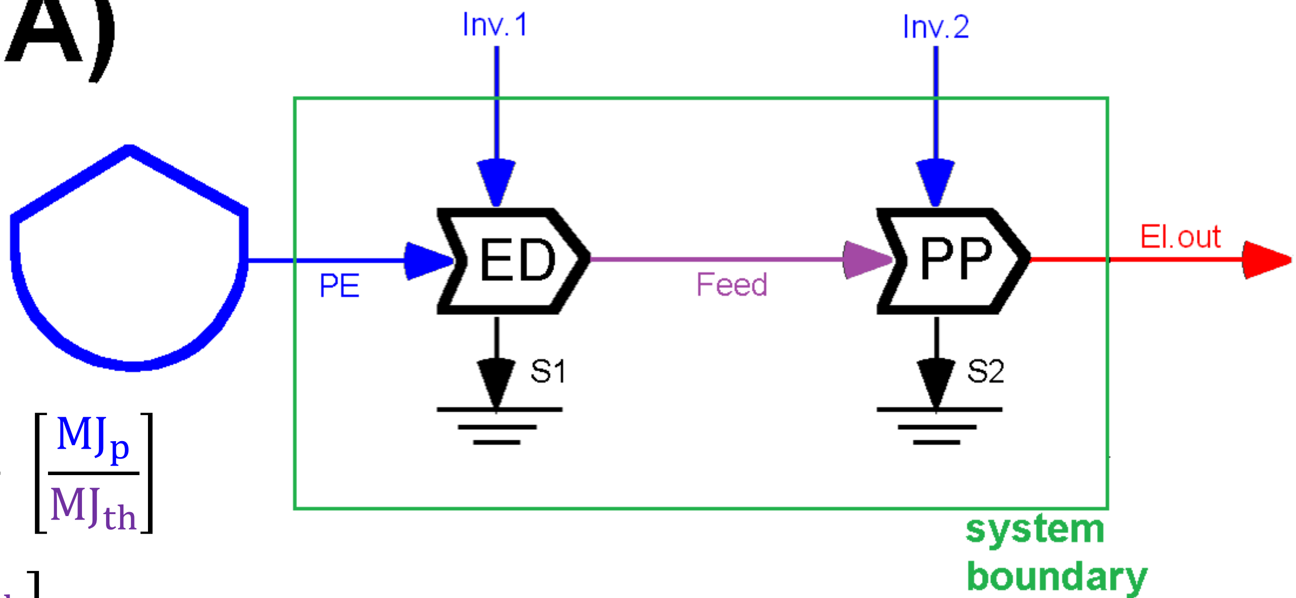
Toolkits (2): Life Cycle Assessment

- LCA seeks to understand the full environmental impacts and overall efficiency of a process or system.
- It is concerned with the total primary energy that must be withdrawn from the environment in order to produce a given amount of usable energy carrier.
- LCA is not equipped to say anything about the immediate viability of an energy technology, since:
  - it does not differentiate between the energy that is directly extracted, delivered and transformed and the energy that is invested in order to do so.

NEA vs. LCA

Indicator (ratio)	***EROI***	***CED*** (and ***nr-CED***)
Numerator	Energy delivered to society (expressed *either* in units of usable energy carrier, *or* in units of primary energy equivalent)	<u>Total</u> energy <u>withdrawn</u> from nature (in units of primary energy)
Denominator	Sum of <u>already available energy carriers diverted</u> from other societal uses (expressed in units of primary energy equivalent)	Energy delivered to society (expressed in units of usable energy carrier)
Distinction between renewable and non-renewable	No, not needed	Yes, recommended
Safeguard subject	Economical / <u>effective</u> use of available energy carriers	Sustainable / <u>efficient</u> use of energy resources
Time perspective	Short term	Long term

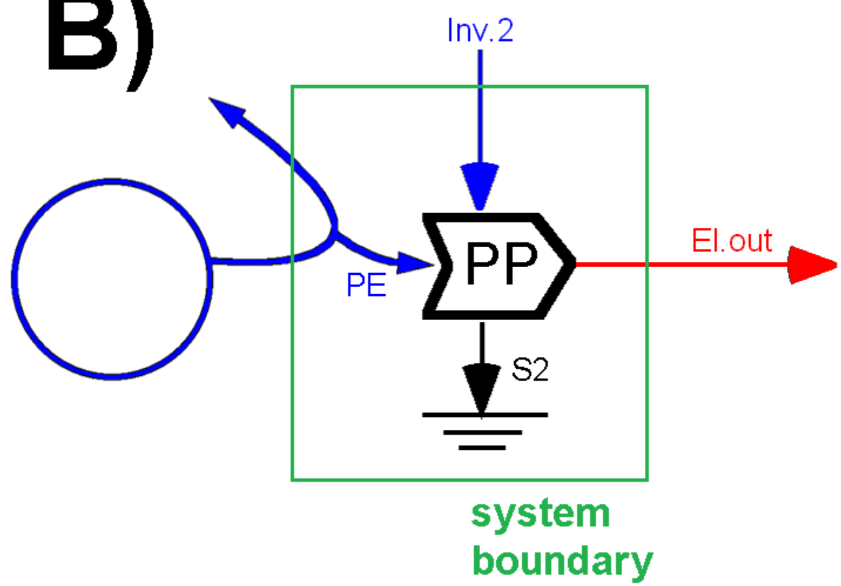
A)



$$CED_{Feed} = \frac{PE + Inv.1}{Feed} \quad \left[\frac{\mathrm{MJ_p}}{\mathrm{MJ_{th}}}\right]$$

$$EROI_{Feed} = \frac{Feed}{Inv.1} \quad \left[\frac{\mathrm{MJ_{th}}}{\mathrm{MJ_p}}\right]$$

B)

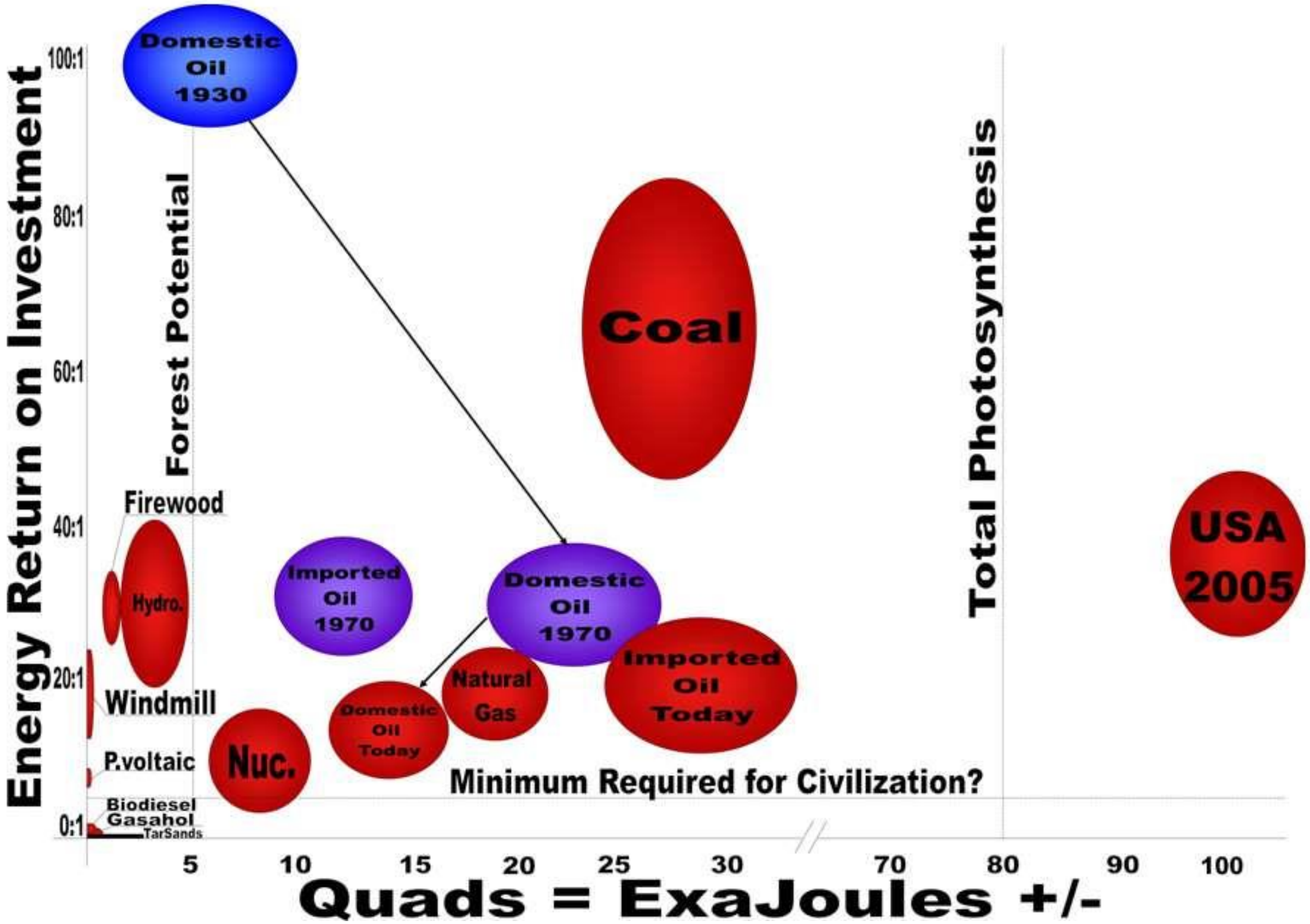


$$CED_{el} = \frac{PE + Inv.1 + Inv.2}{El.out} \quad \left[\frac{\mathrm{MJ_p}}{\mathrm{MJ_{el}}}\right]$$

$$EROI_{el} = \frac{El.out}{Inv.1 + Inv.2} \quad \left[\frac{\mathrm{MJ_{el}}}{\mathrm{MJ_p}}\right]$$

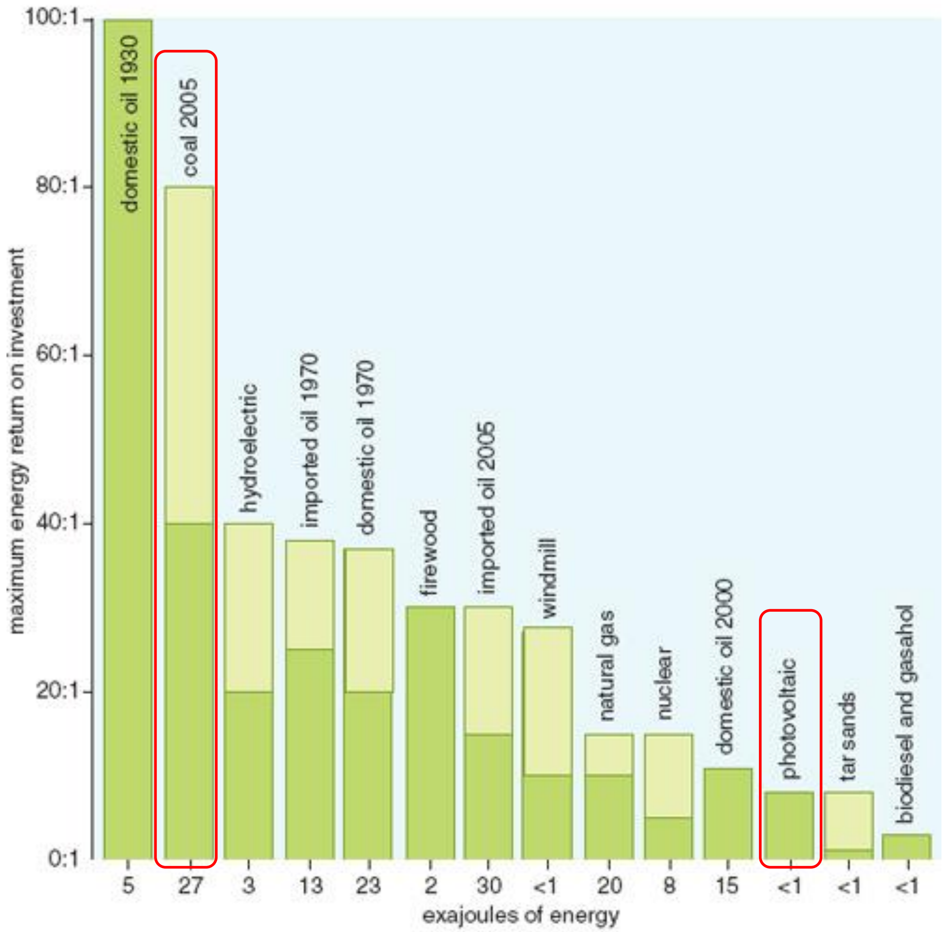
$$EROI_p = \frac{\left(El.out/\eta_G\right)}{Inv.1 + Inv.2} \quad \left[\frac{\mathrm{MJ_p}}{\mathrm{MJ_p}}\right]$$

Well-known “facts” ?



Source: Murphy and Hall, 2010. *An.. N.Y. Acad. Sci.* **1185**:102-118

Or is this only part of the story ?



Source: Hall and Day, 2009. *American Scientist* **97**:230-237

Potential issues in the NEA of thermal *vs.* photovoltaic electricity

- Careless use of LCA databases and CED figures
  Care must be exercised to exclude all forms of energy that are not appropriated by society from the computation of the 'investment'.

- Failure to account for additional energy investments along the supply chain
  i.e. inconsistent use of EROI (at source) instead of EROI (at point of use)

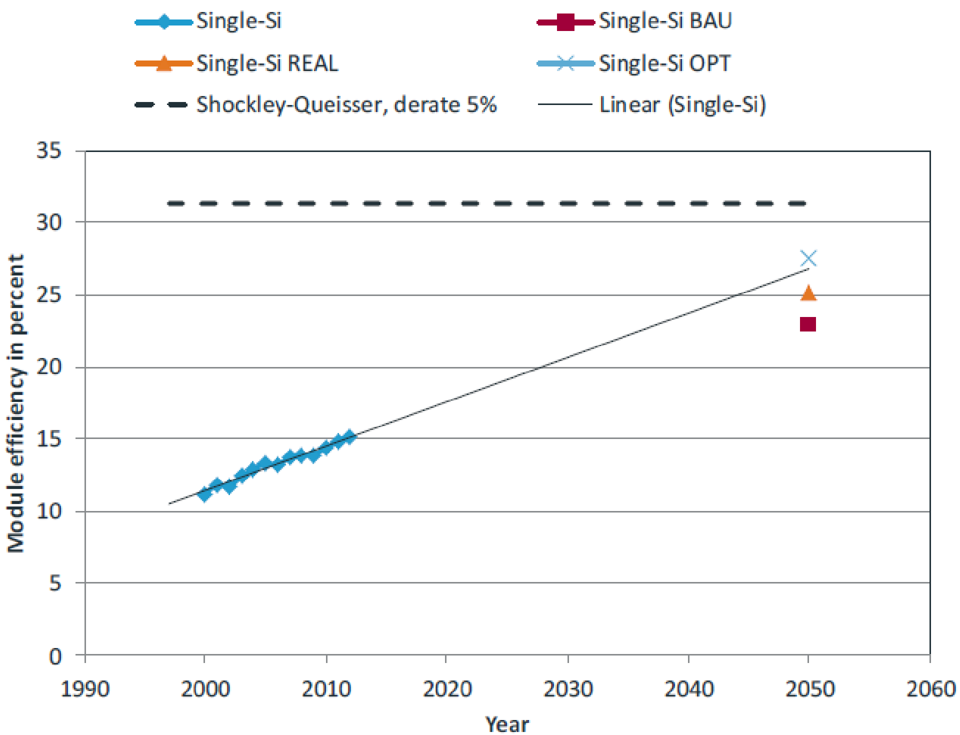
- Inconsistencies in 'functional unit'
  - E.g. 1 kWh of coal-fired electricity is not truly functionally equivalent to 1 kWh of PV electricity, since: (i) the former entails more GHG emissions (may be addressed by CCS), and (ii) the latter is intermittent (may be addressed by energy storage).

Refs: Arvesen and Hertwich, 2015. More caution is needed when using life cycle assessment to determine energy return on investment (EROI). *Energy Policy* **76**:1-6

Hall et al., 2014. EROI of different fuels and the implications for society. *Energy Policy* **64**:141-152

Potential issues in the NEA of thermal *vs.* photovoltaic electricity

- Use of outdated information (especially if aiming for a prospective analysis!)
  - E.g.



Source: Itten et al., 2015. Life cycle assessment of future photovoltaic electricity production from residential-scale systems operated in Europe. IEA PVPS Task 12 report, **in press**

Potential issues in the NEA of thermal *vs.* photovoltaic electricity

- Use of outdated information (especially if aiming for a prospective analysis!)

- Inconsistencies in “goal” definition

  i.e. is it: (A) to compare alternative technologies as they are;

  or (B) to assess the ability of a technology to (single-handedly) support an industrial society?

  - E.g. How much (if any) energy storage is to be included in a NEA of PV?
    (if taken in isolation, baseload technologies such as coal and nuclear are also unable to follow electricity demand, and so they should also be required to deploy some storage capacity)

Ref: Carbajales-Dale et al., 2015. Energy return on investment (EROI) of solar PV: an attempt at reconciliation. *Proceedings of the IEEE*, **in press**

Potential issues in the NEA of thermal *vs.* photovoltaic electricity

- Use of outdated information (especially if aiming for a prospective analysis!)

- Inconsistencies in 'goal' definition

  i.e. is it: (A) to compare alternative technologies as they are;

  or (B) to assess the ability of a technology to (single-handedly) support an industrial society?

- Inconsistencies in 'scope' definition

  i.e. is the analysis carried out: (A) at the level of the individual technology;

  or (B) at the level of the entire industry / country?

Ref: Carbajales-Dale et al., 2015. Energy return on investment (EROI) of solar PV: an attempt at reconciliation. *Proceedings of the IEEE*, **in press**

Example:

Net Energy Analysis of

one unit of coal-fired and PV electricity

in the UK

using the Ecoinvent LCA database

COAL AT MINE	USA	Colombia	Russia	Weighted avg. (UK supply mix)
% of coal supply to UK	25.0%	27.5%	47.5%	
CED (coal at mine) [MJp/kg]	**26.1**	**24.3**	**25.5**	**25.3**
kg (coal in the ground) / kg (coal extracted)	**1.32**	**1.25**	**1.23**	
HHV coal [MJth/kg]	19.1	19.1	19.1	19.1
PE in coal [MJp/kg] (coal extracted)	25.212	23.875	23.493	
Nm3 Pit gas lost / kg (coal exctracted)	**0.0086**	**0.0002**	**0.0149**	
HHV pit gas [MJth/Nm3]	39.8	39.8	39.8	
PE "lost" in gas MJth/kg (coal extracted)	0.342	0.008	0.593	
PE total [MJp/kg]	25.6	23.9	24.1	24.4
Inv1A [MJp/kg] = CED (at mine) - PE	0.5	0.4	1.4	0.923
E.out [MJth HHV/kg]	25.2	25.2	25.2	25.2
EROI (coal at mine)	**46.2**	**60.4**	**17.8**	**27.3**

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COAL AT REGIONAL STORAGE				
CED (coal at regional storage) MJp/kg	**26.8**	**24.5**	**26**	**25.8**
Inv1B = CED (at reg. storage) - PE - Inv1A	0.7	0.2	0.5	0.47
EROI (coal at regional storage)	**20.2**	**40.8**	**13.2**	**18.1**

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COAL SUPPLY MIX (UK)				
transport distance by sea	5478	8019	2360	
tkm by sea	5.48	8.02	2.36	4.7
CED (coal supply mix) [MJp/kg]				**26.7**
Inv1C = CED (supply mix) - (PE + Inv1A + Inv1B) [MJp/kg]				0.9
EROI (coal supply mix UK)				**10.9**

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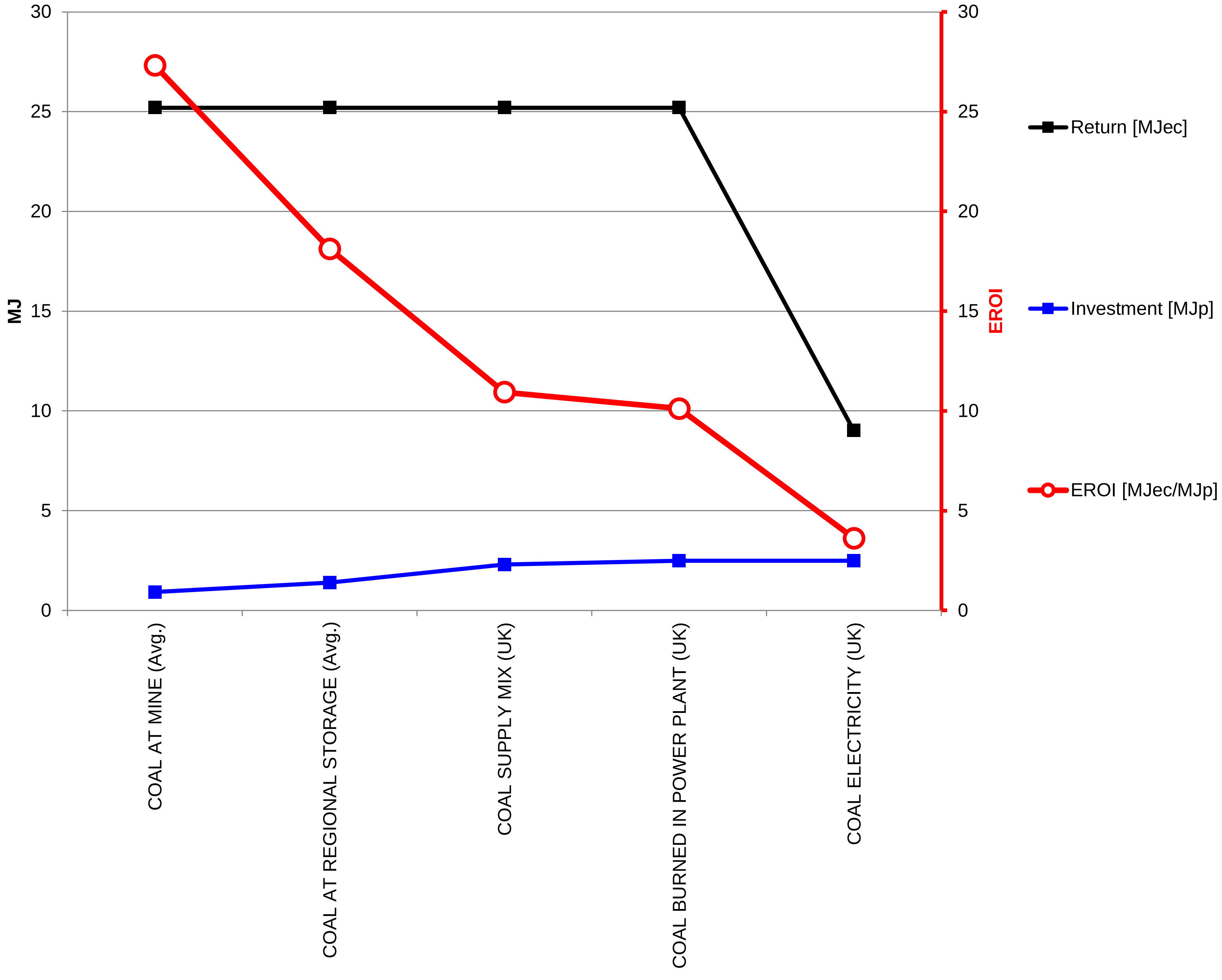
Inv1C = CED (supply mix) - (PE + Inv1A + Inv1B) [MJp/kg]				0.9
EROI (coal supply mix UK)				**10.9**
COAL BURNED IN POWER PLANT (UK)				
CED (coal burned in PP) [MJp/MJthLHV]				**1.14**
1/LHV [kg/MJth]				**0.0424**
LHV [MJth/kg]				23.6
CED (coal burned in PP) [MJp/kg]				**26.9**
Inv2 = CED (coal burned in PP) - (PE + Inv1A + Inv1B + Inv1C) [MJp/kg]				**0.19**
EROI (coal burned in PP - UK)				**10.1**
COAL ELECTRICITY (UK)				
R [MJel/MJthHHV]				0.36
EROIel (coal electricity, UK)				**3.6**
CEDel (coal electricity, UK) [MJp/MJel]				**2.98**


MJ
EROI
30
25
20
15
10
5
0
Return [MJec]
Investment [MJp]
EROI [MJec/MJp]
COAL AT MINE (Avg.)
COAL AT REGIONAL STORAGE (Avg.)
COAL SUPPLY MIX (UK)
COAL BURNED IN POWER PLANT (UK)
COAL ELECTRICITY (UK)

PV SYSTEM		
CED1 (mc-Si PV modules)	MJp/m2	2524
CED2 (BOS goundmount)	MJp/m2	500
CED3 (PV module EoL)	MJp/m2	357
eta (capture efficiency)	%	14%
PR (performance ratio)	%	80%
T (lifetime)	yr	30

Refs:

- de Wild-Scholten, 2013. *Solar Energy Materials & Solar Cells* **119**:296–305
- Fthenakis et al., 2009. *24th EU-PVSEC*
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PV ELECTRICITY (UK)		
Irr (irradiation)	kWh/(m2*yr)	1000
PE = Irr*eta*T*3.6	MJp/m2	15228
El.out = PE*PR	MJel/m2	12182
Inv.2 = CED(1+2+3)	MJp/m2	3381
EROIel = El.out/Inv.2	**MJel/MJp**	**3.6**
CEDel = (PE + Inv.2)/El.out	**MJp/MJel**	**1.53**
nr-CEDel	**MJp/MJel**	**0.28**

Refs:

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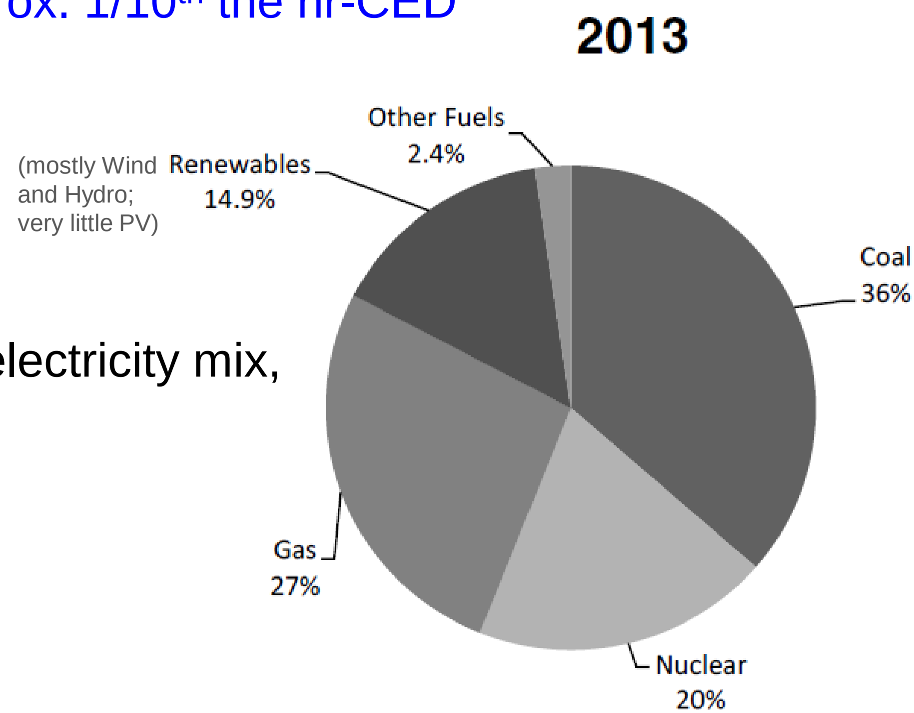
- Fthenakis et al., 2009. *24th EU-PVSEC*
- Fthenakis et al., 2009. *24th EU-PVSEC (preliminary estimate)*

! The same EROI as for coal electricity

! Approx. half the CED

! Approx. 1/10th the nr-CED

Yet, coal features prominently in the UK electricity mix, while PV is still a very minor player:



Source: UK DECC, 2014. Digest of UK Energy Statistics 2014

Now let's see what happens in the countries where the coal comes from:

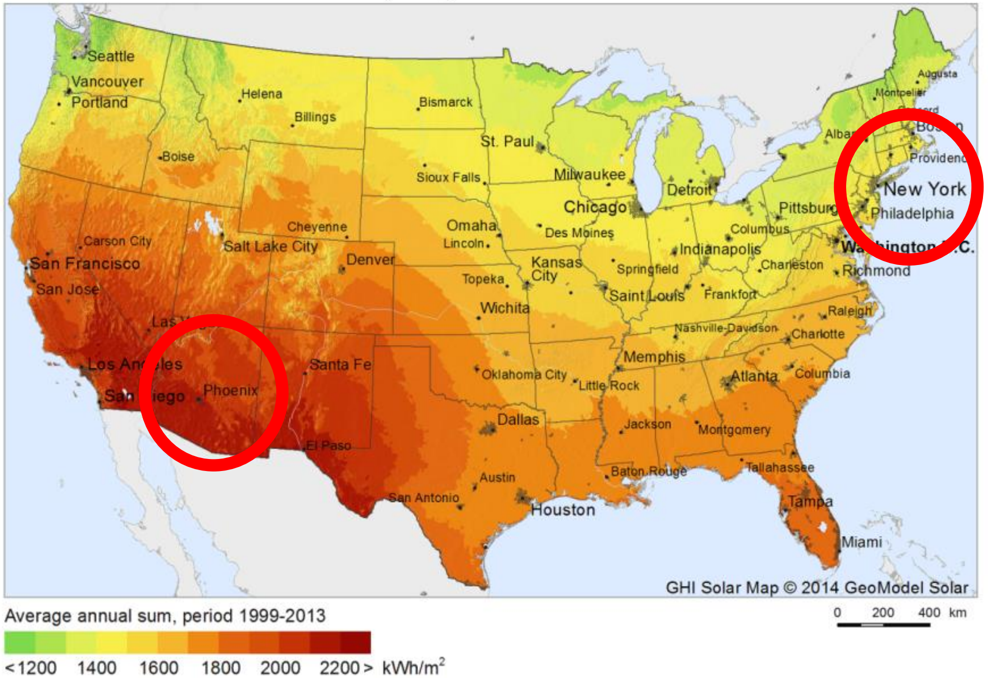
Net Energy Analysis of

one unit of coal-fired and PV electricity

in the USA and in Colombia

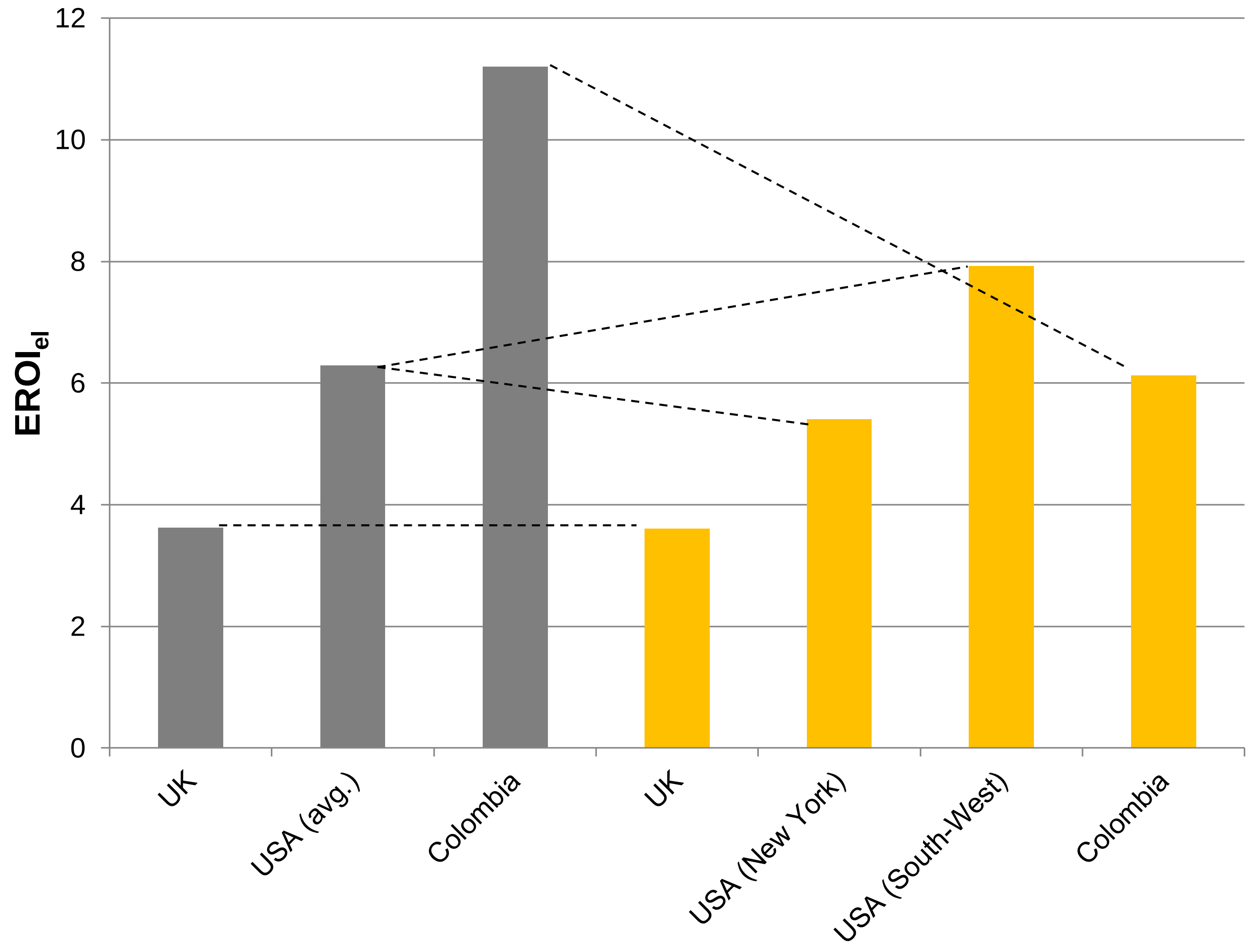
using the Ecoinvent LCA database

Global Horizontal Irradiation (GHI) USA Mainlands



Global Horizontal Irradiation Latin America and the Caribbean

Coal-fired *vs.* PV electricity



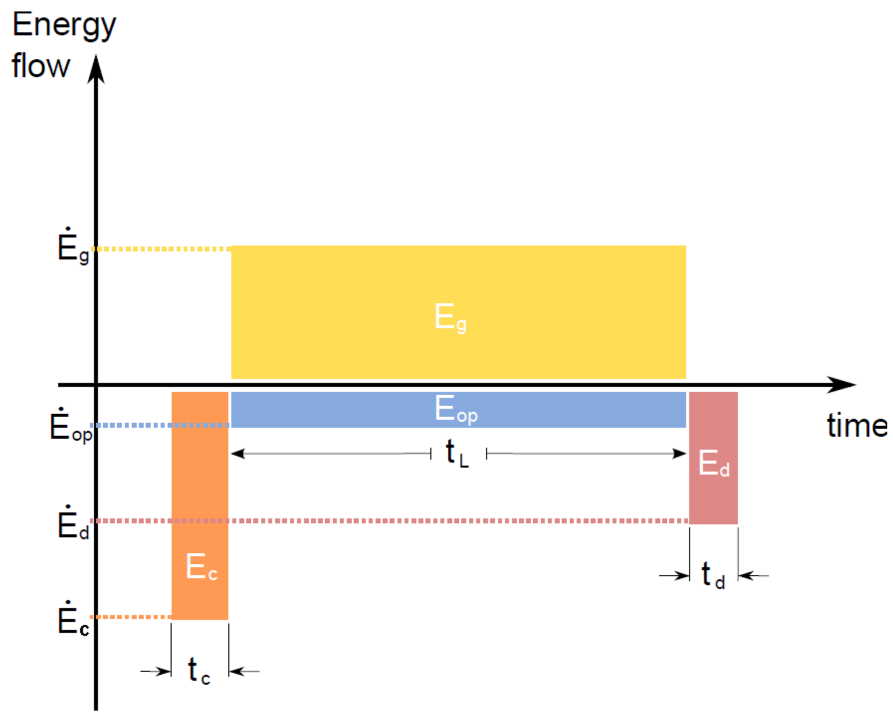
Steady-state *vs*. dynamic analyses

- Conventional NEAs (and LCAs) are 'static'

  i.e. the calculations are performed in the same way, irrespective of when, along the time line of the life cycle of the system, the individual contributions to the total energy 'investment' and to the total energy 'return' actually take place (steady-state assumption).

Steady-state *vs.* dynamic analyses

- Conventional NEAs (and LCAs) are ‘static’
- Most of the energy investment for PV (**E_c**) takes place during a short initial **t_c**, while the energy ‘return’ (**E_g**) is spread over the much longer use phase (**t_L**).



Source: Herendeen R., 2004. Net energy analysis: concepts and methods. In: *Encyclopedia of Energy*, Elsevier.

Steady-state *vs*. dynamic analyses

- Conventional NEAs (and LCAs) are ‘static’
- Most of the energy investment for PV (E_c) takes place during a short initial $\mathbf{t_c}$, while the energy ‘return’ (E_g) is spread over the much longer use phase ($\mathbf{t_L}$).

- This is potentially relevant in prospective and consequential NEAs of PVs.

UK EPSRC "WISE-PV" project

- Novel combined CLCA + NEA approach is adopted, aimed at the research question:
  - "What would be the whole-system environmental consequences of opting for the large-scale deployment of PV in the UK grid (up to 50 GWp in 2035), when compared to previously developed future grid scenarios without PV?"
- Functional unit:1 kWh of electricity produced by the entire grid
  - No allocation of impacts due to e.g. grid reinforcement, storage, etc. between PV and other technologies
- Two stakeholder-informed scenarios
  1. User-led PV deployment (mainly rooftop PV with small-scale battery storage; reduced user reliance on grid)
  2. Network-led PV deployment (more centralized PV installations and large-scale energy storage; network reorganization)
- Both 'steady-state' and 'dynamic' analyses are envisaged

Thank you

Dr. Marco Raugei

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