Differences in CO_2 emissions of solar PV production among technologies and regions: Application to China, EU and USA

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Abstract: A widespread implicit assumption is that renewable energy options are approximately low-carbon. However, production and life cycles of such technologies tend to produce CO_2 emissions. To minimize life-cycle emissions, one should account for such emissions and implement adequate policies to encourage innovation and adoption of well-performing technologies in this respect. We develop a framework to analyse this issue, grounded in the concepts of 'energy return on energy invested' (EROI) and 'net energy return on carbon invested' (EROC). Applying these to the main PV technologies and production regions – namely China, EU and USA – displays considerable discrepancies. We conditionally predict the development of average EROI and EROC over time under business-as-usual and low-carbon electricity generation scenarios. A main policy lesson is that without a systemic policy instrument, such as carbon pricing, incentives for low-carbon production of renewable energy options are too weak, which likely will delays a complete transition to a low-carbon economy.

Keywords: PV technologies; Life-cycle assessment; EROI; EROC; Climate policy

Highlights:

- Framework developed around EROI and EROC to study lifecycle performance of solar PV.
- CdTe turns out to have the highest and mono-Si the lowest EROI and EROC values.
- The EU shows a better performance on EROI and EROC than China and USA.
- We predict average EROI and EROC under BAU and low-carbon electricity scenarios.
- Results show need for systemic policy instruments to stimulate transition to low-carbon economy.

1. Introduction

To limit climate change to 2°C warming, a transition of energy systems to low-carbon alternatives is needed. Much is expected from renewable electricity as it produces few emissions during electricity generation. Among renewable sources, hydropower is limited by natural conditions and also controversial because of detrimental ecological and social consequences (Gernaat et al., 2017; Liu et al., 2015), while biomass generation is hampered by maintenance of raw material supply chains (Sanchez et al., 2015). In view of this, solar and wind power, possibly in combination with energy storage, are widely regarded as the most promising renewable options permitting a low-carbon transition of the electricity system (Chu and Majumdar, 2012; Millstein et al., 2017).

A great amount of capital and human resources have been invested in these two alternatives already. As a result, the global installation capacities of solar and wind power have sharply increased, from 5.8 GW and 74 GW in 2006 to 301.5 GW and 469 GW in 2016, respectively (BP, 2017). Faced with their rapid expansion momentum, it is worthwhile to ask the question which specific technologies within each domain deserve more support in view of total carbon dioxide emissions over their life cycles. This is motivated by the concern that some renewable energy sub-technologies are produced in a much more carbon-intensive manner than others. Differences in the carbon intensity of production of renewable energy technologies can be due to the nature of the production process, being more or less energy-efficient, or to the sources of electricity used by the production process, being more or less carbon-intense – depending on whether electricity is generated using coal, gas or renewables.

Here, we offer an analysis of net energy and net energy per unit of carbon (dioxide) emitted by distinct solar photovoltaic (PV) technologies. To this end, we make use of two indicators: energy return on energy invested (EROI) and net energy return on carbon invested (EROC). EROI is a well-known indicator that measures the quality of energy options by calculating the ratio between the energy gained from the production process and the energy invested in the life cycle (Murphy and Hall, 2010; Hall et al., 2014; Raugei et al., 2012), inspired by the traditional economic notion of 'return on investment' (ROI). EROI is widely adopted to comparative evaluation of energy projects, technologies and sources (Bhandari et al., 2015; Fabre, 2019; Kittner et al., 2016). The new indicator EROC was recently proposed to compare alternative energy options in terms of carbon intensity, thus supporting effective energy choices under the constraint of climate change and an associated limited carbon budget (King and van den Bergh, 2018). Recently, the utilization of this indicator was extended to deal with renewable power (Huang et al., 2019; Walmsley et al., 2017). Other indicators to assess the lifespan performance of PV systems include energy payback time and carbon footprint. Due to EROI and EROC sharing the same ROI root, they have the advantage of providing a consistent set of indicators for comparative analysis of energy options with a focus on energy efficiency and minimum carbon emissions.

In terms of empirical strategy, we have identified mono-Si, multi-Si, a-Si, CdTe and CIS as the most relevant PV technologies, and China, the EU and the USA as the main regions of production. We evaluate the performance of technologies and regions in terms of energy use and carbon dioxide emissions in each stage of the PV life cycle. Our aim is not to argue against solar power in a future, low-carbon electricity system, but to draw attention to effective regulatory policies being needed to assure that good technological choices are being made at the level of production stages and (components of) PV technologies, as well as in associated innovation. This will contribute positively to the speed and direction of a transition to a low-carbon electricity system. The relevance of this issue extends to other energy technologies.

2. Analytical approach

Our analysis framework involves four steps: (i) defining the life cycle of PV generation; (ii) comparing EROIs and EROCs for five mentioned PV technologies; (iii) comparing emissions associated with per unit PV production in China, EU and USA; and (iv) conducting a scenario analysis to estimate associated time patterns in the future. Assessing the EROI is relevant as it reflects the effectiveness of using energy carriers to harvest solar irradiation from nature and convert it into electricity (Hall et al., 2014; Murphy and Hall, 2010). EROC serves the purpose of examining the strategy to maximize the net energy obtained from renewable power under a carbon budget constraint (King and van den Bergh, 2018).

The life cycle of photovoltaic generation consists of five stages, namely producing materials comprising PV system, manufacturing PV modules and the balance of system (BOS) (de Wild-Scholten and Alsema, 2005; Vellini et al., 2017), construction and installation (Beylot et al., 2014; Ito et al., 2008), operation and maintenance (O&M) (Perpiñan et al., 2009), and end-of-life management (Corcelli et al., 2017; Held, 2009; Müller et al., 2005). The life cycle defined in our study contains all these stages while it includes recycling, also as there is a large demand and market potential for secondary materials deriving from decommissioning PV modules. The PV life cycle stages are connected through transportation of production materials and products, which is also accounted for. Related life-cycle data of crystalline silicon and thin film PV generation are extracted from IEA (Frischknecht et al., 2015) and ESU (Jungbluth et al, 2012), respectively.

Solar power has a high proportion of non-energy resource consumption over its life cycle (Zhang et al., 2012), especially in terms of labour input. Moreover, the production of solar power is more labour-intensive than that of other electricity sources (Ferroni and Hopkirk, 2016; IRENA, 2017a). Therefore, indirect energy consumption, i.e. energy embodied in material and labour inputs during the lifetime of solar PV generation, is also accounted for. Despite the difficulty to calculate energy consumption and associated carbon dioxide emissions embodied in the use of labour (Ayres, 2004; Szargut et al., 2002), many efforts have been undertaken to include these in the analysis of environmental impacts of goods and services (Costanza, 1980; Kamp et al., 2016; Rugani et al., 2012). The indirect energy use by labour input is included in this study using a straightforward method based on national statistics including population and total and industrial primary energy supply (Zhang and Dornfeld, 2007). As a result, the extended boundary of the life-cycle energy investment can lead to slight differences with the results from studies. To capture the variation in applications, two common types of PV installation – ground-mounted and roof-integrated approaches – are considered. Hence, we achieve a complete assessment of the carbon intensity of solar PV production and ultimately generation. Figure 1 provides a graphical illustration of the direct and indirect energy inputs of the PV technology life cycle (for technology *i* in region *j*) as well as of associated net energy output and greenhouse gas emissions. This allows the calculation and comparison of EROCs among PV technologies and regions.

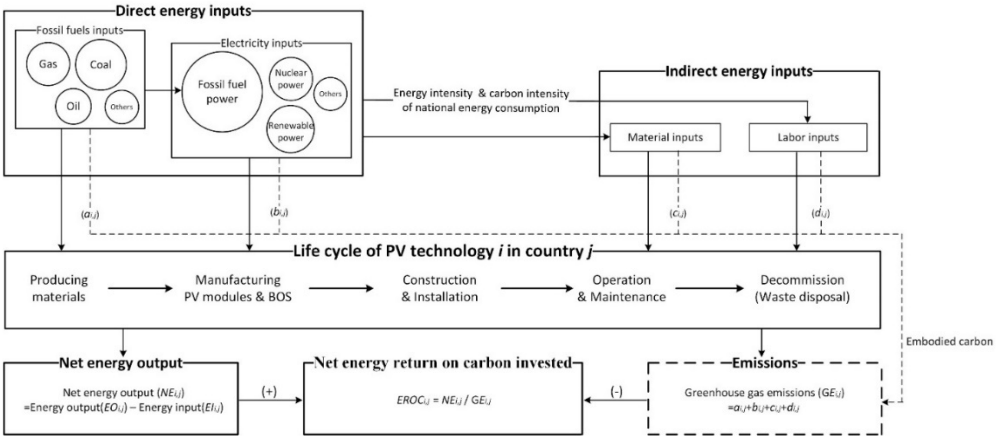

Figure 1. Overview of the life cycle of PV technologies

3. Establishing a relationship between EROI and EROC

Equation 1 provides a formal expression of EROI. Here, EO in the numerator denotes the overall energy output, while *EI* in the denominator represents the commercial energy investment in the life cycle of a solar PV technology. *EROI* as the ratio of *EO* to *EI* delivers a dimensionless number with a feasible range of values greater than 0. When *EO* equals *EI*, *EROI* reaches a critical value of 1 above which a technology delivers net energy and below which it consumes net energy. The indicator *EO* is calculated in equation 2 as the product of solar irradiation (*SI*) and related technical indicators of PV modules, namely conversion efficiency (*CE*), lifetime (*LT*) and performance ratio[1] (*PR*); and *EI* is the sum of direct and indirect energy investments as formalized in equation 3. Here, *s* represents the life-cycle stages of solar PV generation; *N* is the number of stages of the life cycle (as mentioned in Section 2); and *M* and *L* denote the numbers of direct energy and non-energy resources inputs; $D_{i,s}$ is the direct energy input in each stage; $\alpha_i * R_{j,s}$ is the indirect energy consumption due to embodied energy in production factors, with $R_{j,s}$ standing for the quantity of non-energy resource inputs (materials and labour), and the conversion factor α_i representing the energy intensity of factor $R_{i,s}$, i.e. energy embodied per unit of non-energy resources used.

$$EROI = \frac{EO}{EI} \tag{1}$$

$$EO = SI * CE * LT * PR \tag{2}$$

$$EI = \sum_{s=1}^{N} \left[\sum\nolimits_{i=1}^{M} D_{i,s} + \sum\nolimits_{j=1}^{L} (\alpha_j * R_{j,s}) \right] \tag{3}$$

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[1] PR denotes the ratio of actual energy output over theoretical energy output of a PV system which includes all energy losses generated in the production phase.

The concept of EROC was recently proposed to measure the performance of fossil fuels in term of net energy output per carbon dioxide emission under the constraint of climate change targets. A formal representation of it is given in equation 4. The numerator and denominator represent the net energy output and amount of carbon dioxide or greenhouse gas emissions (*GE*) during the life cycle, respectively. The unit of *EROC* is megajoule per kilogram of carbon dioxide (equivalent) emissions. The critical value of *EROC* is 0 and it is reached when *EO* equals *EI*, which is equivalent to the associated value of *EROI* being equal to 1. Unlike *EROI*, *EROC* can take negative values, associated with net energy loss. *GE* is calculated as equation 5. Here, β_i and β_j are coefficients capturing emissions associated with direct energy and non-energy inputs, respectively.

$$EROC = \frac{EO - EI}{GE} \tag{4}$$

$$GE = \sum_{s=1}^{N} \left[\sum\nolimits_{i=1}^{M} (\beta_i * D_{i,s}) + \sum\nolimits_{j=1}^{L} (\beta_j * R_{j,s}) \right] \tag{5}$$

Next, we can derive a relationship between *EROI* and *EROC*, as shown in equation 6. Here, CI represents carbon intensity of the life cycle, which is the ratio of GE to *EI*.

$$EROC = \frac{EO - EI}{GE} = \frac{EI * (EROI - 1)}{GE} = \frac{EROI - 1}{CI} \tag{6}$$

According to this equation, *EROC* is proportionally increasing in *EROI* and proportionally decreasing in *CI*. This means that if innovation or policy improves *EROI* while not altering CI, it will simultaneously improve EROC. On the other hand, if also

CI increases, $EROC$ will increase less than proportionally or even fall. Using the equation, we can derive that if initially we have $EROI'$ and CI', and there is a proportional increase in $EROI'$ by γ and of CI' by δ, then $EROC$ will increase if $\delta < \frac{\gamma * EROI'}{EROI'-1}$ while it will decrease if $\delta > \frac{\gamma * EROI'}{EROI'-1}$ and remain constant if $\delta = \frac{\gamma * EROI'}{EROI'-1}$. This explains why a certain technology or region can at the same time have a higher $EROI$ and lower $EROC$ than other technologies or regions.

4. Comparing EROI and EROC between PV technologies and regions

4.1 Values of relevant parameters

In this section, we conduct comparisons of distinct PV technologies in China, EU and USA in terms of EROI and EROC values as defined in equations 1 and 4. To elaborate how the life cycle of solar power is influenced we estimate for each case overall energy output, commercial energy investment, and carbon dioxide emission – using equations 2, 3 and 5. The values of parameters to calculate the life-cycle energy output of PV technologies and the corresponding results are shown in Table 1. The conversion factor of crystalline silicon and thin film modules are adopted from IEA (Frankl et al., 2010), while the performance ratio of two installation types and the lifetime of PV modules are taken from previous review studies (Bhandari et al., 2015; Koppelaar, 2017; Peng et al., 2013; Sherwani and Usmani, 2010).

Given that the value ranges of solar irradiation in areas where the PV panels are mostly installed are similar (Alsema and de Wild-Scholten, 2007; Espinosa et al., 2011; Fthenakis et al., 2012, 2009; Hou et al., 2016; Ito et al., 2010), and in view of previous studies, we adopt a central value of solar irradiation of 1700 kWh/m^2/year and an interval of 1200-2200 kWh/m^2/year (SOLARGIS, 2018; WEC, 2016). We apply the same irradiation values to all PV panels, irrespective of where they are produced, as we are interested in assessing the impact of differences in production, not in application or instalment.

Table 1. Parameters to calculate life-cycle energy output of PV technologies

	Conversion factor	Performance ratio		Lifetime	Solar irradiation	Energy output (MJ)	
		Roof	Ground	(year)	(kWh/m^2/year)	Roof	Ground
Mono-Si	0.17	0.75	0.80	30	1700	23409	24970
Multi-Si	0.14	0.75	0.80	30	1700	19278	20563
CdTe	0.10	0.75	0.80	30	1700	13770	14688
CIS	0.11	0.75	0.80	30	1700	15147	16157
a-Si	0.075	0.75	0.80	30	1700	10328	11016

4.2 Energy investment and carbon dioxide emissions for PV technologies in the studied regions

The results for energy investments, serving as an input to calculate EROIs and EROCs in Section 4.3, are presented in Figure 2. In this figure, electricity and fossil fuels represent the direct energy input in the life cycle, excluding energy used in the transportation process as this is separately shown. Labour and material represent indirect energy inputs. Differences in energy consumption among PV technologies mainly relate to the stage of manufacturing PV modules. Mono-Si consumes more energy than multi-Si due to encompassing the Czochralski process to extract growing crystals from the melting pot (de Wild-Scholten and Alsema, 2005). Due to a simpler manufacturing technique, less energy is needed to produce thin film PV modules (CdTe, CIS and a-Si) than crystalline silicon PV modules (Ito et al., 2008; Laleman et al., 2011).

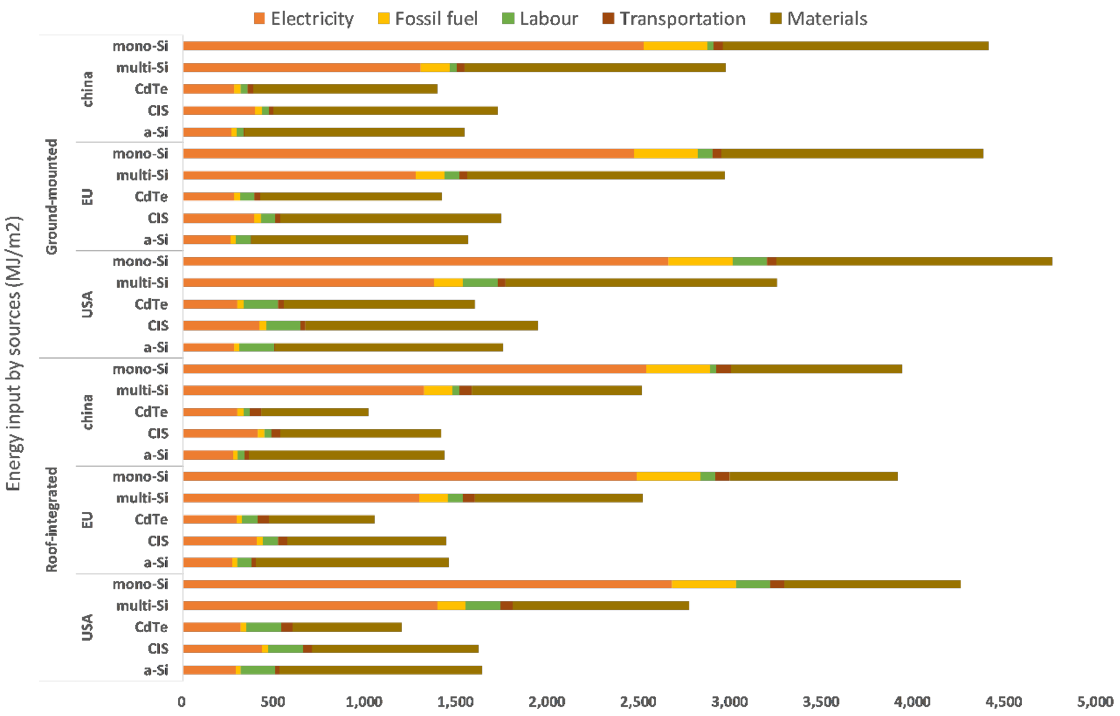

Figure 2. Direct and indirect energy investment of PV technologies in China, EU and US

Differences between regions are small with respect to direct consumption of fossil fuels. Given that the EU has higher share of renewable power, as well as advanced generation technologies, less primary energy is embodied in electricity used during the production cycle of solar power than in China and USA. As shown in Figure 2, due to the additional demand for structure and foundations, more energy is consumed (per square meter) in producing the construction and supporting materials (Rahman et al., 2017) for a ground-mounted installation than for a building-integrated one. Labour is an additional source of indirect energy investment integrated into the life-cycle assessment of solar power. The energy embodied in labour input is calculated based on the sum of worker-hour required for the life cycle of solar power (IRENA, 2017b) and the energy use per worker-hour in the studied regions (IEA, 2018; Zhang and Dornfeld, 2007).

On this basis, we derive Table 2. It reports the energy use per unit of labour input in China, EU and USA. It also mentions carbon intensity of regional energy consumption and of power generation, allowing for estimation of the carbon dioxide emissions. China has the least energy use per worker-hour, followed by the EU and then the USA. The regional difference in indirect energy use by labour reflects mainly differences in energy use by commuting options: in the EU and USA car ownership and average driving distances are higher than in China (Sieminski, 2014). This contributes to more energy being indirectly consumed in the life cycle of PV technologies in the USA, followed by the EU, as shown in Figure 2.

Table 2. Units and values of parameters for comparative analysis of regions (2016)

	Carbon intensity		Energy use by labour (MJ/worker-hour)
	Energy consumption ($kg\ CO_2/MJ$)	Electricity ($kg\ CO_2/kWh$)	
China	0.073	0.673	5.1
EU	0.047	0.354	11.6
USA	0.053	0.478	26.5

Data sources: IEA (2018) and IRENA (2017b).

Next, we compare carbon dioxide emissions over the life cycle of solar power, the results of which are shown in Figure 3. The differences of carbon dioxide emissions among PV technologies are mostly due to the use of electricity (Fthenakis et al., 2009). As a result, more carbon dioxide emissions are embodied in mono-Si than multi-Si. In terms of thin film PV modules, CIS emits more carbon dioxide over its lifetime, followed by a-Si, while CdTe has the lowest emissions.

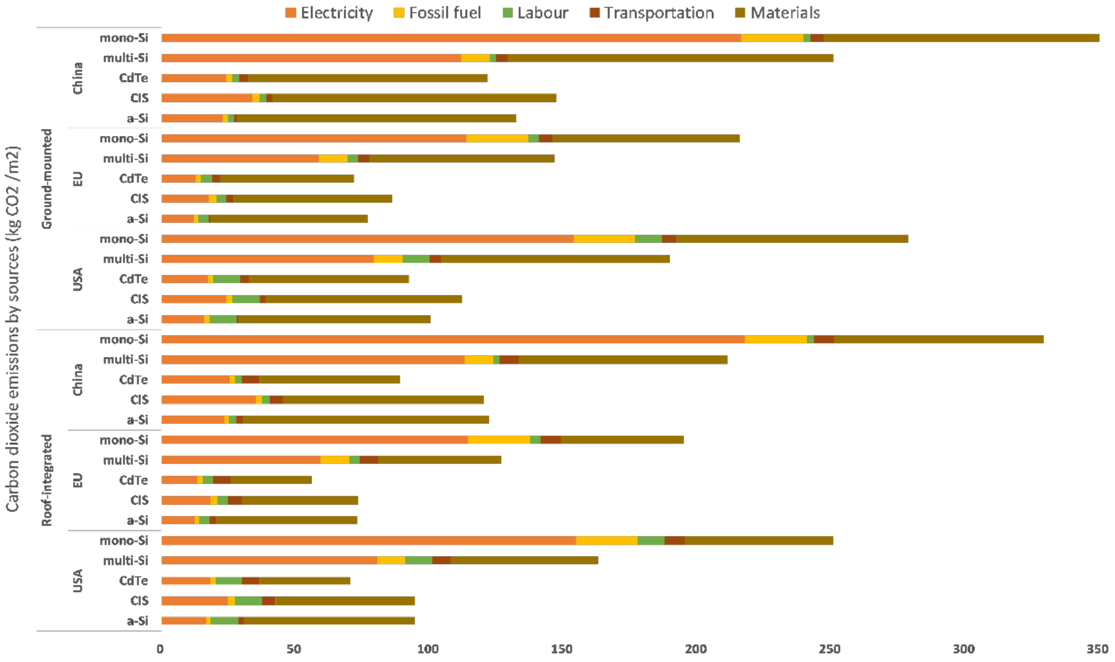

Figure 3. Direct and indirect carbon dioxide emissions for PV technologies in China, EU and USA

Carbon dioxide emissions embodied in solar power are determined by the carbon intensity of energy and non-energy inputs to the life cycle. Table 2 also reports the carbon intensity of power generation in the three regions, showing that the EU has a lower value than other two regions. In line with this, less carbon dioxide is embodied in the electricity used over the life cycle of PV technologies in the EU, followed by the USA. By 2016, over 50% of electricity supply in the EU was renewable and nuclear power (IEA, 2017a.), which contributed to lowest carbon intensity of electricity. Limited by the national resource endowment, the share of coal power in China's electricity system has been over 50% since 1949, which is the main reason for a higher carbon intensity of electricity than the USA and EU. The USA has the lowest share of renewable power in national generation structure. However, 50% of its fossil power is generated by gas, which emits less carbon dioxide than coal. In addition, its nuclear power has a share of 20%, all together leading to a carbon intensity of electricity in between that of China and the EU. Differences in carbon intensity of regional energy consumption are another cause for divergences between regions in terms of energy consumption and carbon dioxide emissions, especially associated with indirect energy use by labour. The net effect of all these differences is that, as shown in Figure 3, more carbon dioxide is emitted in the life cycle of solar power in China, followed by the USA and then the EU.

4.3 EROIs and EROCs of PV technologies in China, EU and USA

To assess the effectiveness of PV technologies to harvest solar irradiation into electricity in China, EU and USA, we calculate their EROIs. Thanks to enduring subsidy policies and efficient and interconnected regional electricity grids, the EU has achieved the highest share (0.579) (Jungbluth et al, 2012) of building-integrated panels in domestic installed capacity of solar power among the three regions, followed by the USA (0.4) (EIA, 2018) and then China (0.17) (NEA, 2017). Here we provide the final results considering the ratio of two installation types in the studied regions. Figure 4 shows the range of EROIs for the interval of solar irradiation of 1200-2000 kWh/m^2/year and for the central value of 1700 kWh/m^2/year. In this figure, results for the studied regions are indicated by different colours, while the grey parts of the bars represent the EROIs under the solar irradiation below 1200 kWh/m^2/year.

As shown in the figure, CdTe have a better performance on EROI than other technologies, followed by CIS. Mono-Si has the lowest EROIs due to requiring the largest amount of energy investment. In terms of comparisons among studied regions, more energy return is obtained for investment in any of the five PV technologies in the EU. An important reason is that the EU has high generation efficiency, causing less energy to be used by electricity than in China and USA during its life time. As a result, the EU has the highest EROIs for PV technologies among studied regions. Moreover, China has higher EROIs than the USA due to having lower indirect energy investment by labour.

A thermal conversion factor is often applied to assess the corresponding "primary energy equivalent" of renewable power (García-Valverde et al., 2009; Laleman et al., 2011) based on the assumption that renewable power displaces thermal generation. Since the conversion factor is creating transformation losses that do not really exist (IEA, 2017c.), excluding it may be argued to give more reliable results. But opinions on this differ (Alsema et al., 1998; IEA, 2017c; Raugei et al., 2007). As we calculate the energy output of PV technologies excluding this conversion factor, EROIs in this study are somewhat lower than previous studies (Bhandari et al., 2015; de Wild-Scholten, 2013).

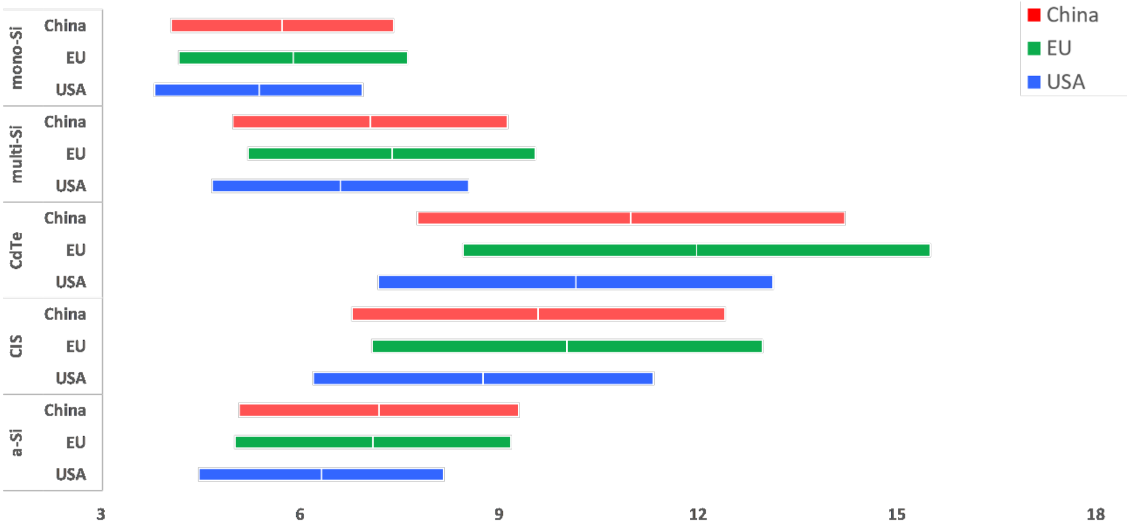

Figure 4. EROI value range for PV technologies in China, EU and USA (for 1200-2000 kWh/m2/year solar irradiation)

Next, we compare the different PV technologies and regions in terms of the indicator EROC. This can be seen as a test of carbon efficiency of net energy production, as shown in Figure 5. CdTe has the highest EROCs compared to other technologies, followed by CIS. The differences between multi-Si and a-Si are small. Due to having the largest amount of life-cycle carbon dioxide emissions (Figure 3), mono-Si has the lowest EROC among all PV technologies. In terms of comparisons among China, EU and USA, EROC values show more variation than EROI values. The generation structure of the EU, which mainly consists of renewable power and nuclear power, has resulted in the least carbon-intensive production cycle. Additionally, in line with equation 6, having the highest EROIs causes the EU to also have a higher EROC than the other two regions. The over-reliance on coal by China gives rise to the highest carbon intensity of domestic energy use and the lowest EROC among the studied regions. If we compare the EROCs between PV and fossil fuel technologies (King and van den Bergh, 2018), we find that all PV technologies in the EU as well as CdTe and CIS in China and USA are higher than those of fossil fuels power, while the rest are lower than gas power with CCS.

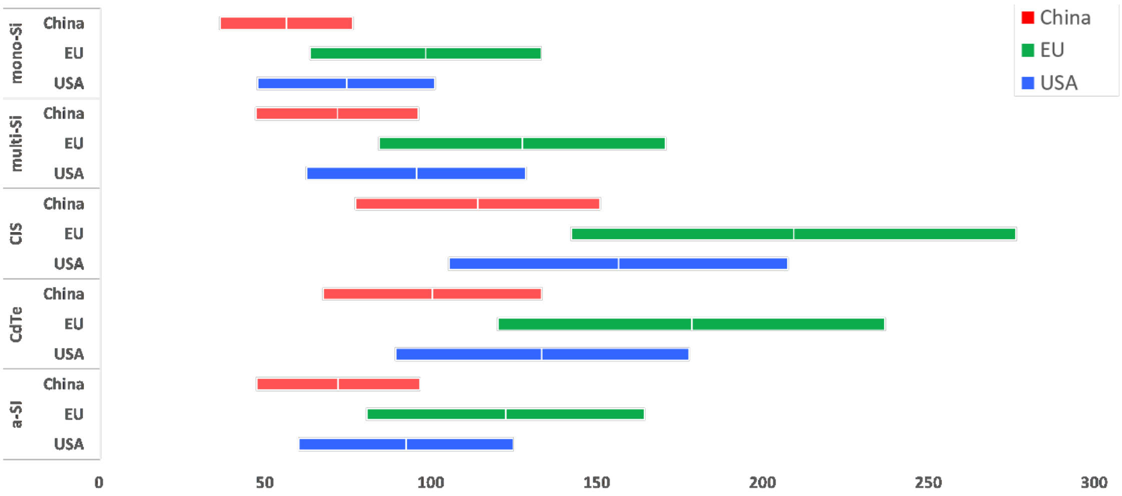

Figure 5. EROC value range for PV technologies in China, EU and USA (for 1200-2000 kWh/m2/year solar irradiation)

A large proportion of PV panels installed in the EU and USA are produced in China. We also consider the EROIs and EROCs of solar power under such circumstances. In this case, the values of energy investments and carbon dioxide emissions during manufacturing stage reflect China, data for the remaining stages reflect where the panels are installed. In addition, we account for emissions due to transregional transportation of PV panels.

4.4 Sensitivity analysis

We conduct a sensitivity analysis of EROIs and EROCs of PV technologies in China, EU and USA with respect to solar irradiation. This is motivated by the trend that further diffusion of solar power will mean PV panels are installed in areas with medium or even low solar irradiation. We consider a variation of solar irradiation from 1200 to 2200 (kWh/m^2/year) are shown in Figure 6. CdTe shows the most drastic change in both indicators over this range of solar irradiation, followed by CIS. Due to having the largest amount of life-cycle energy investment and carbon emissions, mono-Si has EROI and EROC values that are less sensitive to changes in solar irradiation than other technologies. In terms of studied regions, variances between China, EU and USA derive from differences in the regional parameters capturing life-cycle energy investment and carbon dioxide emissions. Due to having the highest generation efficiency and the lowest carbon intensity among the studied regions, the EU's solar power turns out to be more sensitive to changes in solar irradiation than those of China and USA. China has a higher rate of decrease in EROIs for low values of solar irradiation than the USA, while the USA is more sensitive than China in EROCs because of its low life-cycle carbon intensity.

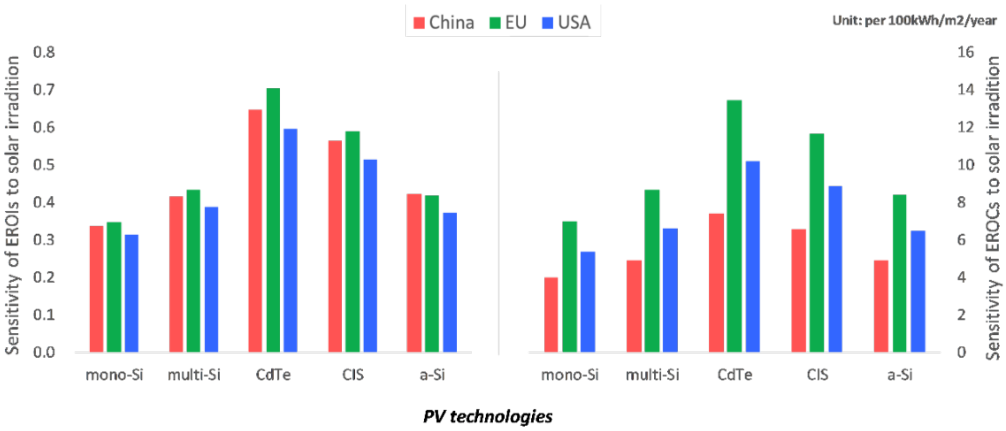

Figure 6. Sensitivity analysis of EROIs and EROCs to solar irradiation

The life time of PV modules was assumed to be 30 years in the comparative analysis. Admittedly, in some studies especially thin-film modules are reported to have a shorter lifetime (Kato et al., 2001; Raugei et al., 2007). We undertake sensitivity analysis of life time to clarify its influence on EROI and EROC. Figure 7 shows the impact of a variation of life time between 15 to 30 (years). In this figure, bars are divided into three parts by reflecting the effect of an additional 5 years lifespan, hence 15 years in total. The EROIs of CdTe and CIS in the studied regions remain higher than that of crystalline silicon modules as long as they have a life time of more than 20 years and 25 years, respectively. The values of EROC are more sensitive to life time than those of EROI. The EROCs of CdTe and CIS are gradually overtaken by those of multi-Si if their life time falls below 25 years.

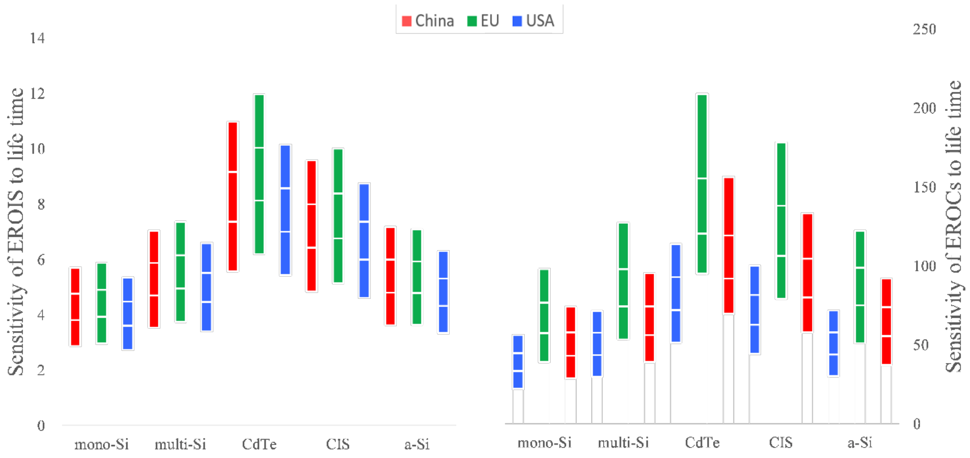

Figure 7. Sensitivity analysis of EROIs and EROCs to life time

Notes: Figure 7 shows the EROIs and EROCs with a variation of life time between 15 and 30 (years); bars are divided into three parts reflecting each additional 5 year lifespan.

5. Prospects for EROI and EROC of solar power

We are now interested in analysing the development of average EROI and EROC per region over time. This will allow us to assess any divergent or convergent patterns. To this end, we perform scenario analysis. This involves two scenarios, namely a business-as-usual (BAU) and a low-carbon electricity (LCE) scenario, both of which take IEA/IRENA scenarios as a reference (IEA, 2017b). Table 3 shows forecasts of core parameters for each region and scenario, based on multiple data sources (Frankl et al., 2010; IEA, 2017b).

Table 3. Parameter values for scenario analyses

1. Regional indicators								
	BAU				LCE			
	Regional generation efficiency	Energy use per worker-hour (MJ)	Emission rate		Regional generation efficiency	Energy use per worker-hour (MJ)	Emission rate	
			Power generation (kg CO2/kWh)	Overall energy consumption			Power generation	Overall energy consumption

					(kg CO2/MJ)			(kg CO2/kWh)	(kg CO2/MJ)
2020	China	0.42	6.13	0.07	0.66	0.43	5.80	0.06	0.62
	EU	0.43	11.14	0.05	0.31	0.43	10.71	0.04	0.27
	USA	0.44	26.38	0.05	0.42	0.45	24.87	0.05	0.36
2030	China	0.43	7.37	0.06	0.6	0.47	5.99	0.05	0.33
	EU	0.46	10.97	0.04	0.28	0.46	9.51	0.03	0.14
	USA	0.46	24.90	0.05	0.38	0.51	20.46	0.04	0.17
2040	China	0.44	8.28	0.06	0.56	0.49	6.17	0.03	0.08
	EU	0.48	10.89	0.04	0.24	0.48	8.64	0.02	0.06
	USA	0.48	24.02	0.05	0.34	0.51	17.81	0.02	0.05

2. Technological indicators

Conversion efficiency	mono-Si	multi-Si	CdTe	CIS	a-Si
2020	0.21	0.17	0.12	0.14	0.10
2030	0.23	0.19	0.14	0.15	0.12
2040	0.25	0.21	0.15	0.18	0.15

Sources: IEA (2017b) and Frankl et al. (2010).

By applying equations 1 and 4 and using parameter values as specified in the BAU and LCE scenarios (Table 3) we can derive patterns of EROI and EROC of solar power for the three regions. The results are shown in Figure 8. Given that the patterns are rather similar among the five PV technologies and two installation types, we only show results for multi-Si of roof-integrated installation.

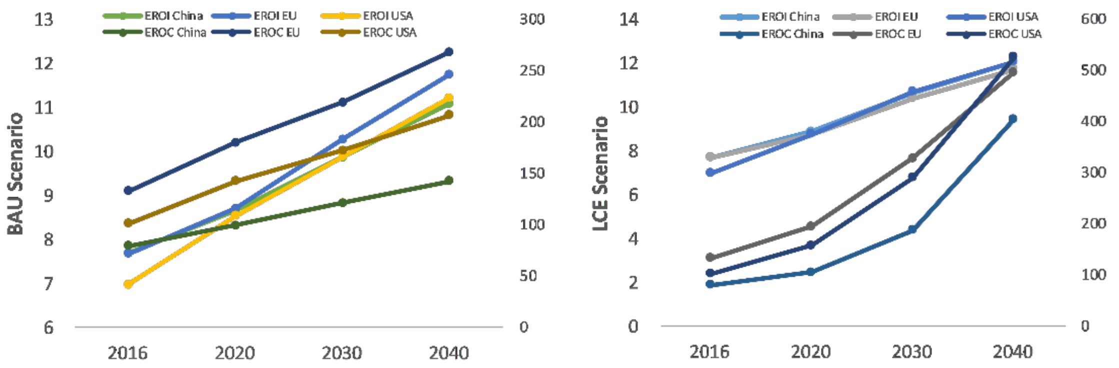

Figure 8. Patterns of EROI and EROC for roof-integrated multi-Si produced in China, EU and USA, under BAU (left) and LCE (right) scenarios

As shown in Figure 8, EROIs in the LCE scenario are higher than in the BAU, because of a higher generation efficiency as well as a lower energy intensity due to the low-carbon transition (Wang et al., 2017, 2014). Moreover, the high share of renewable power installed in the studied regions contributes to higher EROCs in the LCE scenario than that in the BAU scenario. In terms of the studied regions, the EROIs of China and USA will approach the EU in the BAU scenario and even surpass it in the LCE scenario. As shown in the right panel of Figure 8, the EROC of the USA will surpass the EU in 2040 in the LCE scenario. In other cases, the order of EROCs among the studied regions in both scenarios is consistent with the results for 2016.

Details of differences between regions over time are shown in Figure 9. The difference of EROIs between the studied regions are stable in both scenarios, which is caused by the similar extent of changes in related parameters, such as the regional generation efficiency and energy use per worker-hour. In terms of EROCs, the gaps among the studied regions are relatively consistent in the BAU within the considered time interval, while the LCE scenario shows more variation because of the huge changes in regional generation structure. With the substitution of coal power by renewable alternatives in the LCE scenario, China can acquire a significant decrease in its carbon intensity. As a result, the gap of EROCs between China and other two regions will get relatively narrower over time. By contrast, due to the EU having the leading position of using renewable power at present, future opportunities for carbon reduction are smaller than in the other two regions under the LCE scenario. Consequently, the gap between

EROCs for the EU and the other two regions will become smaller under the LCE scenario, resulting in the USA ultimately overtaking the EU, and obtaining the highest value of EROC before 2040.

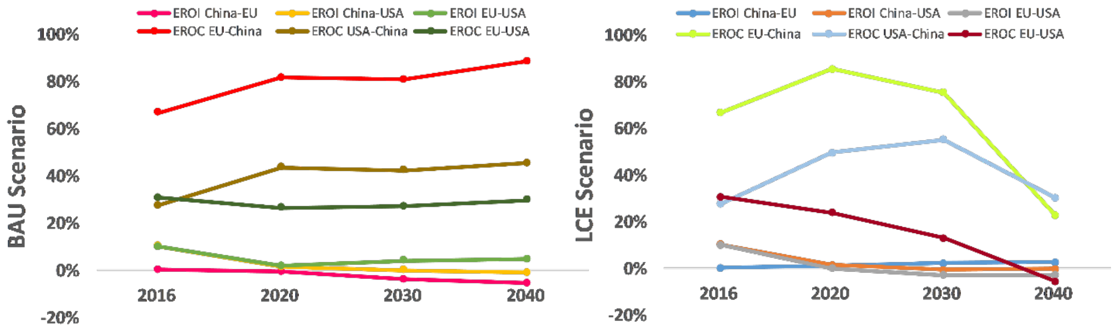

Figure 9. Comparative analysis of regional EROI and EROC patterns under BAU (left) and LCE (right) scenarios

Regional differences as shown in Figure 9 are due to differential changes in EROIs and EROCs between the regions. The growth of EROIs in the three intervals of the BAU scenario is stabilized between 10% and 20%, with the USA having the highest increase rate of EROIs from 2016 to 2040, followed by the EU and China. The increase rates of EROCs of the studied regions are around 25% for each time interval. The order of EROCs growth among the studied regions is consistent with that of EROIs. In terms of the LCE scenario, there is more significant growth of both indicators between 2020 and 2030 than in the other two time periods. The most significant feature of the LCE scenario is the high share of renewable power over the entire period, which causes increases in EROC for the regions to be much higher than under the BAU scenario. Overall, the USA has the highest growth potential of EROIs and EROCs under the LCE scenario. Additionally, China is estimated to achieve a higher increase rate for both indicators than the EU due to having more unused opportunities to develop low-carbon power.

6. Lessons for climate policy

Here insights are derived about potential policies to enhance the performance of solar power for a low-carbon electricity system. This is achieved by considering the connections between energy demand, supply, carbon intensity, EROI and EROC. The related policies are presented based on two main functions of solar power in future electricity systems, namely, supplying energy and reducing carbon dioxide emissions. In line with the framework developed in sections 2 and 3, We take into account energy use and emissions during the distinct life-cycle stages of solar PV. Applying equation 1 from Section 3 to describe the overall net energy generated by a multitude of renewable and fossil energy sources gives rise to equation 7. It illustrates the composition of power supply needed to satisfy a given demand. Assuming market clearing, Q_{net} denotes simultaneously societal energy demand and the amount of net electricity output the system needs to supply to society; $EROI_r$ and EI_r represent the $EROI$ and energy investment of renewable generation approaches; $EROI_f$ and EI_f refer to similar indicators for non-renewable generation (fossil fuels and other energy sources); and P and T denote the numbers of renewable and non-renewable generation approaches in the system. Next, applying equation 6 from Section 3 to the multitude of renewable and fossil energy sources leads to equation 8. It describes how average carbon intensity of electricity generated by all energy sources (CI_{avg}) depends on the carbon intensity share of each approach in the structure of power generation. Here, $EROC_r$ and $EROC_f$ denote the EROCs of renewable and non-renewable generation approaches; according to equation 4 and 5 from Section 3, $EROC_r$ is co-determined by the emission coefficients of energy and non-energy inputs in the life cycle; the shares of renewable and non-renewable electricity generation approaches are denoted by μ_r and μ_f (with $\sum_{r=1}^{P} \mu_r + \sum_{f=1}^{T} \mu_f = 1$), defined in equations 9 and 10, respectively. Here, $EROI_r * EI_r$ and $EROI_f * E_f$ denote the overall energy output of renewable and non-renewable generation approaches; $Q_{overall}$ presents the overall energy output of the system. Applying equation 1 from Section 3 to describe the overall energy output of this system results in equation 11.

$$\sum_{r=1}^{P}(EROI_r - 1)EI_r + \sum_{f=1}^{T}\left(EROI_f - 1\right)EI_f = Q_{net} \tag{7}$$

$$\sum_{r=1}^{P}\frac{(EROI_r - 1) * \mu_r}{EROI_r * EROC_r} + \sum_{f=1}^{T}\frac{\left(EROI_f - 1\right) * \mu_f}{EROI_f * EROC_f} = CI_{\ avg} \tag{8}$$

$$\mu_r = \frac{EROI_r * EI_r}{Q_{overall}} \tag{9}$$

$$\mu_f = \frac{EROI_f * EI_f}{Q_{overall}} \tag{10}$$

$$Q_{overall} = Q_{net} + \sum_{r=1}^{P} EI_r + \sum_{f=1}^{T} EI_f \tag{11}$$

When renewable power does not meet the requirement of net energy supply as in equation 7, three response options are available: (i) increase the installed capacity of renewable power by additional investment and financial subsidies, reflected by an increase in EI_r; (ii) reduce the direct and indirect energy consumption over the life cycle by improving production and upgrading organizational structure; and (iii) improve energy output by technical innovation of conversion efficiency. The latter two options come down to improving $EROI_r$.

To limit the carbon intensity of renewable power within the constraint given by equation 8, three paths can be followed. As most electricity consumed in the life cycle of renewable power is generated from non-renewable approaches, one can try to reduce the carbon intensity of non-renewable power, resulting in a higher $EROC_f$. Two options are available for this: (v) reduce the carbon dioxide emission of fossil fuels power through technical approaches, such as carbon capture and storage; and (vi) increase the share of other forms of low-carbon generation, such as nuclear power, in the structure of power supply. In terms of reducing emissions associated with indirect energy inputs through use of non-energy production factors, there is a final option, namely (vii) striving for a diverse energy structure with a high share of total renewable power ($\sum_{r=1}^{P} \mu_r$) to reduce emissions from non-energy resources.

One instrument can contribute to stimulating all these changes simultaneously, namely carbon pricing: i.e. through a carbon tax or emission permit market putting a charge on each use of carbon or each emission of CO_2. This would make both direct and indirect energy use more expensive, proportional to the indirect effects in terms of CO_2 emissions. Thus, policy stimulates a movement away from fossil fuels and towards renewable energy, as well as a rise in the EROCs of all PV technologies. Such a development will be reinforced by adoption of, and innovation in, these technologies, encouraged indirectly by the carbon price. Both product and process innovations play a role in this. In addition, buyers of PV technologies will be encouraged to purchase the ones that have a relatively low total carbon charge, which in turn will drive firm decisions in production and innovation directions. Governments could complement a carbon price with rules for subsidizing innovation and adoption that focus on improving EROC scores of technologies, along with the requirement that producers of such equipment provide information on EROC performance.

7. Conclusion and Policy Implications

We have presented a systematic assessment of PV technologies in three regions, China, EU and USA. This made use of the well-known measure of net energy production EROI (‘energy return on energy invested’) and the recently proposed indicator of carbon efficiency EROC (‘net energy return on carbon invested’). We have derived a formal framework including an expression relating the two, interposed by a critical third variable, namely carbon intensity.

We applied the framework to the main solar PV technologies and regions. CdTe turns out to have the highest EROIs and EROCs. It is further found that mono-Si has the lowest EROI and EROC values, which is caused by it having the largest amount of energy investment and associated carbon dioxide emissions during its life time. In terms of regions, the EU shows the best performance on EROIs, followed by China. The lowest net average energy return is achieved by the USA, caused by its high amount of energy use by labour and electricity. Due to large differences in carbon intensity of the production cycle, the order of EROC values among regions differs from that of EROI values. That is, the EU has the highest EROC, while China has the worst performance.

A second step in the empirical analysis involved a scenario analysis for the period between 2016 to 2040 to assess potential future patterns of EROI and EROC of solar power under business-as-usual and low-carbon electricity scenarios for the three regions. It was found that values of EROI and EROC are generally higher under the LCE than the BAU scenario. Under the BAU scenario, the relative values of future EROIs and EROCs between China, EU and USA are consistent with those in 2016; under the LCE scenario, the USA will gradually overtake the EU, achieving the highest EROI and EROC values in the long term, while the gaps between China and other two regions in terms of EROC values become narrower.

According to the International Energy Agency (IEA) and The International Renewable Energy Agency (IRENA), a massive deployment of energy storage equipment is required in the near future to address the impact of intermittency and fluctuation of renewable power (IEA, 2009). Associated energy investment and carbon dioxide emissions were not accounted for in this study. Including these would reduce EROIs and EROCs of PV technologies.

Based on a formal model analysis of the life cycle of solar power within the larger electricity system, a number of actions and policies were derived as contributing to improving the EROI and EROC values of solar power. This is summarized in Table 4. A general conclusion is that carbon pricing affects most of these changes and actions, and thus represents the most effective policy to achieve a low-carbon production of electricity.

Table 4. Actions and policies to improve EROI and EROC values of solar power for a low-carbon electricity system

Component	EROI	EROC
Solar power generation	Technical innovation of conversion efficiency and organizational upgrade	-
Other renewable generation approaches	Financial subsidy	Grid connection
Fossil fuel power generation	Improving generation efficiency	Reducing carbon intensity
Non-renewable low-carbon generation approaches	-	Scale-up; Security control
Regional level	Optimizing industrial structure; Improving generation efficiency	Diversity energy structure; Carbon pricing

Our analysis shows that we cannot assume all renewable energy technologies to be equally low-carbon. We have to implement policies to assure that the better performing technologies, over the entire production and life cycle, are recognized as such and are stimulated to be adopted and diffused. Similar stories can be told for wind turbines or electric batteries in electric vehicles. This is a neglected topic which deserves serious attention in research on climate and energy policies.

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References

Alsema, E., de Wild-Scholten, M., 2007. Reduction of environmental impacts in crystalline silicon photovoltaic technology: an analysis of driving forces and opportunities. MRS Online Proc. Libr. Arch. 1041.

Alsema, E.A., Frankl, P., Kato, K., 1998. Energy pay-back time of photovoltaic energy systems: present status and prospects.

Ayres, R.U., 2004. On the life cycle metaphor: where ecology and economics diverge. Ecol. Econ. 48, 425–438.

Beylot, A., Payet, J., Puech, C., Adra, N., Jacquin, P., Blanc, I., Beloin-Saint-Pierre, D., 2014. Environmental impacts of large-scale grid-connected ground-mounted PV installations. Renew. Energy 61, 2–6.

Bhandari, K.P., Collier, J.M., Ellingson, R.J., Apul, D.S., 2015. Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis. Renew. Sustain. Energy Rev. 47, 133–141.

BP, 2017. BP statistical review of world energy. British Petroleum, London.

Chu, S., Majumdar, A., 2012. Opportunities and challenges for a sustainable energy future. Nature 488, 294.

Corcelli, F., Ripa, M., Ulgiati, S., 2017. End-of-life treatment of crystalline silicon photovoltaic panels. An emergy-based case study. J. Clean. Prod. 161, 1129–1142.

Costanza, R., 1980. Embodied energy and economic valuation. Science (80-.). 210, 1219–1224.

de Wild-Scholten, M., Alsema, E.A., 2005. Environmental life cycle inventory of crystalline silicon photovoltaic module production. MRS Online Proc. Libr. Arch. 895.

de Wild-Scholten, M.J.M., 2013. Energy payback time and carbon footprint of commercial photovoltaic systems. Sol. Energy Mater. Sol. Cells 119, 296–305.

EIA, 2018. Electric power monthly report. Avaiable at <www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_01_a >.

Espinosa, N., Garcia-Valverde, R., Urbina, A., Krebs, F.C., 2011. A life cycle analysis of polymer solar cell modules prepared using roll-to-roll methods under ambient conditions. Sol. Energy Mater. Sol. Cells 95, 1293–1302.

Fabre, A., 2019. Evolution of EROIs of electricity until 2050: Estimation and implications on prices. Ecol. Econ. 164, 106351.

Ferroni, F., Hopkirk, R.J., 2016. Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation. Energy Policy 94, 336–344.

Frankl, P., Nowak, S., Gutschner, M., Gnos, S., Rinke, T., 2010. Technology roadmap: solar photovoltaic energy. Int. Energy Assoc.

Frischknecht, R., Itten, R., Sinha, P., de Wild-Scholten, M., Zhang, J., Fthenakis, V., Kim, H.C., Raugei, M., Stucki, M., 2015. Life cycle inventories and life cycle assessment of photovoltaic systems. Int. Energy Agency PVPS Task 12.

Fthenakis, V., Betita, R., Shields, M., Vinje, R., Blunden, J., 2012. Life cycle analysis of high-performance monocrystalline silicon photovoltaic systems: energy payback times and net energy production value, in: 27th European Photovoltaic Solar Energy Conference and Exhibition. pp. 4667–4672.

Fthenakis, V., Kim, H.C., Held, M., Raugei, M., Krones, J., 2009. Update of PV energy payback times and life-cycle greenhouse gas emissions, in: 24th European Photovoltaic Solar Energy Conference and Exhibition. pp. 21–25.

García-Valverde, R., Miguel, C., Martínez-Béjar, R., Urbina, A., 2009. Life cycle assessment study of a 4.2 kWp stand-alone photovoltaic system. Sol. Energy 83, 1434–1445.

Gernaat, D.E.H.J., Bogaart, P.W., van Vuuren, D.P., Biemans, H., Niessink, R., 2017. High-resolution assessment of global technical and economic hydropower potential. Nat. Energy 2, 821.

Hall, C.A.S., Lambert, J.G., Balogh, S.B., 2014. EROI of different fuels and the implications for society. Energy Policy 64, 141–152.

Held, M., 2009. Life cycle assessment of CdTe module recycling, in: 24th European Photovoltaic Solar Energy Conference. pp. 2370–2375.

Hou, G., Sun, H., Jiang, Z., Pan, Z., Wang, Y., Zhang, X., Zhao, Y., Yao, Q., 2016. Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China. Appl. Energy 164, 882–890.

Huang, C., Gu, B., Chen, Y., Tan, X., Feng, L., 2019. Energy return on energy, carbon, and water investment in oil and gas resource extraction: Methods and applications to the Daqing and Shengli oilfields. Energy Policy 134, 110979.

IEA, 2009. Prospects for Large-Scale Energy Storage in Decarbonised Power Grids. International Energy Agency, Paris.

IEA, 2017a. Key world energy statistics. Available at: <https://www.iea.org/statistics/ >.

IEA, 2017b. World energy outlook 2016. International Energy Agency,Paris.

IEA, 2017c. Commentary:Understanding and using the Energy Balance. Available at: <https://www.iea.org/newsroom/news/2017/september/commentary understanding-and-using-the-energy-balance.html>

IEA, 2018. World Energy Balances. International Energy Agency, Paris.

IRENA, 2017a. Renewable Energy and Jobs Annual Review. International Renewable Energy Agency, Masdar City.

IRENA, 2017b. Renewable energy benefits leveraging local capacity for solar PV. International Renewable Energy Agency, Masdar City.

Ito, M., Kato, K., Komoto, K., Kichimi, T., Kurokawa, K., 2008. A comparative study on cost and life-cycle analysis for 100 MW very large-scale PV (VLS-PV) systems in deserts using m-Si, a-Si, CdTe, and CIS modules. Prog. Photovoltaics Res. Appl. 16, 17–30.

Ito, M., Komoto, K., Kurokawa, K., 2010. Life-cycle analyses of very-large scale PV systems using six types of PV modules. Curr. Appl. Phys. 10, S271–S273.

Jungbluth, N., Stucki, M., Flury, Karin., Frischknecht, Rolf., Büsser, Sybille., 2012. Life Cycle Inventories of Photovoltaics. ESU-services Ltd, Uster.

Kamp, A., Morandi, F., Østergård, H., 2016. Development of concepts for human labour accounting in emergy assessment and other environmental sustainability assessment methods. Ecol. Indic. 60, 884–892.

Kato, K., Hibino, T., Komoto, K., Ihara, S., Yamamoto, S., Fujihara, H., 2001. A life-cycle analysis on thin-film CdS/CdTe PV modules. Sol. Energy Mater. Sol. Cells 67, 279–287.King, L.C., van den Bergh, J.C.J.M., 2018. Implications of net energy-return-on-investment for a low-carbon energy transition. Nat. Energy 1.

Kittner, N., Gheewala, S.H., Kammen, D.M., 2016. Energy return on investment (EROI) of mini-hydro and solar PV systems designed for a mini-grid. Renew. Energy 99, 410–419.

Koppelaar, R., 2017. Solar-PV energy payback and net energy: meta-assessment of study quality, reproducibility, and results harmonization. Renew. Sustain. Energy Rev. 72, 1241–1255.

Laleman, R., Albrecht, J., Dewulf, J., 2011. Life cycle analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation. Renew. Sustain. Energy Rev. 15, 267–281.

Liu, J., Zhao, D., Gerbens-Leenes, P.W., Guan, D., 2015. China's rising hydropower demand challenges water sector. Sci. Rep. 5, 11446.

Millstein, D., Wiser, R., Bolinger, M., Barbose, G., 2017. The climate and air-quality benefits of wind and solar power in the United States. Nat. Energy 2, 17134.

Müller, A., Wambach, K., Alsema, E., 2005. Life cycle analysis of solar module recycling process. MRS Online Proc. Libr. Arch. 895.

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

NEA, 2017. Installation capacity of renewable power in 2017. Avaiable at: <http://www.nea.gov.cn/2017-08/04/c_136499745.htm>.

Peng, J., Lu, L., Yang, H., 2013. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renew. Sustain. Energy Rev. 19, 255–274.

Perpiñan, O., Lorenzo, E., Castro, M.A., Eyras, R., 2009. Energy payback time of grid connected PV systems: comparison between tracking and fixed systems. Prog. Photovoltaics Res. Appl. 17, 137–147.

Rahman, M.M., Salehin, S., Ahmed, S.S.U., Islam, A.K.M.S., 2017. Environmental Impact Assessment of Different Renewable Energy Resources: A Recent Development, in: Clean Energy for Sustainable Development. Elsevier, pp. 29–71.

Raugei, M., Bargigli, S., Ulgiati, S., 2007. Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si. Energy 32, 1310–1318.

Raugei, M., Fullana-i-Palmer, P., Fthenakis, V., 2012. The energy return on energy investment (EROI) of photovoltaics: Methodology and comparisons with fossil fuel life cycles. Energy Policy 45, 576–582.

Rugani, B., Panasiuk, D., Benetto, E., 2012. An input–output based framework to evaluate human labour in life cycle assessment. Int. J. Life Cycle Assess. 17, 795–812.

Sanchez, D.L., Nelson, J.H., Johnston, J., Mileva, A., Kammen, D.M., 2015. Biomass enables the transition to a carbon-negative power system across western North America. Nat. Clim. Chang. 5, 230.

Sherwani, A.F., Usmani, J.A., 2010. Life cycle assessment of solar PV based electricity generation systems: A review. Renew. Sustain. Energy Rev. 14, 540–544.

Sieminski, A., 2014. International energy outlook. Energy Inf. Adm. 18.

SOLARGIS, 2018. iMaps. Avaiable at: < https://solargis.info/imaps/>.

Szargut, J., Ziębik, A., Stanek, W., 2002. Depletion of the non-renewable natural exergy resources as a measure of the ecological cost. Energy Convers. Manag. 43, 1149–1163.

Vellini, M., Gambini, M., Prattella, V., 2017. Environmental impacts of PV technology throughout the life cycle: Importance of the end-of-life management for Si-panels and CdTe-panels. Energy 138, 1099–1111.

Walmsley, T.G., Walmsley, M.R.W., Atkins, M.J., 2017. Energy Return on energy and carbon investment of wind energy farms: A case study of New Zealand. J. Clean. Prod. 167, 885–895.

Wang, C., Engels, A., Wang, Z., 2017. Overview of research on China’s transition to low-carbon development: The role of cities, technologies, industries and the energy system. Renew. Sustain. Energy Rev.

Wang, H., Wang, Y., Wang, H., Liu, M., Zhang, Y., Zhang, R., Yang, J., Bi, J., 2014. Mitigating greenhouse gas emissions from China's cities: Case study of Suzhou. Energy Policy 68, 482–489.

WEC, 2016. World Energy Resources Solar. World Energy Council, London.

Zhang, M., Wang, Z., Xu, C., Jiang, H., 2012. Embodied energy and emergy analyses of a concentrating solar power (CSP) system. Energy Policy 42, 232–238.

Zhang, T.W., Dornfeld, D.A., 2007. Energy use per worker-hour: Evaluating the contribution of labor to manufacturing energy use, in: Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses. Springer, pp. 189–193.