

Net Energy Analysis of Photovoltaics: the whys and wherefores...

and the potential pitfalls



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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 <u>effective</u> a system is at <u>exploiting</u> primary energy sources and <u>upgrading</u> environmental stocks and flows into usable energy carriers (*"bang for the buck"*)
- NEA is <u>not</u> equipped to say anything about the long-term <u>sustainability</u> 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 <u>not</u> differentiate between <u>renewable</u> and <u>non-renewable</u> primary energy sources.



Toolkits (2): Life Cycle Assessment





Toolkits (2): Life Cycle Assessment

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withdrawn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



NEA *vs.* LCA

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withdrawn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





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



- 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



 Use of outdated information (especially if aiming for a prospective analysis!)



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**



- 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**



- 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)
 - 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

				Weighted avg.
COAL A	T MINE U	SA Colombia	Russia	(UK supply mix)
% of coal suppl	y to UK 25.0	% 27.5%	47.5%	
CED (coal at mine) [N	1Jp/kg] 26	.1 24.3	25.5	25.3
kg (coal in the ground) / kg (coal ext	racted) 1.	32 1.25	1.23	
HHV coal [M	Jth/kg] 19	.1 19.1	. 19.1	19.1
PE in coal [MJp/kg] (coal ext	racted) 25.2	12 23.875	23.493	
Nm3 Pit gas lost / kg (coal exct	racted) 0.00	86 0.0002	0.0149	
HHV pit gas [MJth	/Nm3] 39	.8 39.8	39.8	
PE "lost" in gas MJth/kg (coal ext	racted) 0.3	42 0.008	0.593	
PE total [N	1 Jp/kg] 25	.6 23.9	24.1	24.4
Inv1A [MJp/kg] = CED (at mi	ne) - PE (0.5 0.4	1.4	0.923
E.out [MJth H	HV/kg] 25	.2 25.2	25.2	25.2
EROI (coal a	t mine) 46	.2 60.4	17.8	27.3

				Weighted avg.
COAL AT MINE	USA	Colombia	Russia	(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
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

			Weighted avg.
USA	Colombia	Russia	(UK supply mix)
25.0%	27.5%	47.5%	
26.1	24.3	25.5	25.3
1.32	1.25	1.23	
19.1	19.1	19.1	19.1
25.212	23.875	23.493	
0.0086	0.0002	0.0149	
39.8	39.8	39.8	
0.342	0.008	0.593	
25.6	23.9	24.1	24.4
0.5	0.4	1.4	0.923
25.2	25.2	25.2	25.2
46.2	60.4	17.8	27.3
26.8	24.5	26	25.8
0.7	0.2	0.5	0.47
20.2	40.8	13.2	18.1
5478	8019	2360	
5.48	8.02	2.36	4.7
			26.7
			0.9
			10.9
	USA 25.0% 26.1 1.32 19.1 25.212 0.0086 39.8 0.342 25.6 0.5 25.2 46.2 26.8 0.7 26.8 0.7 20.2	USA Colombia 25.0% 27.5% 26.1 24.3 1.32 1.25 19.1 19.1 25.212 23.875 0.0086 0.0002 39.8 39.8 0.342 0.008 25.6 23.9 0.5 0.4 25.2 25.2 46.2 60.4 20.2 40.8 5478 8019 5.478 8.02	USAColombiaRussia25.0%27.5%47.5%26.124.325.51.321.251.2319.119.119.125.21223.87523.4930.00860.00020.014939.839.839.80.3420.0080.59325.623.924.10.50.41.425.225.225.226.824.5260.70.20.520.240.813.25478801923605.488.022.36

COAL AT MINE USA Colombia Russia (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 52.3 kg (coal in the ground) / kg (coal extracted) 1.32 1.25 1.23 HHV coal [MUltr/kg] 19.1 19.1 19.1 19.1 PE in coal [MUlp/kg] (coal extracted) 0.0086 0.0002 0.0149 MM3 Pit gas lost / kg (coal extracted) 0.342 0.008 0.593 PE 'lost'' in gas MUth/kg (coal extracted) 0.342 0.008 0.593 PE 'lost'' in gas MUth/kg (coal extracted) 0.342 0.008 0.593 COAL AT REGIONAL STORAGE Exott [MUlth/HW/kg] 25.5 23.9 24.1 24.4 Inv1A [MUp/kg] = CED (at at regional storage) MD //s 60.4 17.8 27.3 COAL AT REGIONAL STORAGE EXOI (coal at regional storage) 20.2 40.8 18.2 18.1 COAL SUPPLY MIX (UK) COAL SUPPLY MIX (UK) COAL SUPPLY MIX (UK) 0.9 26.7					Weighted avg.
% 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 1.32 1.32 1.33 HHV coal [MJp/kg] (coal extracted) 25.21 23.875 23.493 HHV pit gas [ost / kg (coal extracted) 0.006 0.0002 0.0149 HHV pit gas [MUth/kg] (coal extracted) 0.342 0.008 0.593 PE "lost" in gas Muth/kg (coal extracted) 0.342 0.008 0.593 PE "lost" in gas Muth/kg (coal extracted) 0.342 0.008 0.593 PE "lost" in gas Muth/kg (coal extracted) 0.342 0.008 0.593 PE "lost" in gas Muth/kg (coal extracted) 0.342 0.008 0.593 Eout [MUlp/kg] = CED (at mine) - PE 0.5 0.4 1.4 0.923 Eout [MUlp/kg] 25.2	COAL AT MINE	USA	Colombia	Russia	(UK supply mix)
CED (coal at mine) [MUp/kg] 26.1 24.3 25.5 25.3 kg (coal in the ground) / kg (coal extracted) 1.32 1.25 1.23 HV coal [MUp/kg] (coal extracted) 25.212 23.875 23.493 Nm3 Pit gas lost / kg (coal extracted) 0.0086 0.0002 0.0149 HHV pit gas [MUth/kg] 29.8 39.8 39.8 PE "lost" in gas MUth/kg (coal extracted) 0.342 0.008 0.593 PE "lost" in gas MUth/kg (coal extracted) 0.342 0.008 0.593 PE "lost" in gas MUth/kg (coal extracted) 0.342 0.008 0.593 PE total [MUp/kg] 25.6 23.9 24.1 24.4 Inv1A [MJp/kg] 2E.0 (MIth HHV/kg] 25.2 25.0 24.1 24.1 24.1	% of coal supply to UK	25.0%	27.5%	47.5%	
kg (coal in the ground) / kg (coal extracted) 1.32 1.25 1.23 HHV coal [MUth/kg] 19.1 19.1 19.1 19.1 PE in coal [MUth/kg] 125.212 23.875 23.493 Nm3 Pit gas lost / kg (coal extracted) 0.0086 0.0000 0.0149 HHV pit gas [Nuth/kg] 39.8 39.8 39.8 PE "lost" in gas Muth/kg (coal extracted) 0.342 0.008 0.593 PE "lost" in gas Muth/kg (coal extracted) 0.542 0.04 1.4 0.923 Leout [MUth/kg] 25.2 25.4 26.5 26.5 26.5	CED (coal at mine) [MJp/kg]	26.1	24.3	25.5	25.3
HHV coal [Mth/kg] 19.1 19.1 19.1 PE in coal [Mtp/kg] (coal extracted) 25.212 23.875 23.493 Mm3 Pit gas lost / kg (coal extracted) 0.0006 0.0002 0.0149 HHV pit gas [Mth/Nm3] 39.8 39.8 39.8 9E "lost" in gas Mth/kg (coal extracted) 0.342 0.008 0.593 PE "lost" in gas Mth/kg (coal extracted) 0.342 0.004 0.933 1mv1A [Mlp/kg] = CED (at mine) PE 0.5 0.4 1.4 0.923 Ecout [Mith HHV/kg] 25.2 25.2 25.2 25.2 25.2 COAL AT REGIONAL STORAGE T 0.7 0.2 0.5 0.47 EROI (coal at regional storage) MIp/kg 26.8 24.5 26 25.8 1mv1B = 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 COAL SUPPLY MIX (UK) I 2360 47.7 25.6 25.7 25.7 25.7 25.7 25.7 25.7 25.7 25.7 25.7 25.7 25.6 <t< td=""><td>kg (coal in the ground) / kg (coal extracted)</td><td>1.32</td><td>1.25</td><td>1.23</td><td></td></t<>	kg (coal in the ground) / kg (coal extracted)	1.32	1.25	1.23	
PE in coal [Mup/kg] (coal extracted) 25.212 23.875 23.493 NmB Pit gas lost / kg (coal extracted) 0.0086 0.0002 0.0149 HHV pit gas [Muth/Nm3] 39.8 39.8 39.8 PE "lost" in gas Muth/kg (coal extracted) 0.342 0.008 0.593 PE total [Mup/kg] 25.6 23.9 24.1 24.4 Inv1A [Mup/kg] = CED (at mine) - PE 0.5 0.4 1.4 0.923 E.out [Muth HHV/kg] 25.2 25.2 25.2 25.2 COAL AT REGIONAL STORAGE 7	HHV coal [MJth/kg]	19.1	19.1	19.1	19.1
Nm3 Pit gas lost / kg (coal exctracted) 0.0086 0.0002 0.0149 HHV pit gas [Mtth/Nm3] 39.8 39.8 39.8 PE"lost" in gas Mtth/kg (coal extracted) 0.342 0.008 0.593 PE total [Mlp/kg] 25.6 23.9 24.1 24.4 Inv1A [Mlp/kg] = CE0 (at mine) - PE 0.5 0.4 1.4 0.923 E.out [Mth HHV/kg] 25.2 25.2 25.2 25.2 E.Out [Mth HHV/kg] 26.8 24.5 26 25.8 COAL AT REGIONAL STORAGE 0.0 0.5 0.47 EROI (coal at regional storage) PE - Inv1A 0.7 0.2 0.5 0.47 EROI (coal at regional storage) 20.2 40.8 13.2 18.1 1.1 COAL SUPPLY MIX (UK) 0 0.5 0.47 1.1 1.1 COAL SUPPLY MIX (UK) 0.7 0.2 0.5 0.47 CED (coal supply mix) (WL/Kg] 0.6 0.9 2360 1.1 Inv1C = CED (supply mix) - (PE + Inv1A + Inv1B) [Mlp/kg] 0.1 0.9 2	PE in coal [MJp/kg] (coal extracted)	25.212	23.875	23.493	
HHV pit gas [Mlth/Nm3] 39.8 39.8 39.8 PE "lost" in gas Mlth/kg (coal extracted) 0.342 0.008 0.593 PE total [Mlp/kg] 25.6 23.9 24.1 24.4 Inv1A [Mlp/kg] = CED (at mine) - PE 0.5 0.4 1.4 0.923 E.out [Mlth HHV/kg] 25.2 25.2 25.2 25.2 COAL AT REGIONAL STORAGE	Nm3 Pit gas lost / kg (coal exctracted)	0.0086	0.0002	0.0149	
PE "lost" in gas MUth/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 [MUH HHV/kg] 25.2 25.2 25.2 25.2 COAL AT REGIONAL STORAGE 0.4 1.7.8 27.3 COAL AT REGIONAL STORAGE 0.7 0.2 0.5 0.47 CED (coal at regional storage) MIp/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 COAL SUPPLY MIX (UK) 0.7 0.2 0.6 4.7 CED (coal supply mix) (MIp/kg) 0.48 20.6 4.7 CED (coal supply mix) (MIp/kg) 0.9 26.6 25.7 Inv1C = CED (supply mix) - (PE + Inv1A + Inv1B) [MIp/kg] 0.9 10.9 10.9 EROI (coal supply mix) (W/W/Kg) 0.9 11.14 0.0424 11.14 CED (coal burned in PP) [MIp/MIthLHV] 0.0424 23.6<	HHV pit gas [MJth/Nm3]	39.8	39.8	39.8	
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 COAL AT REGIONAL STORAGE	PE "lost" in gas MJth/kg (coal extracted)	0.342	0.008	0.593	
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 COAL AT REGIONAL STORAGE COAL at REGIONAL STORAGE T T 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 COAL SUPPLY MIX (UK) T T 26.7 26.7 transport distance by sea 5478 8019 2360 26.7 Inv1C = CED (supply mix) - (PE + Inv1A + Inv1B) [MJp/kg] 548 8.02 2.36 4.7 CED (coal supply mix [MJp/kg] EROI (coal supply mix UK) 10.9 26.7 10.9 EROI (coal supply mix [MJp/kg] 10.9 26.7 10.9 26.7 10.9 CED (coal supply mix [MJp/kg] 10.9 26.7 10.9 26.7 10.9 26.7 Inv1C = CED (supply mix) - (PE + Inv1A + Inv1B) [MJp/kg] 10.9 26.7 10.9 26.7 10.9 26.7 10.9 <td>PE total [MJp/kg]</td> <td>25.6</td> <td>23.9</td> <td>24.1</td> <td>24.4</td>	PE total [MJp/kg]	25.6	23.9	24.1	24.4
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 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 COAL SUPPLY MIX (UK) 47.7 Tansport distance by sea 54.48 8.02 2.36 4.7 CED (coal supply mix) [MJp/kg] 26.7 Inv1C = CED (supply mix) - (PE + Inv1A + Inv1B) [MJp/kg] 26.7 Inv1C = CED (supply mix) - (PE + Inv1A + Inv1B) [MJp/kg] 0.9 EROI (coal supply mix UK) 10.9 0.9 EROI (coal supply mix UK) 10.9 0.9 CED (coal burned in PP) [MJp/kg] 11.4 1/LHV [kg/MIth] 0.0424 11.4 10.2 10.9 0.0424 11.4	Inv1A [MJp/kg] = CED (at mine) - PE	0.5	0.4	1.4	0.923
EROI (coal at mine) 46.2 60.4 17.8 27.3 COAL AT REGIONAL STORAGE <	E.out [MJth HHV/kg]	25.2	25.2	25.2	25.2
COAL AT REGIONAL STORAGE Implementation 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 COAL SUPPLY MIX (UK) CAL SUPPLY MIX (UK)	EROI (coal at mine)	46.2	60.4	17.8	27.3
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 COAL SUPPLY MIX (UK)	COAL AT REGIONAL STORAGE				
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 COAL SUPPLY MIX (UK) COAL SUPPLY MIX (UK) 18.1 COAL SUPPLY MIX (UK) <td< td=""><td>CED (coal at regional storage) MJp/kg</td><td>26.8</td><td>24.5</td><td>26</td><td>25.8</td></td<>	CED (coal at regional storage) MJp/kg	26.8	24.5	26	25.8
EROI (coal at regional storage) 20.2 40.8 13.2 18.1 COAL SUPPLY MIX (UK)	Inv1B = CED (at reg. storage) - PE - Inv1A	0.7	0.2	0.5	0.47
COAL SUPPLY MIX (UK) Image: mark of the second	EROI (coal at regional storage)	20.2	40.8	13.2	18.1
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 COAL BURNED IN POWER PLANT (UK) 11.4 CED (coal burned in PP) [MJp/MJthLHV] 0.0424 LHV [kg/MJth] 0.0424 LHV [MJth/kg] 23.6 CED (coal burned in PP) [MJp/kg] 0.0424 LHV [MJth/kg] 23.6 CED (coal burned in PP) [MJp/kg] 0.0424 LHV [MJth/kg] 23.6 CED (coal burned in PP) - (PE + Inv1A + Inv1B + Inv1C) [MJp/kg] 0.19 EROI (coal burned in PP - UK) 0.19 EROI (coal burned in PP - UK) 0.38 R [MJe//MJHHHV] 0.38 EROIe (coal electricity, UK)	COAL SUPPLY MIX (UK)				
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 COAL BURNED IN POWER PLANT (UK) 10.9 COAL BURNED IN POWER PLANT (UK) 1.14 CED (coal burned in PP) [MJp/MJthLHV] 0.0424 LHV [kg/MJth] 23.6 CED (coal burned in PP) [MJp/kg] 23.6 CED (coal burned in PP) [MJp/kg] 0.0424 LHV [MJth/kg] 0.19 Inv2 = CED (coal burned in PP) - (PE + Inv1A + Inv1B + Inv1C) [MJp/kg] 0.19 EROI (coal burned in PP - UK) 10.1 0.36 R [MJel/MJthHHV] 0.36 3.6 CEDel (coal electricity, UK) [MJp/MJel] 3.6 3.6	transport distance by sea	5478	8019	2360	
CED (coal supply mix) [MJp/kg]26.7Inv1C = CED (supply mix) - (PE + Inv1A + Inv1B) [MJp/kg]0.9EROI (coal supply mix UK)10.9COAL BURNED IN POWER PLANT (UK)10.9CED (coal burned in PP) [MJp/MJthLHV]1.141/LHV [kg/MJth]0.0424LHV [MJth/kg]23.6CED (coal burned in PP) [MJp/kg]26.9Inv2 = CED (coal burned in PP) - (PE + Inv1A + Inv1B + Inv1C) [MJp/kg]0.19EROI (coal burned in PP - UK)10.1COAL ELECTRICITY (UK)0.36EROIel (coal electricity, UK)3.6CEDel (coal electricity, UK) [MJp/MJel]2.98	tkm by sea	5.48	8.02	2.36	4.7
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COAL ELECTRICITY (UK) Image: Coal electricity (UK) R [MJel/MJthHHV] 0.36 EROIel (coal electricity, UK) Scene (Coal electricity, UK) CEDel (coal electricity, UK) [MJp/MJel] 0.36	EROI (coal burned in PP - UK)				10.1
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EROIel (coal electricity, UK)3.6CEDel (coal electricity, UK) [MJp/MJel]2.98	R [MJel/MJthHHV]				0.36
CEDel (coal electricity, UK) [MJp/MJel] 2.98	EROIel (coal electricity, UK)				3.6
	CEDel (coal electricity, UK) [MJp/MJel]				2.98



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

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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	3281
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

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! The same EROI as for coal electricity ! Approx. half the CED ! Approx. 1/10th the pr CED

! Approx. 1/10th the nr-CED

2013







- one unit of coal-fired and PV electricity
- in the USA and in Colombia
- using the Ecoinvent LCA database



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). _{Energy}



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 t_c, while the energy 'return' (E_g) is spread over the much longer use phase (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 largescale energy storage; network reorganization)
- Both 'steady-state' and 'dynamic' analyses are envisaged



Thank you

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