An in-depth look at the energy performance of photovoltaics: the devil is in the details

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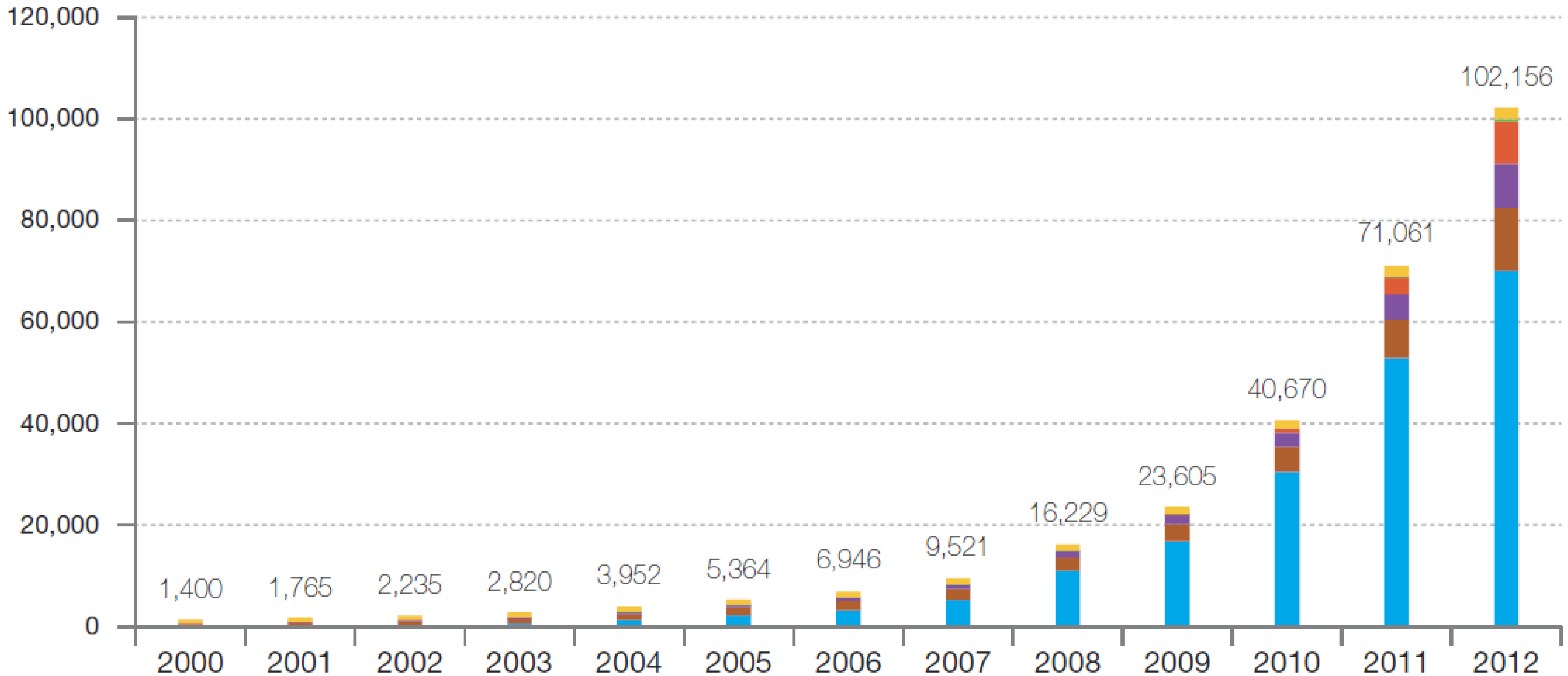
Introduction

Figure 1 - Evolution of global PV cumulative installed capacity 2000-2012 (MW)



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
ROW	751	807	887	964	993	1,003	1,108	1,150	1,226	1,306	1,590	2,098	2,098
MEA	n/a	n/a	n/a	n/a	1	1	1	2	3	25	71	192	601
China	19	24	42	52	62	70	80	100	140	300	800	3,300	8,300
Americas	146	178	225	290	394	501	650	863	1,209	1,752	2,780	4,959	8,717
APAC	355	495	686	916	1,198	1,500	1,825	2,096	2,631	3,373	4,956	7,628	12,397
Europe	129	262	396	598	1,305	2,289	3,281	5,310	11,020	16,850	30,472	52,884	70,043
Total	**1,400**	**1,765**	**2,235**	**2,820**	**3,952**	**5,364**	**6,946**	**9,521**	**16,229**	**23,605**	**40,670**	**71,061**	**102,156**

ROW: Rest of the World. MEA: Middle East and Africa. APAC: Asia Pacific.

Introduction

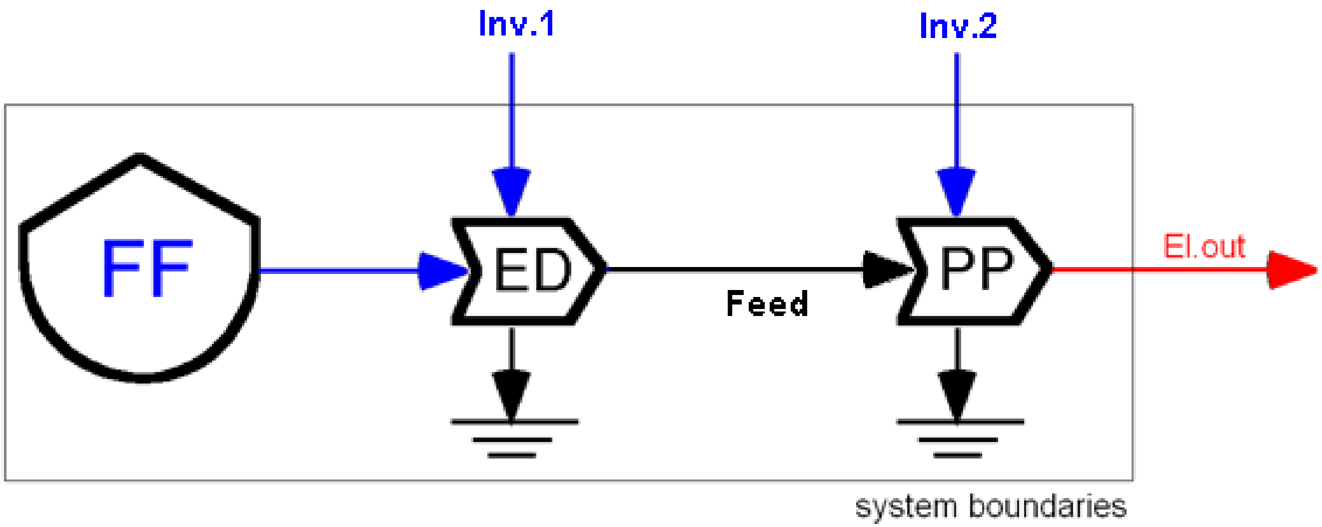
- In order to correctly estimate and predict various aspects of the present and future energy and environmental performance of photovoltaics, a careful multi-pronged methodological approach is required, lest oversimplified and potentially misleading conclusions are drawn.

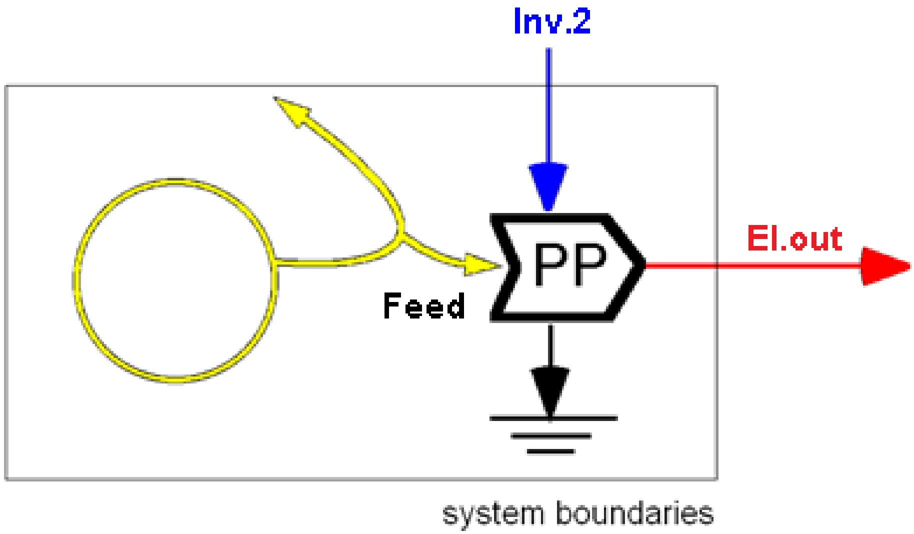
- I will focus on and discuss here two key classes of indicators:

1) **Cumulative Energy Demand (CED)**
   Non-Renewable Cumulative Energy Demand (NRCED)

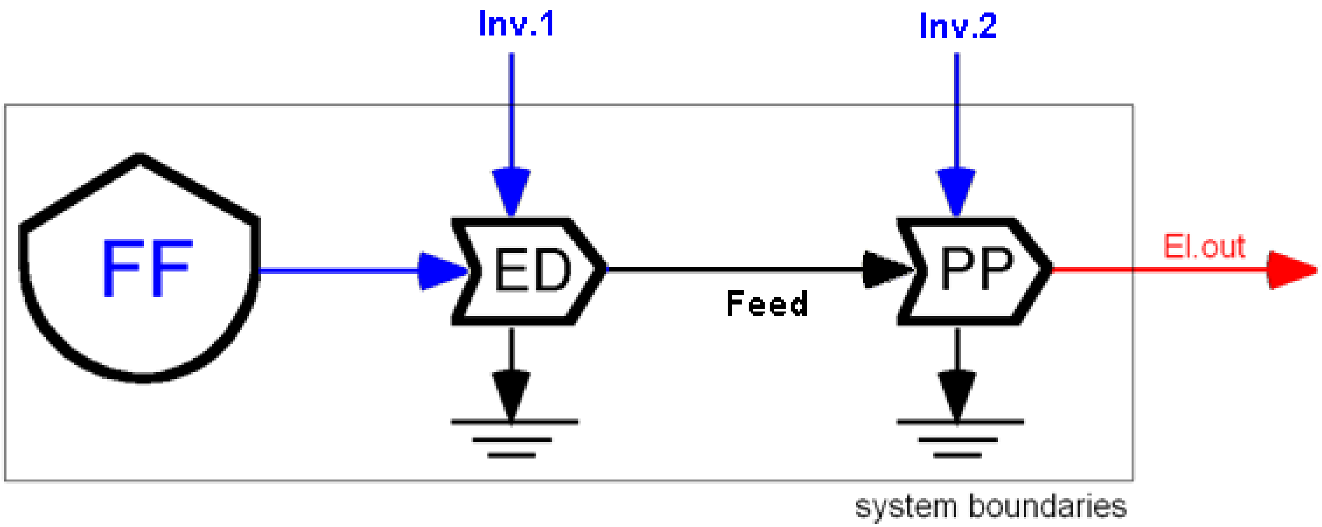
2) **Energy Return On Investment (EROI)**
   Energy Pay-Back Time (EPBT)

Thermal *vs*. PV electricity generation

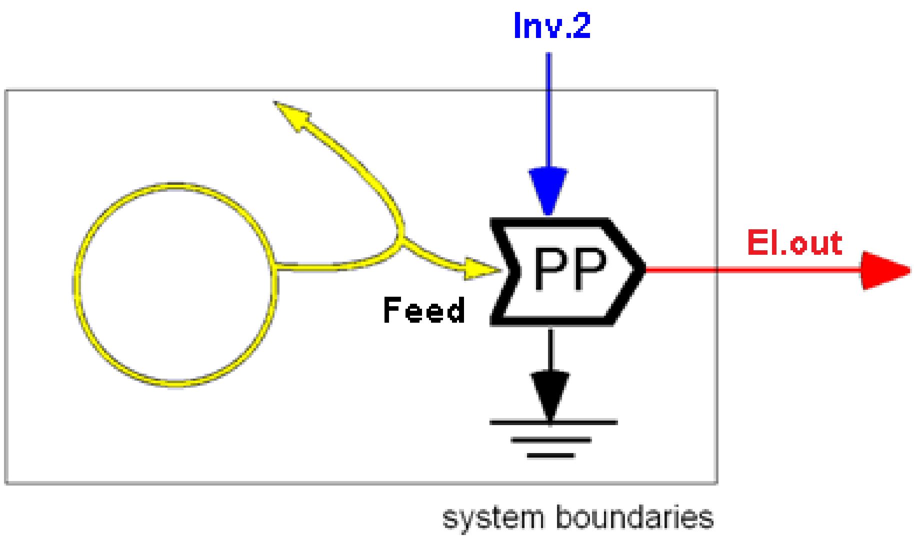




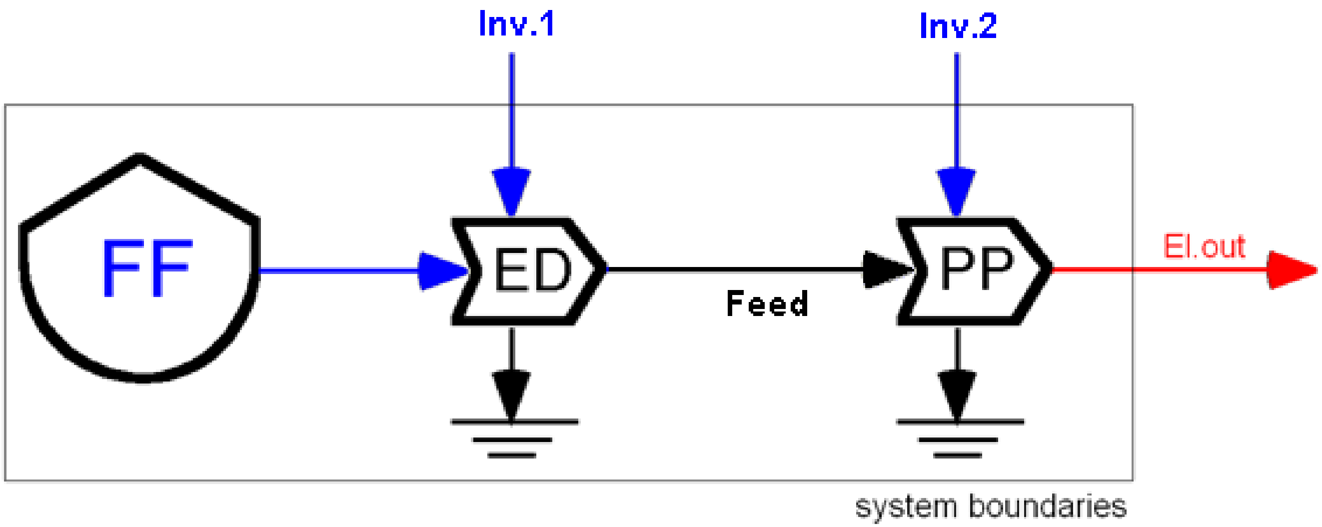
Thermal *vs.* PV electricity generation



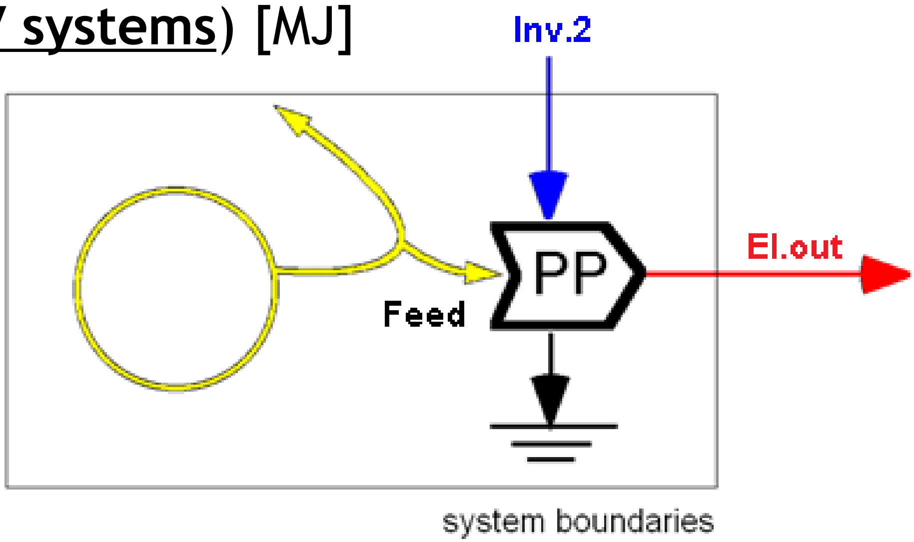
Feed = Energy input that is *converted* into electricity (i.e. chemical energy of the feedstock fuel; energy of captured solar irradiation; etc.) [MJ]



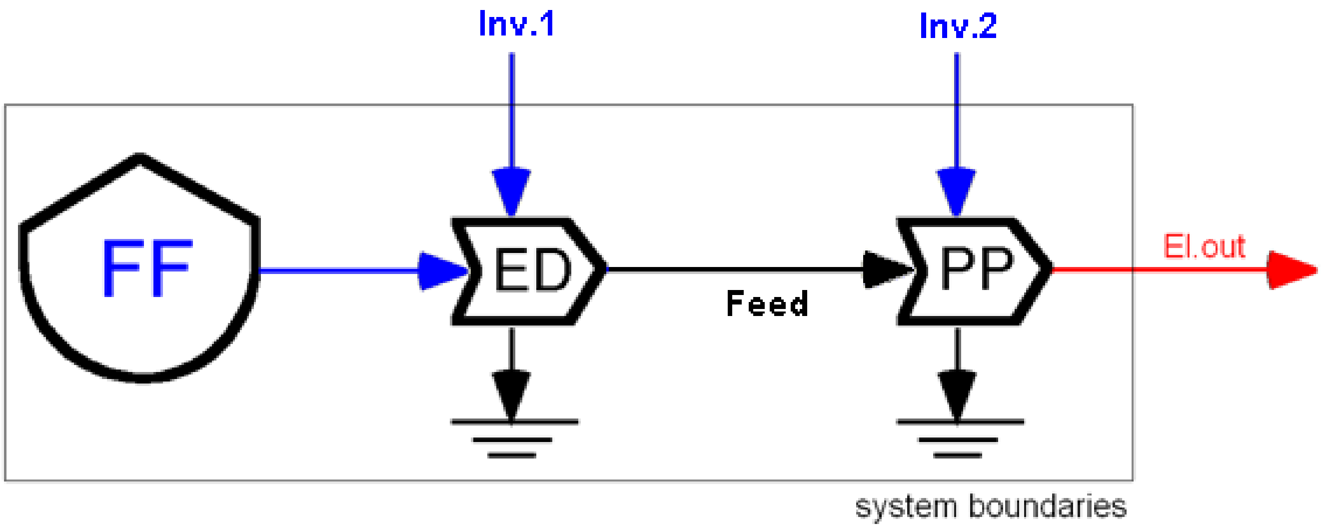
Thermal *vs.* PV electricity generation



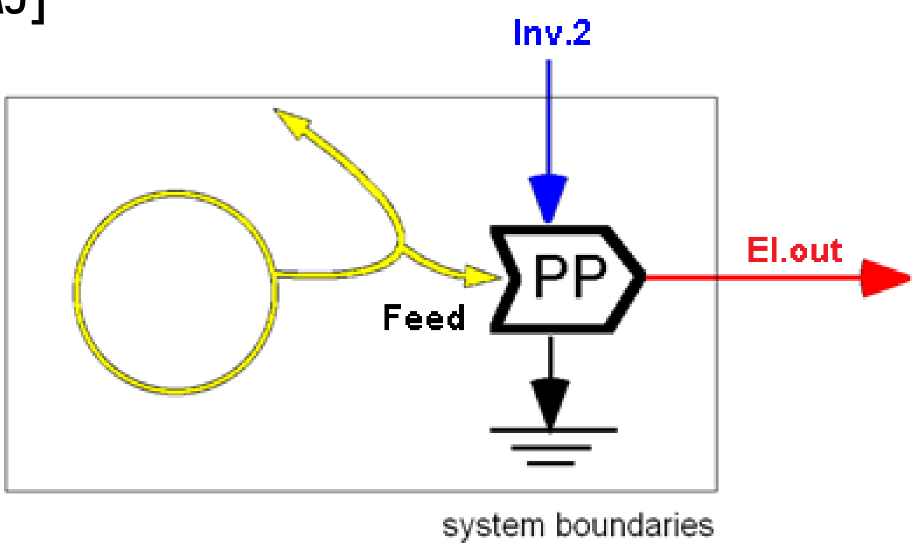
Inv.1 = Energy invested to extract and deliver the 'feedstock' energy consumed over the lifetime of the power system (**= 0 for PV systems**) [MJ]



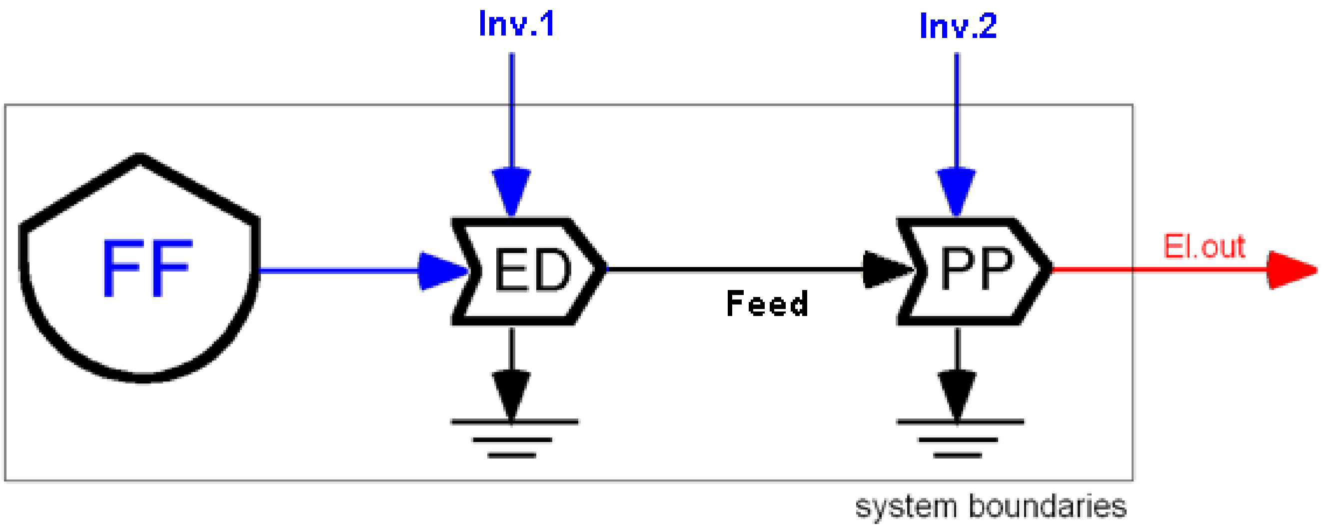
Thermal *vs*. PV electricity generation



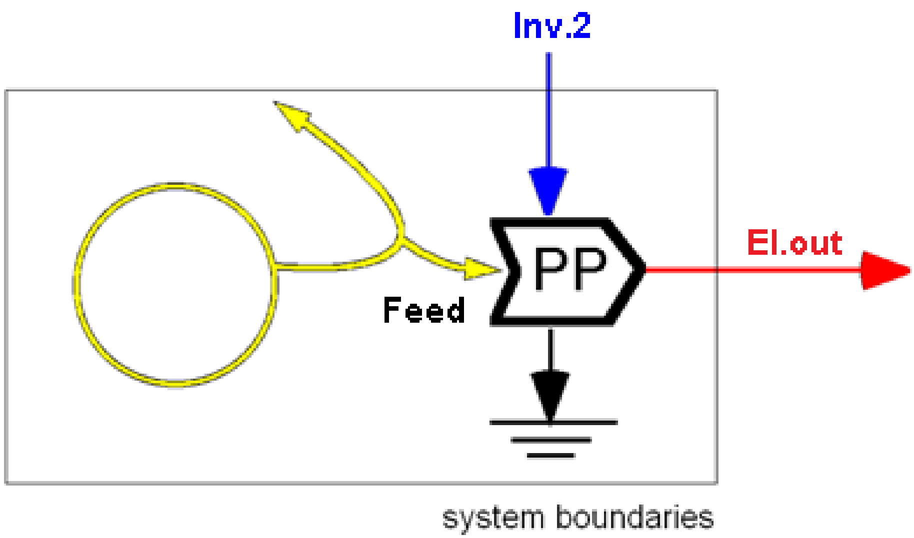
Inv.2 = Energy invested to build, operate and dismantle the power system (at EoL) [MJ]



Thermal *vs*. PV electricity generation



El.out = Electricity produced over the lifetime of the power system [MJ]



INDICATORS (1)

- **Cumulative Energy Demand (CED)** =

  = (**Inv.1** + **Inv.2** + **Feed**) / **El.out**

- **Life-cycle energy efficiency (η_{LC})** (*) = **1 / CED**

(*) For an electric grid composed of N different power systems, the grid efficiency on the life cycle scale (η_G) is calculated as the weighted sum of the η_{LC} of each individual power system.

- **Non-Renewable Cumulative Energy Demand (NRCED)** =

  = (**Inv.1$_{NR}$** + **Inv.2$_{NR}$** + **Feed$_{NR}$**) / **El.out**

Interpretation(1)

CED and **NRCED** are arguably the most commonly employed energy performance indicators in the LCA literature of energy systems.

⇒ They provide an indication of the relative *sustainability* of alternative (and often competing) energy systems,

where *sustainability* is intended as the ability to *sustain* their operation in the long term, given the notion of ultimately finite resource stocks.

INDICATORS (2)

- **Energy Return On Investment (EROI)** =

  = El.out / (Inv.1 + Inv.2)

- **Energy Return On Investment ($EROI_{PE\text{-}eq}$)** =

  = (El.out / η_G) / (Inv.1 + Inv.2)

And, in the specific case of PV:

- **Energy Pay-Back Time (EPBT)** [yrs] =

  = Inv.2 / [El.out / (T*η_G)] = **T / $EROI_{PE\text{-}eq}$**

T = Lifetime of the power system [yrs]

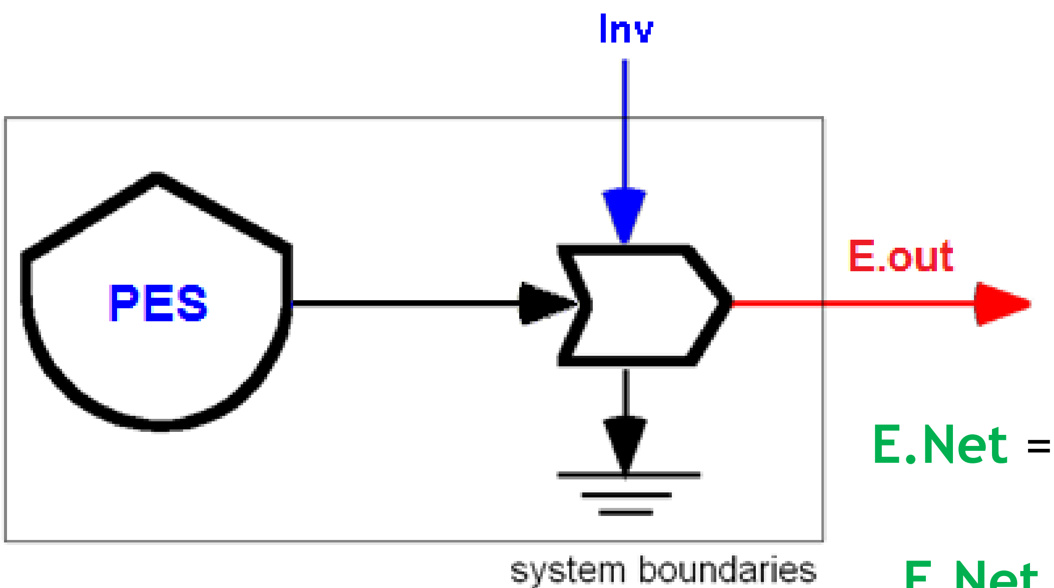
Interpretation(2)

EROI only provides an indication of the net energy output per unit of energy *invested* in exploiting a given energy source (**Inv.1** + **Inv.2**), *irrespective* of how much energy is directly required to flow through the system in absolute terms (**Feed**) in order to *sustain* its operation.

$\Rightarrow$ It *is not*, and should never be interpreted as, an indicator of a system's *sustainability.*

Interpretation(2)

What **EROI** *does* provide is a valuable indication of the capability of an energy system to effectively *exploit* the available energy resources (be they renewable or non-renewable) so as to provide the end user with a *net* output of usable energy.



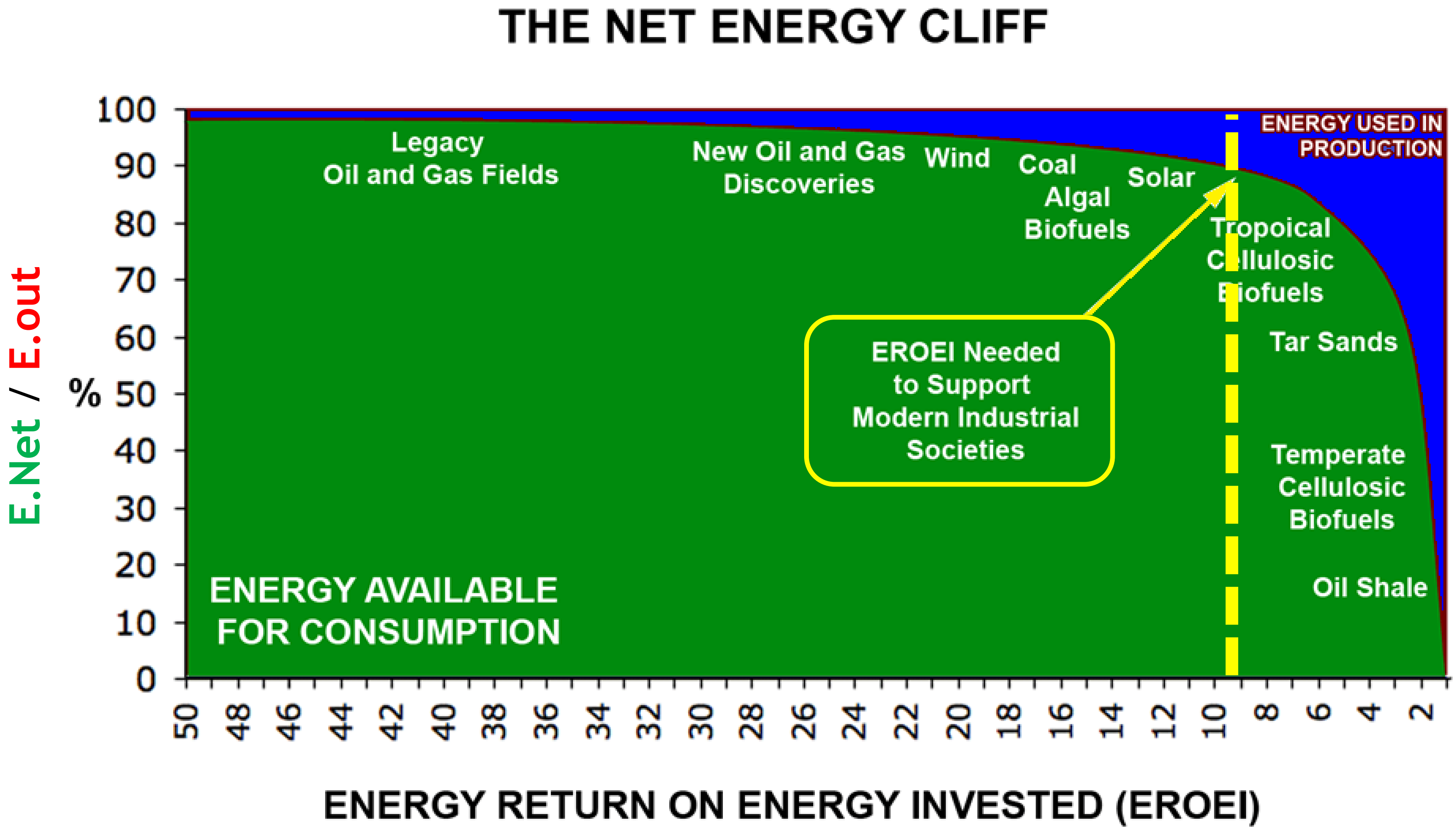
EROI = **E.out** / **Inv**

E.Net = (**E.out** – **Inv**)

E.Net = **E.out** * [(**EROI**-1) / **EROI**]

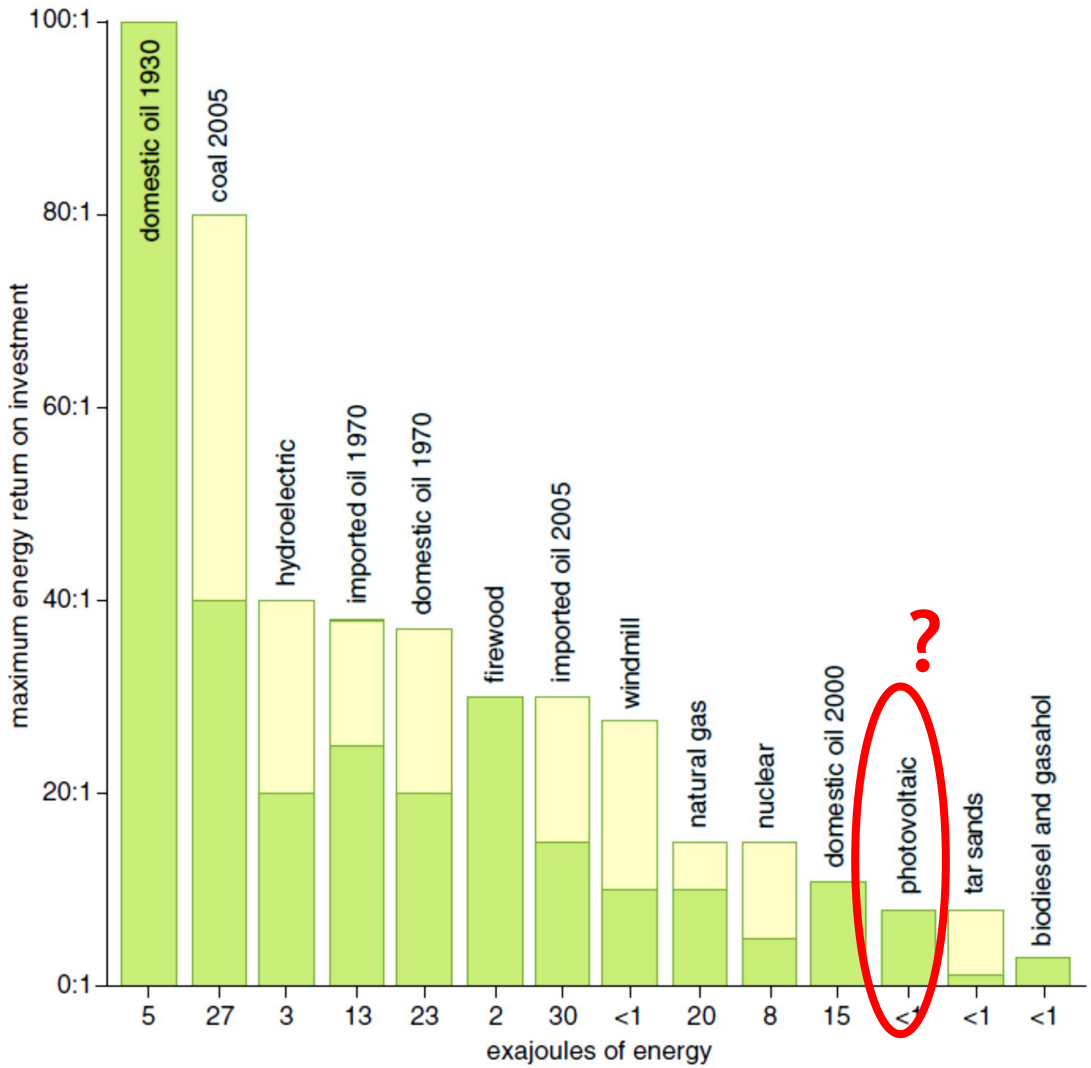
E.Net / **E.out** = (**EROI**-1) / **EROI**

Interpretation(2)



Source: Murphy D., Hall, C.A.S., 2010. Year in review—EROI or energy return on (energy) invested. Ann. N.Y. Acad. Sci. 1185:102-118

The **EROI** of PV



Source: Hall, C.A.S., Day, J.W., 2009. Revisiting the limits to growth after peak oil. American Scientist 97, 230-237.

EROI of PV *vs.* conventional electricity

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The energy return on energy investment (EROI) of photovoltaics: Methodology and comparisons with fossil fuel life cycles

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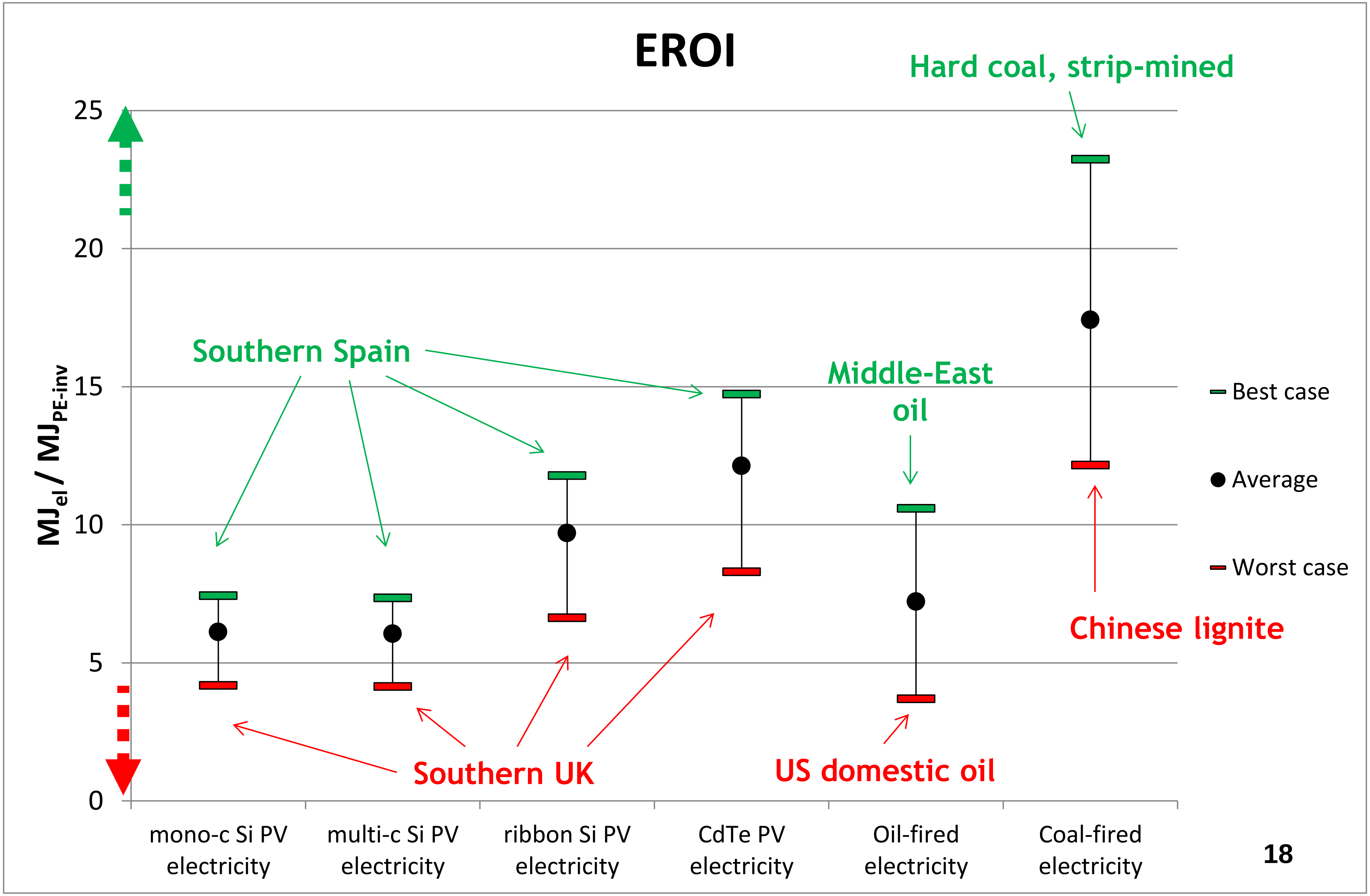
A B S T R A C T

A high energy return on energy investment (EROI) of an energy production process is crucial to its long-term viability. The EROI of conventional thermal electricity from fossil fuels has been viewed as being much higher than those of renewable energy life-cycles, and specifically of photovoltaics (PVs). We show that this is largely a misconception fostered by the use of outdated data and, often, a lack of consistency among calculation methods. We hereby present a thorough review of the methodology, discuss methodological variations and present updated EROI values for a range of modern PV systems, in comparison to conventional fossil-fuel based electricity life-cycles.

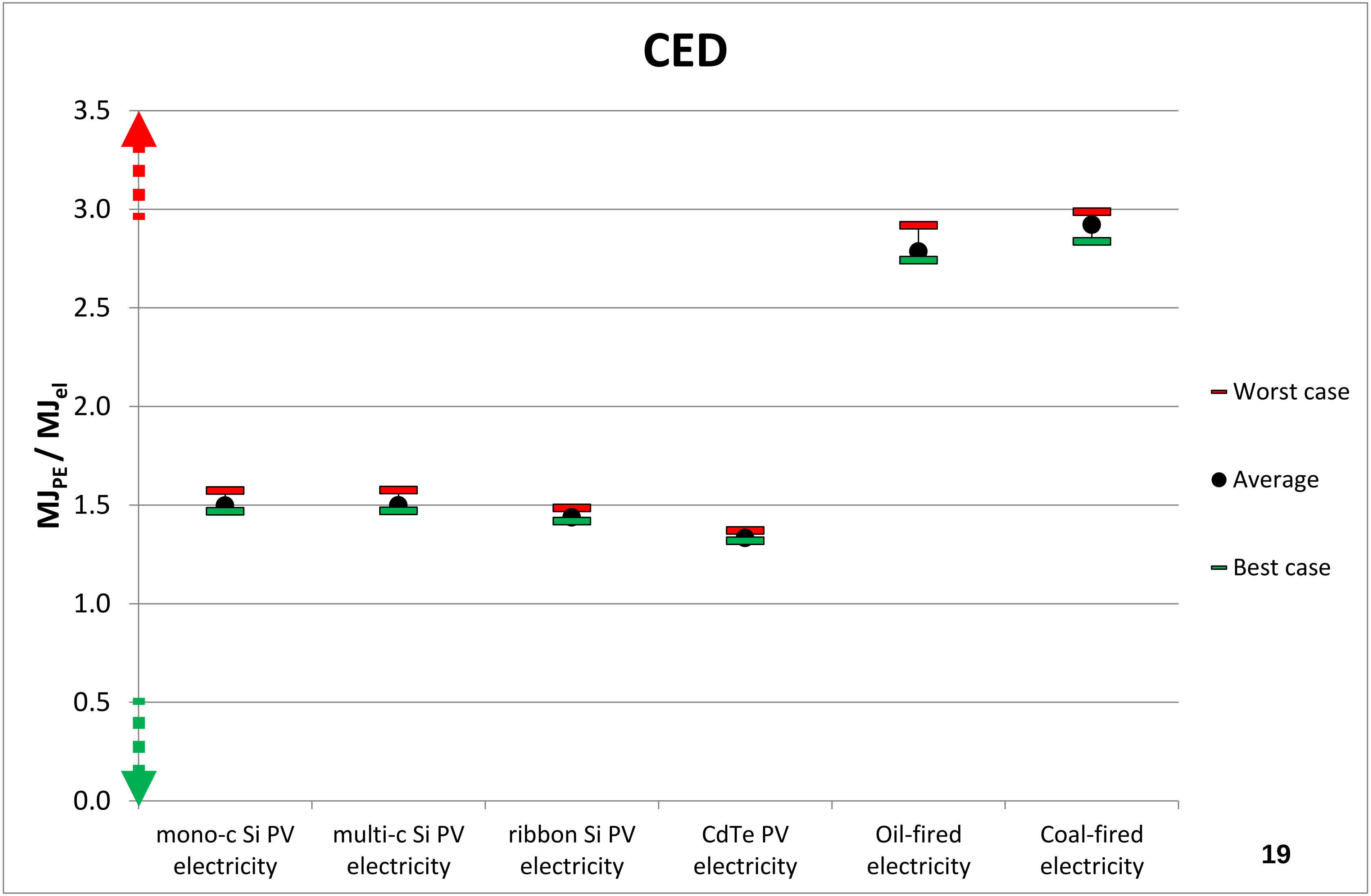
EROI of PV *vs.* conventional electricity

	mono-c Si PV (rooftop)			multi-c Si PV (rooftop)			ribbon Si PV (rooftop)			CdTe PV (ground)		
	S-UK	**World Avg.**	**S-Spain**	**S-UK**	**World Avg.**	**S-Spain**	**S-UK**	**World Avg.**	**S-Spain**	**S-UK**	**World Avg.**	**S-Spain**
Irradiation [kWh/(m2*yr)]	1200	1700	2000	1200	1700	2000	1200	1700	2000	1200	1700	2000
Performance Ratio	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.8	0.8	0.8
Module efficiency	14%	14%	14%	13%	13%	13%	13%	13%	13%	11%	11%	11%
El.out,yr [kWhel/(m2*yr)]	126	179	210	117	166	195	117	166	195	106	150	176
T [yr]	30	30	30	30	30	30	30	30	30	30	30	30
El.out [kWhel/(m2)]	**3780**	**5355**	**6300**	**3510**	**4973**	**5850**	**3510**	**4973**	**5850**	**3168**	**4488**	**5280**
Inv.2 [MJp/m2]	**3257**	**3257**	**3257**	**3057**	**3057**	**3057**	**1907**	**1907**	**1907**	**1375**	**1376**	**1377**

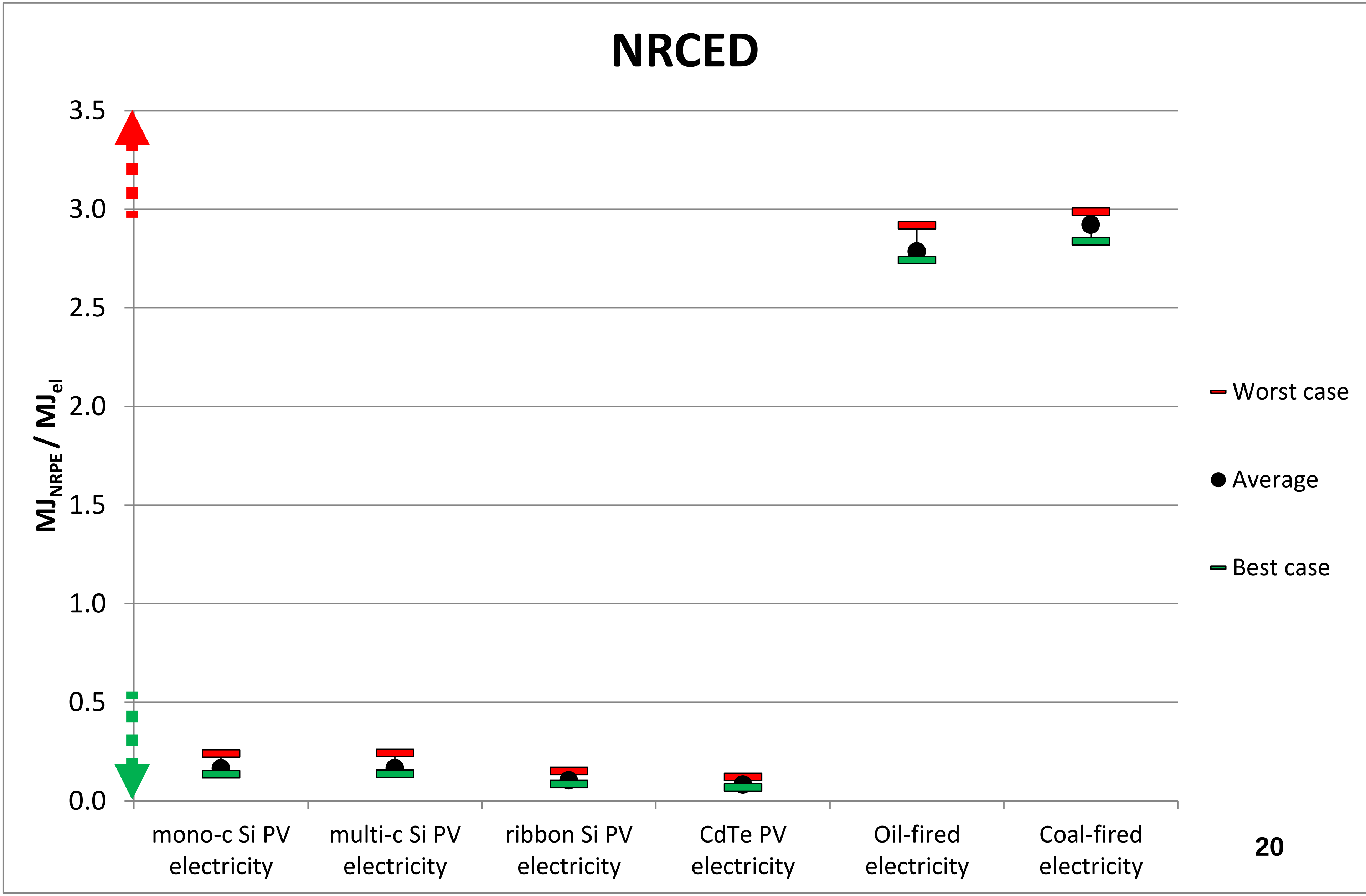
EROI of PV *vs.* conventional electricity



CED of PV *vs*. conventional electricity



NRCED of PV *vs*. conventional electricity



Discussion of results: the present

- **EROI** of PV *electricity* ≈ **4 ÷ 15** ⇒ comparable to **EROI** of conventional thermal *electricity* without CCS (≈ **4 ÷ 23**)

Similar ability to provide *net output* in terms of electricity

- **CED** ⇒ Factor of 2 in favour of PV
- **NRCED** ⇒ Order of magnitude in favour of PV

Much better long-term *sustainability*

Future outlook (PV electricity)

- Large **up-front investment** (mostly fossil energy), while 'return' is spread over ~ 30 years
- **Intermittent** and **non-despatchable** source
  $\Rightarrow$ its large-scale deployment will require some (fossil) back-up & potentially *massive* energy storage
  - Pumped hydro
  - AA-CAES
  - New battery concepts

Future outlook (FF electricity)

- **Global Warming**

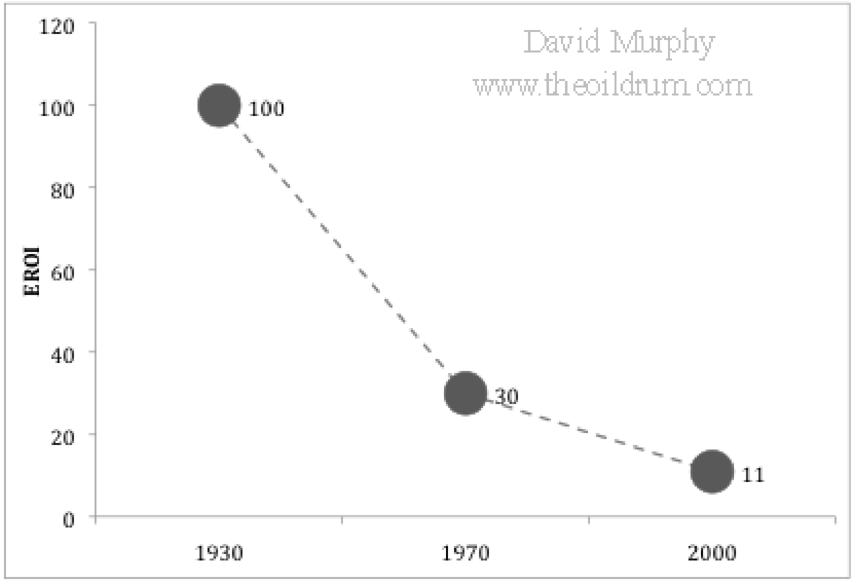
  ⇒ CCS will require larger **Inv.2** and thus increase **CED** and reduce **EROI**

- **Peak oil**

  ⇒ dwindling reserves lead to lower **EROI**

- **Non-conventional FFs**

  ⇒ already lower **EROI**



CONCLUSIONS

- PVs are already a viable and more sustainable alternative to generate electricity
- Growing constraints in terms of Global Warming and dwindling FF reserves will make conventional electricity less viable in the future (higher CED and lower EROI)
- The transition to a grid largely based on renewable energy and PV will inevitably be slow and require long-term commitment and sustained investment (slow returns, need for storage, grid restructuring, …)
- *If we are to make it, we had better start while we can still afford it*

Work in progress

- **UK EPSRC Project 'WISE-PV':**
  - Jones C.W., Gilbert P.J., Mander S., *Raugei M.*, 2014.
    UK Solar PV Scenarios – Dealing with Geographic Sensitivities and Distributed Power Generation.
    Energy Systems Conference, London (UK), 24-25 June 2014
  - Jones C.W., Gilbert P.J., Mander S., *Raugei M.*, 2014.
    Analysing stakeholder-informed scenarios of high PV deployment for a low-carbon electricity grid in the UK: a consequential LCA approach.
    29th European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam (NL), 22-26 September 2014
- **IEA PhotoVoltaic Power Systems (PVPS) Programme, Task 12:**
  - Olson C., *Raugei M.*, Wade A., Heath G., Schidler S., Fang L., Jia Z., Blanc I., Hino M., Yamamoto A., Glöckner R., de Wild-Scholten M., Frischknecht R., Sinha P.
    Towards a robust and integrated framework for evaluating the sustainability of PV electricity.
    29th European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam (NL), 22-26 September 2014

Thank you

Questions?

Comments?

Concerns?

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