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Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation

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HIGHLIGHTS

- Data are available from several years of photovoltaic energy experience in northern Europe.
- These are used to show the way to calculate a full, extended ERoEI.
- The viability and sustainability in these latitudes of photovoltaic energy is questioned.
- Use of photovoltaic technology is shown to result in creation of an energy sink.

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ABSTRACT

Many people believe renewable energy sources to be capable of substituting fossil or nuclear energy. However there exist very few scientifically sound studies, which apply due diligence to substantiating this impression. In the present paper, the case of photovoltaic power sources in regions of moderate insolation is analysed critically by using the concept of Energy Return on Energy Invested (ERoEI, also called EROI). But the methodology for calculating the ERoEI differs greatly from author-to-author. The main differences between solar PV Systems are between the current ERoEI and what is called the extended ERoEI (ERoEI $_{EXT}$). The current methodology recommended by the International Energy Agency is not strictly applicable for comparing photovoltaic (PV) power generation with other systems. The main reasons are due to the fact that on one hand, solar electricity is very material-intensive, labour-intensive and capital-intensive and on the other hand the solar radiation exhibits a rather low power density.

1. Introduction

Publications in increasing numbers have started to raise doubts as to whether the commonly promoted, renewable energy sources can replace fossil fuels, providing abundant and affordable energy. Trainer (2014) stated inter alia: “Many reports have claimed to show that it is possible and up to now the academic literature has not questioned the faith. Therefore, it is not surprising that all Green agencies as well as the progressive political movements have endorsed the belief that the replacement of the fossil with the renewable is feasible”. However, experience from more than 20 years of real operation of renewable power plants such as photovoltaic installations and the deficient scientific quality and validity of many studies, specifically aimed at demonstrating the effective sustainability of renewable energy sources, indicate precisely the contrary. A meta-analysis by Dale and Benson (2013) has been concerned with the global photovoltaic (PV) industry’s energy balance and is aimed at discovering whether or not the global industry is a net energy producer. It contains reviews of cumulative energy demand (CED) from 28 published reports, each concerning a different PV installation using one of the currently available technologies. The majority use either single-crystal or multi-crystalline silicon solar panels, which together effectively comprise around 90% of the market. The huge scatter in the reported CEDs is itself a strong indication that the authors of the 28 publications studied were not following the same criteria in determining the boundaries of the PV system:

- in setting the criteria for the calculation of the values of the embodied energy of the various materials,
- in the calculation of the energy invested for the necessary labour,
- in the calculation of the energy invested for obtaining and servicing the required capital and,

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- in defining the conversion factors for the system's inputs and outputs consistently in terms of coherent energy and monetary units.

In fact, the CEDs show a range, from maximum of 2000 kW h_e/m² of module area down to a minimum of 300 kW h_e/m² with a median value of 585 kW h_e/m². For such cases, a meta-analysis would require an additional investigation to explain the system boundary conditions leading to the more extreme values.

Pickard (2014) expresses concerns similar to those of Trainer. He examines: "the open question of whether mankind, having run through its dowry of fossil fuels, will be able to maintain its advanced global society. Given our present knowledge base, no definite answer can be reached". His conclusion is: "it appears that mankind may be facing an obligatory change to renewable fuel sources, without having done due diligence to learn whether, as envisioned, those renewable sources can possibly suffice".

We wish at this point to emphasise the significance of the factor ERoEI (often abbreviated elsewhere to EROI), which lies at the heart of the present paper (Please see also Section 4). Arithmetically, it is most simply expressed as a ratio - the quotient obtained by dividing the total energy returned (or energy output) from a system by the total energy invested (the energy input or the system's CED). If the quotient is larger than one, then the system can be considered to be an energy source and if the quotient is lower than one, then the same system must be considered to be an energy sink. Clearly, the difference between the total energy returned and the total energy invested is equal in absolute units to the net energy produced during system lifetime. The words "TOTAL" and "NET" are critical here.

In this paper the ERoEI analysis is applied to systems including the PV installations located in regions of modest insolation in Europe, in particular in Switzerland and Germany. The energy returned and the energy invested will be treated separately. Sufficient data records are now available for the regions of interest, from which the electrical (i.e. secondary) energy returned can be derived. The energy invested, on the other hand, is based on the actual industrial situation for the production of silicon-based PV modules, for their transport, their installation, their maintenance and their financing. Due to the elevated costs and local environmental restrictions in Europe, PV module/panel manufacture takes place primarily in China.

Let us consider first the energy returned as the specific electrical energy produced, per unit of PV-panel surface (annually, in kW h_e/m^2 yr and over plant lifetime, in kW h_e/m^2).

2. Energy returned per unit of photovoltaic panel surface

There are two ways of approaching the calculation of yearly average and lifetime levels of electrical energy production.

The first starts with the yearly total of global horizontal irradiation, used currently as an indicator for the insolation levels at a site. The average value for Switzerland of this primary (thermal) energy (Haeberlin, 2010) lies between 1000 and 1400 kW h_t/m^2 yr. However, measurements with a pyranometer, from which these values are derived do not take into consideration the reduction of irradiation and hence of solar cell performance due to the presence, in the course of real operation, of accumulations of dust, fungus and bird droppings, due to surface damage, ageing and wear and finally due to atmospheric phenomena like snow, frost and condensing humidity. We use therefore the published statistical data for thermal collectors actually in operation as an indicator for the insolation. Such data are measured as a function of the surface given in square meters. The data are available in the Swiss annual energy statistics (Swiss Federal Office of Energy, 2015) prepared and published in German and French by the Swiss Federal Office of Energy (Bundesamt für Energie) and show an average value of 400 kW h_t/m^2 yr (suffix "t" means "thermal") for the last 10 years. This is an indication of the rather low effective level of the insolation in Switzerland. It is to be noted that further to the North, in Germany, the value is about 5% lower than this. The uptake from the incoming solar radiation is converted into electrical energy by the photovoltaic effect. The conversion process is subject to the Shockley-Queisser Limit, which indicates for the silicon technology a maximum theoretical energy conversion efficiency of 31%. Since the maximum measured efficiency under standard test conditions (vertical irradiation and temperature below 25 °C) is lower, at approximately 20%, the yearly energy return derived by this first method in the form of electricity generated, amounts to only 80 kW h_e/m^2 yr.

An alternative route to obtaining the energy return starts with the published statistical data of the PV installations themselves. The values measured are the electrical energy flow after conversion in the inverter from direct to alternating low voltage current and the indication of the kW_p peak rating of the installed PV system. In this case, applying the module surface per installed peak kW_p, it is possible to calculate the electricity production per square meter of the module. According to the official Swiss energy statistics (Swiss Federal Office of Energy, 2015), an average for the last 10 years of 106 kW h_e/m^2 yr is obtained for relatively new modules.

At this stage, we need to define the operational lifetime of a PV installation. This requires an assumption. Currently, vendors of PV installations quote a lifetime of 30 years, but the warranty for the material is normally limited to 5 years and all damaging events, such as damage due to incorrect installation or maintenance, hail, snow and storm, etc. lie outside the scope of responsibility of the vendor. Modules, which have failed during transport, installation or operating are collected for disposal by the European Association PV CYCLE (PV CYCLE – Operational Status Report - Europe, 2015), which is published on a monthly basis. Over the whole of Europe 13239 t of failed or exhausted modules had been collected by the end of December 2015.

We must concentrate here on the history in Germany, where the records are most complete. Table 1, below, shows the peak power of PV systems installed and the weight of the modules at a range of dates starting in 1985. It is necessary to compare these figures with the mass of module material from Germany treated so far (by the end of 2015). This was 7637 t. A module of 1 m^2 weighs 16 kg and 1 kW_p peak rating needs 9 m^2 and consequently, scaling this up, a 1 MW_p module will weigh approximately 144 t.

The source of the values of installed capacity has been Report IEA-PVPS T1-18: 2009 "Trends in Photovoltaic Application." This is a survey report concerning selected IEA countries between 2002 and 2008.

If the system lifetime were 30, or 25 years the quantity of dismantled modules (Table 1) should be practically zero, since by the year 1985 or 1990 (30 or 25 years ago) practically no PV

Table 1
Installed PV module capacities and weights between 1985 and 1998 in Germany

	End of year	Installed capacity (MW_p)	Weight of installed modules (tonnes)
30 years ago	1985	0.5	72
25 years ago	1990	2	288
20 years ago	1995	17.7	2549
19 years ago	1996	27.8	4003
18 years ago	1997	41.8	6019
17 years ago	1998	53.8	7747

systems had been installed. Now, at the end of 2015, modules corresponding to some 53 MW_p , the peak power capacity installed by 1998, a time between 17 and 18 years ago, have already been dismantled. Therefore, the average lifetime could be said to be nearer to 17 than to 30 years, due to the fact that the quantity of treated material by the end of 2015 (7637 t) corresponds to the capacity installed by 1998. In more recent years the quantity of new installations has increased very sharply and quality of installation design and building may be improving, or may have improved, but an extended lifetime remains to be demonstrated.

There are also other, external factors, which can reduce PV module lifetime, for instance the site, the weather and indeed climatic conditions. These aspects do not appear to have been treated in the scientific literature in connection with photovoltaic energy usage. The thermal cycling effects of passing clouds, the alternating night and day air temperatures varying strongly with season, the corrosion effects of humidity and the surface loading due to snow, ice and hailstones impacts should be studied and accounted for.

Furthermore, the performance during operation of PV installations has not been problem-free. For instance, in the "Quality Monitor, 2013" of the TUV Rheinland, it is stated that 30% of the modules installed in Germany have serious deficiencies. A further review published in the January 2013 issue of the magazine PHOTON states that about 70% have minor defects. It is clear that these faults influence lifetimes, downtimes and efficiencies of PV installations. Considering that many installations are not maintenance-friendly, it can be expected that such figures will continue to be seen. For the remainder of the present study a lifetime of 25 years is assumed, realising that this too, based on the above data, tends to be optimistic.

Thus, if we now adopt the lifetime of N=25 years as a working value, it is possible to work from the initial specific energy production of 106 kW h_e/m^2 yr mentioned above in this section, which we shall call $E_{n=0}$. We can now consider the effects of events occurring during a module's lifetime. Experience has shown that, on average, efficiency and hence performance degradations of around 1% per year of operation must be expected (Jordan and Kurtz, 2012). In addition, module failures have been found to cause operational downtime of some 5% per year (Jahn et al., 2005). Please note that this does not include electric grid losses. Accounting for these points leads to Eq. (1) below. This gives an expression for average yearly, specific electrical energy production – i.e. the average annual return of secondary energy - during a module's N=25 year lifetime at a figure of 88.1 kW h_e/m^2 yr:

$$E_{Average} = f_1 \cdot E_0\left(1 - 0.01\frac{N}{2}\right) \tag{1}$$

and to Eq. (2) for the total energy returned over plant lifetime:

$$E_{Total} = \sum_{n=1}^{N} f1 \cdot E_0(1 - 0.01n) \tag{2}$$

where :

E_o	initial ideal annual energy return (106 kW h_e/m^2 yr)
$E_{Average}$	average energy returned annually over the plant's lifetime (25 years)
E_{Total}	sum of the annual returns of energy during the whole plant lifetime
N	The plant's lifetime in years
n	the number of each operating year ranging from 1, 2, …. N (=25)
f_1	the reduction factor applied to the typical Swiss initial annual energy production level of 106 kW h_e/m^2 yr to correct for down time.

The first result is therefore, that we can now use Eq. (2) to quote the total energy returned over plant lifetime as 88.1 times 25, or: 2203 kW h_e/m^2. The analysis continues now, using this, the higher and more optimistic of the two values derived earlier in Section 2.

3. The photovoltaic technology is material, labour and capital intensive

For general information on the photovoltaic technology we refer to the "White Paper – Towards a Just and Sustainable Solar Energy Industry" – (Silicon Valley Toxics Coalition, 2009). In Sections 3.1, 3.2 and 3.3 of this Chapter we shall evaluate separately the characteristics, relevant for the comparison of the energy invested in PV plants with that necessary for other energy sources. This is important, as it enables us to understand the relative position in the energy mix of PV energy imposed by the limited power density of the incoming radiation, by the level of efficiency of its conversion to electricity and by the intermittent and frequently non-deliverable nature of the power output. Since most data offered by the solar energy industry refer to the installed peak power and not to the potential deliverable electrical energy, it is necessary to convert the power-based data to electrical energy relationships by the following formula:

The electricity production of any sort of power plant during a period T is shown in generalised form in Eq. (3), below:

$$E = P \times T \times C \tag{3}$$

where the units used will be: multiples of kW h_e for E, the energy produced multiples of kW_p for P, the electrical peak power rating.

Now, if P_N is the same rated power of a Nuclear Power Plant and P_S for a PV-plant and C is the capacity factor, which is 85% for a NPP (subscript N) and 9% for a PV-plant (subscript S), it is apparent that, in order to obtain the same energy production over the same period of operation, the PV-plant must have a rated power higher by a factor of f_2 than the NPP.

$$E = P_N \times T \times C_N = f_2 \times P_S \times T \times C_S \text{ that is } f_2 = C_N/C_S \text{ or } 9.44 \tag{4}$$

Thus Eq. (4) implies that a PV-plant should have a rated power (MW_p) of 9.44 larger than an NPP to produce the same amount of electrical energy.

3.1. Use of materials

The average weight of a photovoltaic module is 16 kg/m^2 and the weight of the support system, inverter and the balance of the system is at least 25 kg/m^2 (Myrans, 2009), whereby the weight of concrete is not included. Also, most chemicals used, such as acids/bases, etchants, elemental gases, dopants, photolithographic chemicals etc. are not included, since quantities are small. But, we must add hydrochloric acid (HCl): the production of the solar-grade silicon for one square meter of panel area requires 3.5 kg of concentrated hydrochloric acid. Summarizing now, we have a total weight of used materials per square metre of PV module panel area of:

16 kg (module)+25 kg (balance of plant)+3.5 kg (significant chemicals)=44.5 kg/m^2

Since the total lifetime energy return is 2203 kW h_e/m^2, we obtain a material flow of 20.2 g per kW h_e (principally steel, aluminium and copper). To compare this number with the corresponding numbers for other low CO_2-emission power sources, we use the values for a nuclear power plant adapted from the "Environmental Product Declaration of Electricity from Sizewell B Nuclear Power Station" (EDF Energy, 2009) for a modern power plant rated at 1500 MW_e and with a design lifetime of 60 years. The resulting material flow (principally steel) amounts to 0.31 g per kW h_e for a load factor of at least 85%. Thus the consumption of material resources using the photovoltaic technology is at least 64 times that of nuclear energy. This will also have a great influence on the energy invested during transport, which is not included in the usual type of energy balance analysis.

3.2. *Use of labour*

The suppliers involved in the renewable energies industry advertise their capability to create many new jobs. The European Photovoltaic Industry Association (EPIA-Job creation, 2012) gives the value of 10 for the direct and indirect jobs needed for installation, operation and decommissioning per MW_p installed. This refers to the peak power of a PV-system. Using Eq. (1), the job creation in respect to the energy produced is 94.4 jobs. Comparison with an estimate for the job creation by nuclear power plants is significant. Our study finds 13 jobs created per MW installed for the site construction, the operation, the maintenance and the decommissioning of a nuclear power plant. The human resources involved in the photovoltaic industry are thus revealed to be rather high – the PV technology is more than 7 times (or 94.44/13) more labour intensive than other energy sources.

3.3. *Use of capital*

The actual capital cost for a sample group of fully installed PV units, 2/3 roof-mounted and 1/3 free-field-mounted, in Switzerland lies at or above 1000 CHF/m^2 with large cost variations of up to 30%, due principally to the uncertainty in the price developments of PV modules. The NREL (National Renewable Energy Laboratory of the U.S. DOE) reports capital cost for fully installed PV units in the lower end of the price range given above. The 1000 CHF/m^2 cost, translated into specific cost for installed peak power is 6000 CHF/kW_p and is a result of personal experience of the authors. Now, using Eq. (4) we can compensate for the differing capacity factors of PV (9%) and fossil or nuclear (85%) plants multiplying by 9.44. This enables a comparison between PV and a nuclear power plant, which itself is much more capital intensive than other, fossil-fuelled plants. The overnight cost of a large, advanced nuclear power plant is estimated currently at 5500 CHF/kW, from a report (International Energy Agency-Projected Costs of Generating Electricity (IEA)-2015 Edition, according to Table 8.2). The capital resource taken by the PV technology is therefore around 10 times that of a nuclear power plant and nearly 45 times that of fossil-fuelled power plants.

3.4. *Summary*

In Section 3.4 the reader will note that the costs for the use of materials, labour and capital are all expressed in terms of equivalent electrical energy. PV technologies, consume per unit of electricity produced, 64 times more material resources, 7 times more human resources und 10 times more capital than nuclear technology.

This is a clear indication of the extreme inefficiency of the PV technologies in regions of moderate insolation in helping to achieve the objective of providing an efficient electricity supply system, which consumes a minimum of resources. In this section, we have still not considered the facts that in the winter period the PV is producing at its peak power for the equivalent of only 1.7 h per day on average and in the summer period, still for only 3.3 hours daily and that, due to the intermittent nature of the electricity production, a parallel electricity supply infrastructure also has to be provided.

The data used in this section have been published by the solar or nuclear industries and may be biased. Important however, is that the differences in the energy balances be known in their orders of magnitude rather than in great detail.

4. Methodology for the calculation of the energy invested

The purpose of this section is to define and present the calculations for the total energy invested. For this, it is important first to define the system under investigation, its boundaries and what flows across them – i.e. materials, money and energy. There are several stages in the life cycle of an energy system. These include the production of the necessary materials, the manufacture of the components, their transportation, installation, commissioning, operation and maintenance, decommissioning, financing, administration, their integration in the electricity supply system duly revised according to the needs of the users, and finally the essential accompanying research and development work. It is important with respect to this latter point that the quality of the energy produced be considered. As derived and shown in Section 3, photovoltaic plants are material, labour and capital intensive, but provide only intermittent and irregular energy production. These characteristics have a significant and clear effect on the total energy, which must be invested in each system, whereby a system must be understood to consist of a segment of the production and manufacturing industries and then of a unit-sized PV plant and the contribution demanded by it from the revised electricity supply infrastructure.

There are many definitions of the energy invested for the ERoEI. The article "Year in review-EROI or energy return on (energy) invested" (Murphy and Hall, 2010) outlines some definitions for the EI such as:

a) The energy required to collect the energy to be returned, or
b) The energy required to collect, deliver, and use that energy.

Most ERoEI analyses are not very clear in defining the system boundary for the energy invested. Here we consider on one side, the methodology used by the IEA, which uses in principle the definition a) for the calculation of the ERoEI , which we shall refer to as $\text{ERoEI}_{\text{IEA}}$ and our own methodology, using the definition b) for the calculation of the extended ERoEI as referred to by Murphy and Hall as $\text{ERoEI}_{\text{EXT}}$.

4.1. *IEA methodology guidelines on life cycle of photovoltaic electricity*

The Report IEA-PVPS T12-03: 2011 (IEA-PVPS T12, 2011) has been prepared as a document of the International Energy Agency (IEA) by a group of experts involved in the photovoltaic industry and is more suitable for a comparison of the different PV technologies rather than for the determination of the efficiency and sustainability of the PV system as energy source. For the determination of the ERoEI, the guideline has the following deficiencies:

a) The energy flux across the system boundaries and invested for the labour is not included.
b) The energy flux across the system boundaries and invested for the capital is not included.
c) The energy invested for integration of the PV-generated electricity into a complex and flexible electricity supply and

Table 2
CED for production of PV-systems

Reference of the study	KW h_e/m^2	Notes
Nawaz and Tiwari (2006)	1380	Roof-installed
Nawaz and Tiwari (2006)	1710	Free-field
Lu and Yang (2010)	1237	Roof-mounted
Kannan et al. (2006)	1224	Roof-mounted
Kato et al. (1998)	1291	Only modules, no Balance of System
Ferroni (2014)	1287	2/3roof, 1/3 free field
Lundin (2013)	1317	No support included

distribution system is not included (energy production does not follow the needs of the customer).

d) The IEA guidelines specify the use of “primary energy equivalent” as a basis. However, since the energy returned is measured as secondary electrical energy, the energy carrier itself, and since some 64% to 67% of the energy invested for the production of solar-silicon and PV modules is also in the form of electricity (Weissbach et al., 2013) and since moreover, the rules for the conversion from carrier or secondary energy back to primary energy are not scientifically perfect (Giampietro and Sorman, 2013), it is both easier and more appropriate to express the energy invested as electrical energy. The direct contribution of fossil fuel, for instance in providing energy for process heating, also has to be converted into secondary energy. The conversion from a fossil fuel's internal chemical energy to electricity is achieved in modern power plants with an efficiency of 38% according to the BP statistic protocol (BP Statistical Review of World Energy, June 2015). In the present paper, in order to avoid conversion errors, we shall continue to use electrical (i.e. secondary) energy in kW h_e/m^2 as our basic energy unit.

e) The recommended plant lifetime of 30 years, based on the experiences to date, must be regarded as unrealistic.

f) The energy returned can and should be based on actual experimental data measured in the field. Use of this procedure will yield values in general much lower than the electricity production expected by investors and politicians.

Estimated ERoEI values for a variety of cases, have been calculated by several authors following the IEA guidelines: 5.8 was given, for example, by Brandt et al. (2013); 5.9 by Raugei et al. (2012). Weissbach et al. (2013) indicated in Table 3 in their paper an EROI of 4.95 expressed in coherent units. The tendency, when using the IEA methodology is to make use of ideal parameter values, which, in their turn, tend to yield optimistic levels of EROI.

In the authors' opinion the IEA-guideline is not suitable for evaluating the ERoEI of the PV systems against non-PV systems in view of the fact that, as stated above, the PV technology is extremely material, labour and capital intensive, the capacity factor during the winter period is only about 3% (or more recently in Germany during January 2015, only 2%). The methodology is only suitable for comparing the various PV technologies with each other.

Table 3
Principal energy losses and extra energy investments due to plant and grid integration

Losses or energy invested for additional infrastructure	kW h_e/m^2
Losses due to the pump-storage hydroelectric system 2203 (el. production) × 25% × 27.1% (efficiency losses)	149
Construction of pump storage systems (1 m^3 Concrete → 300 kW h_e)	100
Construction of back-up gas turbine power plant	25
Grid-adaptation (1 kg copper → 11 kW h_e)	25
Operation of smart-grid infrastructure	50
Total	349

4.2. Methodology based on “extended ERoEI”

Historically the methodology for the “extended ERoEI” is derived from the works of the ecologist Howard T. Odum, who was introducing a generalized approach to analysing energy systems, the concept of “net energy” of renewable and non-renewable energy sources and the concept of “emergy” as an expression of all the energy and material resources used in the work processes that generate a product or service (now termed embodied energy). In Odum's book, “Environmental Accounting: Emergy and Environmental Decision Accounting” (Odum, 1995) he showed that from a PV installation, considering the labour associated with the construction, operation and decommissioning no “net energy” is obtained. Charles Hall and his team, developed further the concept of ERoEI in Hall et al. (2009), in Murphy and Hall (2010) and in Murphy and Hall (2011). They have suggested that a technology with an $\mathrm{ERoEI_{EXT}}$ less than 5 be considered as unsustainable.

In the extended ERoEI, the system's boundaries are defined so as to encompass all energy-relevant activities related to the ability to deliver a reliable, flexible and available product to the consumer on demand. The first has to do with “upstream” factors, such as, for example, the energy it took to construct the plant for the purification of silicon to solar grade Silicon. According to the Hemlock Semiconductor Group (HSC), the investment required for the construction for such a plant for 21,000 t of yearly production was approximately 4 billion US $. Due to the high flow of materials necessary to produce 1 kW h_e from photovoltaic installations in comparison with those from other types of energy sources, such factors should, strictly speaking, be taken into consideration. Only vague data are available at present, so in the present study they have not been included. This reduces (optimistically) the amount of energy input during the “upstream” phase. The remaining factors for the $\mathrm{ERoEI_{EXT}}$ are the “downstream“ energy fluxes and losses attributable to PV.

The book “Spain's Photovoltaic Revolution-The Energy Return on Investment” (Prieto and Hall, 2013) indicate more than 20 activities or tasks, outside the production process of the modules, which should be included in defining the system boundary and the energy or equivalent energy fluxes, which cross it. The activities are based on the comprehensive experience gained by Pedro A. Prieto during the construction of several photovoltaic projects in Spain. The estimated ERoEI including labour and financing as given in Section 7 of Prieto and Hall's book and using coherent units, results in an ERoEI of 2. According to our calculations, their values of the specific embodied energy for the modules, inverters and Balance of Plant are somewhat too low. Moreover, in Spain the PV installations are in operation typically for 1.9 times the annual productive operational hours of PV installations in Switzerland or Germany, so it is possible to deduce that PV technology is not sustainable for these regions with their more modest levels of insolation.

Apart from the work of Prieto and Hall, only a few other studies have corrected any of the weak points of the IEA methodology. One of these was that by Weissbach et al. (2013), in which an energy storage capacity of 10 full-load days was estimated to be necessary to enable a system's service target to be met. Adding this storage capacity to a system, according to Table 3 in Weissbach et al. (2013) results in an additional 10 years of equivalent energy payback time and a dramatic EROI reduction to 2.3, using coherent units. Such a result cannot be ignored and is a sound justification for working with the $\mathrm{ERoEI_{EXT}}$.

5. Calculation of the energy invested for the PV System

In this section the calculations made for the energy invested are reported. In addition to the system boundary as recommended in the IEA-guidelines, the following additional factors have been considered:

1. The integration of intermittent, PV-generated electricity into the grid,
2. The labour and the capital requirements.

The treatments and detail used for the estimations presented here correspond closely to those described by Prieto and Hall (2013). "Upstream" activities, such as the energy invested in building manufacturing plant (see Section 4.2, above), have not been included in either case. The resulting reduction of the invested energy represents again an optimistic assumption.

5.1. Cumulative energy demand (CED) or energy invested in the PV-based system

As shown in the review by Dale and Benson (2013) the results of the 28 cases reported indicate a considerable scattering of CED values. Our analysis of these studies indicates that those originally done in Japan, India, China and Malaysia all show a higher CED and a limited scattering. Whilst a large part of the solar module production industry was located in Europe before 2010, including companies such as Q-Cell, SolarWorld, BP Solar, Siemens, Bosch and REC, today almost all European companies have either been closed, have suffered huge losses or have undergone bankruptcies. Leadership of the solar industry has been taken over by Chinese companies who now represent over 70% of current world production. The main reason for this shift is the high cost of electricity in Europe, and this is very important for the energy intensive solar industry.

The production of PV modules requires a process consisting of approximately 200 steps, starting from crystalline silica mining, upgrading silica sand to metallurgical grade silicon, upgrading metallurgical grade silicon to solar grade silicon. The pulverized metallurgical grade is combined with hydrochloric acid to produce trichlorosilane. This is subjected to a multistage distillation process, referred to commonly as the Siemens process, to obtain polysilicon. Solar cells are produced by transforming polysilicon into cylindrical ingots of monocrystalline silicon, which are then shaped and sliced into thin wafers. Next a textured pattern is imparted to the surface of the wafer in order to maximize the absorption of light. The wafer is then doped at high temperature with phosphorus oxychloride, provided with an anti-reflective coating of silicon nitride and finally printed with a silver paste (lead should be avoided) to facilitate the transport of electrical energy away from the cell. A typical PV module consists of several cells wired together and encapsulated in a protective material, commonly made of ethylene vinyl acetate. To provide structural integrity the encapsulated cells are mounted on a substrate frequently made of polyvinyl fluoride. A transparent cover, commonly hardened glass, further protects these components. The entire module is held together in an aluminium frame.

The CED values of some of the oriental-based cases reviewed by Dale and Benson (2013) have been analysed and the results transformed into our coherent units, kW h_e per square meter in Table 2.

Many potentially hazardous chemicals are used during the production of solar modules. To be mentioned here is, for instance, nitrogen trifluoride (NF_3), (Arnold et al., 2013), a gas used for the cleaning of the remaining silicon-containing contaminants in process chambers. According to the IPCC (Intergovernmental Panel on Climate Change) this gas has a global warming potential of approximately 16600 times that of CO_2. Two other similarly undesirable "greenhouse" gases appearing are hexafluoroethane (C_2F_6) and sulphur hexafluoride (SF_6). For further information on the chemicals involved in the solar industry, please read the White Paper "Towards a Just and Sustainable Solar Energy Industry" by the Silicon Valley Toxics Coalition (Silicon Valley Toxics Coalition, 2009).

It is stressed that, in addition to the flow of materials necessary for the production and installation estimated at 44.5 kg/m^2 - see Section 3 -, one must also account for the energy used to treat and transport all used chemicals and the sludge waste to a final repository. These quantities are estimated at 20 kg per square meter of solar panels. Therefore, the energy required for the total quantity of material to be transported and estimated to be 64.5 kg per square meter of panel cannot be neglected.

For the evaluation made for the present paper of a hypothetical situation in Switzerland, the case was assumed to concern a production volume, from which 2/3 of the PV installations were destined for roof-mounting and the remaining 1/3 for free field placement. The CED value is approximately 1300 kW h_e/m^2, consistent with the other examples in the table.

5.2. Integration of the intermittent PV-electricity into the existing grid

The intermittent generation of energy by photovoltaic and wind sources implies a need for availability of a mixture of back-up power plants, mainly fossil-fuelled, and for large-scale energy storage systems. Many concepts for energy storage are available, such as hydroelectric pumped storage schemes, pressurised air storage, hydrogen production by electrolysis and storage or batteries. Here we shall consider only the pumped storage option, since this system has the lowest energy losses, at 25%, in pumping up the water and then letting it down through the turbine. Our estimation assumes further that 25% of the electricity generated by the PV system will be used to pump the water into an upper storage lake to be discharged when the consumers need electricity. In addition, losses due to conversion from low to high voltage for the pumps estimated to be 2,1% are to be included. Furthermore, in order to guarantee creation of a reliable electricity system, back-up power preferably from gas turbine driven generating plants and a smart grid will have to be devised and constructed. This too implies energy invested or energy needed for the operation of the smart grid. It has to be noted that a smart grid cannot save energy, but will consume energy to fulfil its task. Of course, the existing grid itself needs adaptation to the different electricity supply.

In Table 3, we list the calculated energy losses and extra energy to be invested in order that the customers are served according to their requirements in an integrated power supply system.

5.3. Estimation of the energy invested for labour and generation of capital

5.3.1. Energy intensity in an advanced economy

It is a widely held assumption that energy consumption is related to economic activity and plays a key role in the process of economic growth. In addition, the relationship of energy to GDP (Gross Domestic Product) is also termed the "Energy Intensity" - that is to say, the energy required to produce a unit of income or GDP. This gives the connection between monetary units and energy units. The publication: " The underestimated contribution of energy to economic growth" (Ayres et al., 2013) underlines the fact that *"The rather standard assumption that economic growth is independent of energy availability must be discarded absolutely"* and that neither labour nor capital can function in an advanced economy without inputs of energy to the different sectors such as materials, manufacturing and services, etc.

This interdependence is seen clearly in the work of Gael Giraud, Research Director at CNRS (Centre de la recherche scientifique) in Paris. The presentation by Giraud and Kahraman (2014) summarizes the literature on the subject, showing that primary energy consumption is indeed a key factor of growth in OECD countries.

The comprehensive study “Energy and Growth: the Stylized Facts” (Csereklyei et al., 2016) analyses the energy to GDP data of 99 countries from 1971 to 2010. The main findings are that over the last 40 years there has been a stable relationship between per capita energy use and income per capita. Furthermore, energy intensity has declined globally as the world economy has grown and there has been a convergence of the figures for wealthy nations towards a value (see Figure 18 of the study) of 7.4 MJ/USD, which converts to 2.05 kW h_{th} primary energy per dollar. This value has remained stable during recent years due to the global technological progress in advanced economies in using energy more efficiently and wisely. Of course it is related to the overall make-up of the economy, which includes energy-intensive sectors as well as less energy-intensive sectors, such as service industries.

No statistical data are available for the energy intensity due to the installation, operation, repair, servicing and decommissioning of PV-systems. Since the manufacturing sector – a sector in content similar to the diverse activities necessary for a PV system – exhibits an energy intensity higher than the overall value, we assume as a conservative value for the energy intensity of labour the typical overall value in an advanced economy. For the energy intensity of capital generation, it is reasonable again to assume the overall value of an advanced economy. Capital is the result of energy invested in previous economic activities for housing, transport, food, goods, services and other. Therefore, knowing the amount of money required and the energy intensity, it is possible to calculate the energy use.

For this analysis, since we are using the higher Swiss costs of labour and goods, we will also determine separately the Swiss secondary energy intensity to avoid statistical weak points as explained (Giampietro and Sorman, 2013). The internal national secondary energy consumption for the year 2014 may be extracted from the Swiss annual energy statistics (Swiss Federal Office of Energy, 2015). It is the sum of the primary energy of imported fossil fuels, converted to secondary energy assuming a 38% conversion efficiency according the BP statistic protocol and added to the electricity produced inland, mainly by hydro-electric or nuclear power, the figures for which already available in terms of secondary energy.

Furthermore it is necessary to consider the nature of the Swiss economy, going through a process of de-industrialization and now having practically no energy-intensive industries, but with a huge imports of energy embodied in the materials used in products made inland, such as in metals, plastics, paper and construction materials etc.. To estimate this value, using Fig. 18 of the (German language) study by the Swiss Federal Office of the Environment (2013), “Climate Change in Switzerland” (2013) and assuming that the net energy imported is proportional to the net CO_2- emissions (i.e.: CO_2-import minus export), it is evinced that we have to multiply the internal Swiss energy consumption by a factor of 2.17 to determine the total energy consumption. It is important to note that the national energy statistics do not attach sufficient attention to the European de-industrialization process, giving the impression that we are saving energy. However, in reality we are outplacing energy-intensive industries to regions offering low price energy and labour. This, for instance, has been the case for the energy-intensive production of solar-grade silicon.

Using the Swiss GDP, a secondary energy intensity of 0.43 kW h_e/CHF is obtained. Note that this value is lower than the primary global value of 2.05 kW h_{th}/ USD that, converted to secondary energy with an efficiency of 38%, would result in 0.78 kW h_e/CHF. Low energy intensity indicates high energy-efficiency – that is to say, the generation of more units of GDP per unit of energy consumed. The higher efficiency in Switzerland is also due to the fact that the energy consumption there shows a stronger correlation with the proportion of energy used in the form of electricity. Use is made here of the BP statistics protocol for the USA, where this protocol is always used, and for Switzerland. The comparison demonstrates the proportion of electrical energy consumed in Switzerland is 48% in against 40% in the USA.

5.3.2. *Energy invested for the labour*

An additional factor neglected in the majority of studies on ERoEI is the human labour associated with the installation, operation, decommissioning and final disposal of the hazardous materials used in the production of the PV plant and of the modules themselves, where such materials as, for example, Cd, Ga and Pb are present. According to Section 3.2 we have shown that the labour involved is proportionately so much higher for PV systems than for other types of energy generation systems and therefore it must be taken into account.

Equally, the human resources involved for back-up power plants and power storage systems must be considered. This, optimistically again, has not yet been included in the present study, due to a high degree of uncertainty in the chosen development plans.

Based upon the authors' experiences for typical local labour costs per square meter of PV module are: project management (10% of capital cost), installation (506 CHF per m^2), operation for 25 years, including insurance (1.67% of capital cost per year for 25 years) and decommissioning (30% of installation). The total labour costs amount to 1175 CHF/m^2.

To derive from these cost figures the energy involved, we use the energy intensity (kW h_e/CHF) for Switzerland as calculated in 5.3.1 which is 0.43. Therefore, the amount of energy invested for the human resources is an optimistic 505 kW h_e /m².

Faulty modules and inverters appearing during the lifetime of the PV installation must be considered as a loss of embodied energy. According to the experience in Spain (Prieto and Hall, 2013) about 2% of the modules were returned or scrapped during their installation. In Switzerland many modules have been damaged by the weight of snow or the intensity of hail impacts. In addition, inverters too, are subject to failure and during the plant's operational lifetime an inverter often has to be replaced. The embodied energy calculated for the faulty modules and inverters amounts to 90 kW h_e /m².

5.3.3. *Energy invested for the capital*

In Section 3, we were able to see that solar energy in the form of electricity is capital intensive compared to other energy sources. Capital is the result of labour previously performed and therefore of energy previously consumed.

We assume an average capital requirement of 1100 CHF/m² for a mix of PV plants consisting of two thirds as roof-installations and one third as free field installations including project management activities. For the sake of simplicity, we neglect the capital necessary for the construction of the back-up power sources and the power storage system as well as the capital for the necessary land to install all the equipment. We apply the method of constant annuity in order to calculate the capital required to service the necessary capital of 1100 CHF/m^2, assuming an amortization period of 25 years and an average interest rate of 5%. The annuity is 7.1% minus the amortisation of the energy invested over the 25

Table 4
Summary of the components of the total energy investments

Principal energy investments	kW h_e/m^2
Cumulative energy demand (CED) for the production of the PV-system	1300
Integration of the intermittent PV-electricity in the grid and buffering	349
Energy invested for the labour	505
Energy embodied for faulty equipment	90
Energy invested necessary for the capital	420
Total	2664

years at 4%, leaving 3.1%. The total capital necessary to serve the capital invested for 25 years is 872 CHF/m^2 or 436 kW h_e/m^2.

The renewable energy will have to compensate for the same amounts of taxes, duties or levies as are paid by the existing electric power supply system. In Switzerland these amount to 0.0424 CHF/kW h_e with the addition of the Value Added Tax for the maintenance work. The total amounts to 127 CHF/m^2 or 54 kW h_e/m^2.

We see now, that the total energy required for obtaining and servicing the capital necessary for a PV-system is the sum of 366 and 54=420 kW h_e/m^2.

6. Total energy invested

Table 4 summarizes the calculated essential energy investments for a PV system as foreseen, which can guarantee a reliable electricity supply to the customers. The energy contributions of subsequent activities, such as the research and development for the PV industry, have not been included. Also not included are the additional personnel that have been employed within the utility companies and the state-owned renewable energy agency, the energy required for the final disposal of the hazardous conditioned material and the energy loss due to the dumping of excess energy. Such energy dumping is a necessity to stabilize the grid during summer weekends, when, for instance, excess energy is dissipated by heating railway tracks or by disconnecting hydraulic turbines, which use river water.

7. Conclusion and policy implications

The calculated value for ERoEI is dimensionless, constituting the energy return (2203 kW h_e/m^2) divided by the energy invested (2664 kW h_e/m^2) – a ratio of 0.82. It is estimated that these numbers could have an error of ± 15%, so that, despite a string of optimistic choices resulting in low values of energy investments, the ERoEI is significantly below 1. In other words, an electrical supply system based on today's PV technologies cannot be termed an energy source, but rather a non-sustainable energy sink or a non-sustainable NET ENERGY LOSS. The methodology recommended by the expert working group of the IEA appears to yield EROI levels which lie between 5 and 6, (see Section 4.1), but which are really not meaningful for determining the efficiency, sustainability and affordability of an energy source. The main conclusions to be drawn are:

- The result of rigorously calculating the “extended ERoEI” for regions of moderate insolation levels as experienced in Switzerland and Germany proves to be very revealing. It indicates that, at least at today's state of development, the PV technology cannot offer an energy source but a NET ENERGY LOSS, since its $\text{ERoEI}_{\text{EXT}}$ is not only very far from the minimum value of 5 for sustainability suggested by Murphy and Hall (2011), but is less than 1.
- Our advanced societies can only continue to develop if a surplus of energy is available, but it has become clear that photovoltaic energy at least will not help in any way to replace the fossil fuel. On the contrary we find ourselves suffering increased dependence on fossil energy. Even if we were to select, or be forced to live in a simpler, less rapidly expanding economic environment, photovoltaic technology would not be a wise choice for helping to deliver affordable, environmentally favourable and reliable electricity regions of low, or even moderate insolation, since it involves an extremely high expenditure of material, human and capital resources.
- Research and development should however, be continued in order in future to have more efficient conversion from sunlight to electricity and a cheaper, more reliable PV-technology offering increased efficiency and a longer, failure-free lifetime. The market will then develop naturally.

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