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

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ABSTRACT

A paper by Ferroni and Hopkirk (2016) provided evidence that presently available PV systems in regions of moderate insolation like Switzerland and countries north of the Swiss Alps act as net energy sink. These findings were disputed in a paper (Raugei et al., 2017). Additional clarifications in support of our conclusions are explained, including mention of weak points in the argumentation by Raugei et al.

Our study is based on the concept of the extended ERoEI ($ERoEI_{EXT}$) for PV systems, knowing that this is not the mainstream concept in the Life Cycle Assessment (LCA), applying the Process-Based Life Cycle Assessment. The concept of the $ERoEI_{EXT}$ considers many possible energy contributions needed for assessing the envisioned transition from fossil fuel to other types of energy sources and here in particular to photovoltaics in regions of moderate insolation.

The conclusions of our original study remain unchanged. Any attempt to adopt an Energy Transition strategy by substitution of intermittent for base load power generation in countries like Switzerland or further north will result in unavoidable net energy loss. This applies both to the technologies considered, to the available data from the original study and to newer data from recent studies.

1. Introduction

The paper published by the authors (Ferroni and Hopkirk, 2016) has provided evidence that presently available PV systems in regions of moderate insolation like Switzerland and countries north of the Swiss Alps, provide little more than material-intensive, labour-intensive and capital-intensive energy, resulting in high consumption of resources. These findings have been disputed in a recent paper (Raugei et al., 2017). In the following we shall offer additional clarification in support of our conclusions and expose basic errors in the argumentation by Raugei et al. (2017).

Regions of higher insolation (e.g. in southern Europe) as well as geographical diversity or combination with wind turbines were explicitly excluded from our published study. Our proof was accompanied by a short comparison between electricity production from solar generators with other energy sources to demonstrate that PV energy is particularly material, labour and capital intensive. Since nuclear power generation is also more labour and capital intensive than the combustion of fossil fuels, we had included estimations valid for nuclear energy. However, our conclusions stand for themselves: the extended ERoEI ($ERoEI_{EXT}$) for PV systems is below 1 and thus has a negative impact. Society receives few or no benefits from their use. For this reason, it will not be necessary to comment further on statements made by Raugei et al. regarding nuclear energy.

The concept of $ERoEI_{EXT}$ has been applied, knowing that this is not the mainstream concept in the Life Cycle Assessment (LCA) community. However, this concept has gained and is gaining more attention, especially since the current LCA does not take into consideration many possible energy contributions needed for assessing the envisioned transition of our civilisation from fossil fuel to other types of energy sources and here in particular to the photovoltaic energy source in regions of moderate insolation.

Important in this respect is the recent publication of a book by Charles A. S. Hall “Energy Return on Investment – A Unifying Principle for Biology, Economics, and Sustainability” (Hall, 2017) outlining the basic generally valid methodology for the calculation of the ERoEI for different energy sources.

In addition, the experience gained from the “Energiewende” (Energy Transition) in Germany has shown that 464 billion Euro have been spent up to the end of 2015 (Limburg and Müller, 2015) for the

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renewable energy program without any notable reduction of CO_2 emissions. In 2015 these amounted to 535 g CO_2-eq/kWh (Emissionen des deutschen Strommix, 2016). Servicing such huge amounts of capital also implies a considerable consumption of energy.

We recommend that the $ERoEI_{EXT}$ approach be applied to all energy system sources, including nuclear energy. Therefore, the standards and protocols such as those recommended by the International Standards Organisation (ISO) and the International Energy Agency (IEA) can only be partially applied for the better calculation of the $ERoEI_{EXT}$. We are aware of the fact that the results of the various ERoEI-analyses published up to now in the scientific literature cannot be compared with each other, without a rigorous and deontological investigation. In our previous paper, we specified the scope of the $ERoEI_{EXT}$, bearing in mind the full specification of this extended scope. In our case this amounts to: energy demand for the materials, for the labour, for the installation, operation, decommissioning, integration of the intermittent PV generated electricity into the grid with storage capability and for obtaining and servicing the required capital.

The purpose of the study is to assess the energetic feasibility of the envisaged electricity policy in Switzerland – one aspect of the Swiss Energy Transition – where the actual base load assured by nuclear power plants generating yearly 25 TWh is to be substituted until the end of the year 2050 by intermittent electricity produced by PV-systems or wind power plus geothermal electricity. Note that a recent study (Heard et al., 2017) concludes that this is not feasible. In Germany the energy policy is also to substitute the baseload assured by coal power plants with so-called renewable energy. For our scenario, we have selected a hypothetical division of the PV-system in 2/3 as roof mounted and 1/3 as free field PV-plants.

The use of the $ERoEI_{EXT}$ methodology and not of the LCA methodology should be mandatory in the future to avoid annihilation of resources and to provide a clear answer to consumers, faced with the huge increase in electricity prices. It is worth noting that in Germany and Denmark, the two countries with the highest installed wind and solar capacity per capita in Europe, the electricity prices for residents are also high, at about 0.30 Euro/kWh (2016), as discussed by Gail Tverberg in her article "Intermittent Renewables Can't Favorably Transform Grid Electricity" published online in Tverberg (2016). A similar observation can be made for the domestic consumer prices of energy. The data collected by Eurostat (2017), the statistical office of the European Union, as "Energy and Supply" over the last ten years shows that the electricity prices for households in countries with very high installed solar capacity per capita are also quite high, as evidenced for example by the numbers for Spain, the United Kingdom and Italy.

The emphasis of valid scientific research should be placed on calculations of the energy return based on the actual experience in a specific country and on the energy invested, including all energetic factors contributing to this investment. In our review, we discuss the points considered as “*supposed errors*” or “*double counting*” in the so-called "*comprehensive response*" by Raugei et al., which are:

- Methodology used for the extended ERoEI ($ERoEI_{EXT}$)
- Energy return of photovoltaic systems in regions of moderate insolation
- Energy demand/ invested for materials
- Energy demand for the integration of the intermittent PV-electricity into the existing grid
- Energy demand for labour
- Energy demand for servicing the capital
- Other arguments of the “comprehensive response”

All our data are supported by references. This is not the case for some key data from the Raugei et al. paper as for example for their purported cumulative energy demand (CED), degradation rate, downtime (or lack thereof) and module prices, as shown hereafter.

What is important for societal needs is to know whether PV systems in regions of moderate insolation are producing energy at a net energy gain or loss. In the latter case the depletion of fossil resources is accelerated by state subsidies for solar electricity generation.

2. Methodology used for the ERoEI extended ($ERoEI_{EXT}$)

Raugei et al. claim that our methodology of the extended ERoEI ($ERoEI_{EXT}$) "…. *shifts the goal of the analysis from the (comparative) assessment ….to the assessment of the ability of the analysed system to support the entire societal demand for the type of energy carrier it produces..* and *makes inappropriate comparisons"*. This claim is incorrect.

The goal of our analysis is the determination of $ERoEI_{EXT}$ for calculating the quotient: Energy Return on Energy Invested, considering thereby all energy contributions to both numerator and denominator. Therefore, there is no shift in the goal of the analysis. No energy input should *a priori* be excluded. We have considered additional energy contributions that are excluded from the "mainstream" analysis, which follows the recommendations of the IEA. The IEA guidelines reflect rather the position of the PV industry and offer false and misleading results through erroneous calculation of the energy invested and do not provide a comprehensive examination of the value of PV to our society. As a consequence, the societal benefits of PV turn out to be wrongfully amplified.

The concept of $ERoEI_{EXT}$ applied specifically to photovoltaic systems has been treated in two books. The first one is entitled “Spain's Photovoltaic Revolution – The Energy Return on Investment “ (Prieto and Hall, 2013) and the second one “Energy in Australia - Peak Oil, Solar Power, and Asia's Economic Growth“ (Palmer, 2014). In addition, the investigations performed by Weissbach in Germany (Weissbach et al., 2013) include some energy contributions in the $ERoEI_{EXT}$.

Therefore, the concept of $ERoEI_{EXT}$ is not new and is quite independent of the standardized method used in the LCA. The main question should be to know whether the photovoltaic energy for regions of moderate insolation like Switzerland and Germany is a net energy source or a net energy sink and how much it contributes to human welfare. Where is our energy going to come from as we rely less on fossil fuel? What operating energy systems are replaced by the new energy sources? This is a task for ERoEI researchers and not for Life Cycle analysts, who often confine themselves within unrealistic boundaries.

Furthermore, we should like to add that energy contributions due to labour and servicing the capital (not the capital itself) are already considered in standard analyses of the cumulative energy demand in the building industry. The financial interest that society demands for servicing the principal sum of a loan represents additional capital, which flows from the activity for which its principal is used and which is paid to the lender. This additional capital has its equivalent in an amount of energy. The engineers involved in such analyses in the civil construction sector are probably unaware of any IEA guidelines, but apply common sense in considering labour and servicing the capital. The fact that Raugei et al. entirely disregard such contributions indicates the narrowness of their boundary conditions and their reluctance to seriously deal with subjects outside the strict IEA fence.

Our study has demonstrated that important contributions were previously not accounted for in most of the published literature on PV systems. The breakdown and the details of our methodology ($ERoEI_{EXT}$) are given in our original paper (Ferroni and Hopkirk, 2016) under chapter 4.

Because of the different methodologies, it is necessary before comparing our results with those of other analyses to first consider the details of the system boundaries and the climatic conditions. As we shall see, the "mainstream" methodology considers only about 30–50% of the total invested energy and this is an important source of misconceptions and errors.

Since the concept of the extended ERoEI can be applied to other methods of energy conversion, we recommend such analyses be performed with current electrical generation methods in order to understand the consequences of selecting specific techniques and their influences on the net energy provided to society.

Furthermore, we base our data regarding the energy return and the energy invested on the actual state of the art of photovoltaics, anticipating that in the near or medium term future only incremental or purely technical improvements may be expected from industrial systems for large-scale deployment. We discard non-validated projections into the future.

The claim by Raugei et al. that we present *"inappropriate comparisons"* is therefore unjustified.

3. Energy return of photovoltaic systems in regions of moderate insolation

The "comprehensive response" by Raugei et al. states that for Switzerland the cumulative electrical output is significantly higher than the one considered by us (2827 versus our 2203 kWh_e/m^2) assuming a yearly output of 120 kWh_e/m^2, a performance degradation of 0.5%, a downtime of 0% and a lifetime of 25 years.

The details of the calculations are omitted in our original paper. It is clear that the official Swiss energy statistics indicate only the installed capacity (kW_p) at the end of each year and the electricity production (kWh_e). To transform these values into functions of the module surface we have to distinguish between the value indicated by a module supplier and what is used in the real planning of PV systems. Modules are sold on the basis of money per peak Watt, which is understood to come from a reference sunlight intensity level of 1 kW/m^2. For a conversion efficiency of 20% for example the required area would be 5 m^2. But efficiency is measured at a standard cell temperature of 25 °C, an air mass of 1.5 and the vertical incidence of radiation from a flash lamp, that cannot simulate precisely solar radiation at the earth's surface. The ideal orientation, however, is rarely found in the field. In addition, many factors like snow reduce the efficiency (see paragraph 2 of our original paper). In reality, other values are used in planning: In Germany a value of 10 m^2 per kW_p is generally applied. In our published paper, we have made an average for Switzerland over the previous 10 years and have used a value of 8.2 m^2 per kW_p to determine the electricity production. This value is based on earlier projects realized in Switzerland. Such projects were planned and built on the basis of 8–9 m^2 per kW_p. On page 9 of their brochure for 2014, "Solarstrom unerschöpfliche Energie 03/2013", Swissolar, the Swiss Association of Solar Energy, still recommended (Swissolar, 2013) planning PV plants with similar values.

Our figure for yearly output was a conservative value of 106 kWh_e/m^2 at the start of operation. Hence, there is no double counting as claimed by Raugei et al. In effect, it was deemed reasonable to simplify the calculation by stating that the modules are "*relatively new*". In fact, 80% of the PV capacity has been installed in the years 2012, 2013 and 2014 (we had not considered the year 2015, since our paper was submitted only in 2015) and therefore the older PV plants have not contributed significantly to the final result. The average age of the modules is in fact between 1.5 and 2 years, which would give an error of about 2%. In our conclusion, we have stated that the error of our analysis is ± 15%.

To put our numbers in perspective, let us consider the statistical PV data from Germany as given in Table 1. The methodology for the calculation of the average electricity production as a function of the peak power is indicated:

Table 1
Statistical PV data from Germany.

Year	Capacity installed at end of year MW_p	Electricity produced during the year MWh	Average capacity at mid-year MW_p	MWh divided by Average capacity MW_p
2012	32’700	26’380’000		
2013	36’010	31’010’000	34’355	903
2014	38’240	34’930’000	37’125	941

The annual values of 903 or 941 (average 922) have the units of kWh_e/kW_p. To transform the value in function of the module surface we have to divide by 10 m^2/kW_p. The result is 92,2 kWh_e/m^2 and gives the average annual electricity production valid for Germany. For Switzerland, this value needs to be increased, using the ratio of the thermal heat performances to determine the relative insolation between Switzerland and Germany, which is 1.08. The result for Switzerland then becomes 100 kWh_e/m^2. We consider our value of 106 kWh_e/m^2 at the start of operation as conservative in the application of our analysis.

Utilities and governmental agencies in favour of the energy transition are reluctant to provide all electricity production data per square meter, apparently in order to avoid revealing their poor results. The first author of the present paper has submitted a legal complaint to a Swiss court against a utility, by stating that the annual average electricity production is only approximately 100 kWh_e/m^2. This value could not be disputed by the utility.

The average value assumed by Raugei et al. of 120 kWh_e/m^2 for Switzerland is based on a ten-year linear regression model and this is highly questionable.

Raugei et al. make reference to an unsupported claim (Fraunhofer ISE, 2016, page 6) that in the last 10 years, the efficiency of average commercial wafer-based silicon modules increased from about 12–17%. Our verification of this reference shows no evidence for supporting the above statement. On the contrary, one finds on page 25 of the same document (Fraunhofer ISE, 2016) a figure showing the Development of Laboratory Solar Cell Efficiencies, whereby there appears to be practically no increase in the efficiencies during the last 15 years, a fact which contrasts strongly and strangely with the increase in efficiency of 40% (i.e. from 12 to 17 per cent in absolute terms) cited on page 6 of this document.

Furthermore, Kurtz and Emery (2016) have presented figures relating to the progress of cell efficiencies from 40 years ago up to the present, which show clearly that since 1995 no significant efficiency improvement in mono- or multi-crystalline silicon PV cells has indeed taken place.

Raugei et al. show clearly in the Table 1 of their paper (Raugei et al., 2017) that for Swiss conditions between 2005 and 2015 (Swiss Federal Office of Energy Bundesamt für Energie-BFE, 2016) the average specific yield remained practically constant during that period, varying according to weather conditions. An improvement of 40% in module efficiency would have increased the average specific yield also by close to 40% considering that almost 70% of the installed capacity was added in the last three years.

In the same Table, Raugei et al. then calculate the weighted average efficiency of installed PV capacity per year to have increased by about 33%, from 12% in 2005 to 16% in 2015. Yet again, the data provided in Table 1 does not show a respective increase in the average specific yield over the same period of time. The value remains almost the same.

Now, still in their Table 1, Raugei et al. use their calculated weighted average efficiencies to determine the total PV surface area in Switzerland and thereafter the specific yield per surface area. Thus, we see that neither of the data sets can be corroborated by measurements, but are merely based upon the unsupported claims for an efficiency increase by 40% (Fraunhofer) or 33% (Raugei et al., 2017) respectively.

The graphical presentation in Figure 1 of the same paper (Raugei et al., 2017) then shows the calculated specific yield per surface area and year in Switzerland, for the years 2005–2015 (Note that the legend in Figure 1 is wrong). The associated linear regression line obviously does not correspond to the reality, as observed in the field, since it is in stark contrast to the values of the corresponding Table 1 reported for the average specific yield (kWh_e/kW_p) between 2005 and 2015. Therefore, the value of 120 kWh/m2 represents only an unsupported claim.

Similarly, the two new references (Leccisi et al., 2016; Hou et al., 2016) also rely on assumed efficiencies, 16% and 17% respectively, unproved by measurements in the field at large scale.

In addition, Raugei et al. assume a mean degradation rate of 0.5% per year. According to a recent article (Jordan et al., 2016) this figure of 0.5% refers to a limited group of better quality crystalline silicon modules (1936 data points). The mean value for all module data collected (9977 data points) is 0.9–1.0% per year. The long tail of the degradation spectrum shown in the report beyond one percent annually up to 5% per year is likely driven by equipment issues caused by poor quality manufacturing, materials or product design. It is incorrect to select only the best 20% of the modules, whilst neglecting the 80% majority of the data points. For this reason, we used the value of the all module data. Note that these values refer to the modules only and are measured on the dc-side. Our value given as "*performance degradation*" of 1% accounts additionally for the module degradation and furthermore, for the degradation of the balance of plant. This is measured on the ac-side. Although it is difficult to quantify in detail, it includes nevertheless increased cable termination resistance and increased mismatch due to uneven module degradation. This gives rise to an additional degradation of 0.1%. We judge the value of 0.5% per year not justified and our figure of 1% as realistic.

Raugei et al. refer to a conference paper by Chianese et al. (2003) indicating a degradation value of 0.2% per year for Swiss conditions. The authors clearly state: "*however, such a result does not allow to determine the modules long-term stability, due to changes in the measurement system during 20 years*". In addition, nearly 13% of the modules did not reach 20 years of lifetime and were completely neglected when determining the degradation of all modules. Therefore, the calculated values cannot be used. Note that this refers to a single type of module, no longer available on the market.

Raugei et al. also make reference to the paper "Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development" (Louwen et al., 2016) in support of the thesis of the steady increase in PV efficiencies. This Nature Communication refers to global theoretical considerations. We have stressed that our paper is based on regions of moderate insolation like Switzerland and Germany. Furthermore, this new reference is not based on actual measurement of electricity production per unit of module surface and therefore is not applicable to our study.

Raugei et al. assume an astonishing 0% operational downtime for the whole lifetime of 25 years without offering any references. Our value of 5% is based on the study by Huang et al. (2011) "Performance and Availability Analysis of PV Generation Systems in Taiwan" (Huang et al., 2011). The data of these authors are derived from the IEA (International Energy Agency) – team Task 2, that studied the operational performance in countries like Switzerland, Germany, Japan and Italy and is based only on high quality PV plants. As we explained, Raugei et al. wrongfully interpreted our specific yield per surface area of 106 kWh_e/m^2 as an average over the first ten years instead of being our value at the start of operation. However, the assumption of 0% operational downtime ignores the fundamentals of reliability engineering such as the so-called bathtub curve of failure rates, showing that the failure rates at the end of the lifetime exhibit a sharp increase.

The lifetime adopted in our original study is not challenged by Raugei et al. However, we should like to reiterate the statement: Based on the experience of the huge quantity of modules already dismantled, we consider the value of 25 years as optimistic.

Finally, no evidence is available to add credence to the value of the lifetime energy return of 2827 kWh_e/m^2 as given by Raugei et al. Our value of 2203 kWh_e/m^2 is coherent with the data from Switzerland and Germany.

4. Energy demand/invested for the material

In our paper (2016) we have worked with the value of 1300 kWh_e/m^2 as a cumulative energy demand (CED) for the manufacturing of a PV system having 2/3 as roof-mounted and 1/3 as free-field installed units. This does not refer to the actual situation of PV systems in Switzerland as partially outlined by Hüsser in his IEA national survey report (2016), but envisages a future situation with no base load power plants such as nuclear power plants. Solar and wind power generators are supposed to substitute the electricity produced by base load power plants. Raugei et al. (2017) claim that the actual CED is 290 kWh_e/m^2, referring to three recent publications.

The first publication (Görig and Breyer, 2016) reproduces their presentation at the 27th European Photovoltaic Solar Energy Conference which took place four years before the publication (24th–28th September 2012). The work in question is based on the idealistic assumption that the learning curve will cause a sharp decrease in the CED. In the above paper, not even the energy required due to the thermodynamic properties of the many substances involved in the fabrication of a PV system is considered. In addition, the paper refers to older work of M. de Wild-Scholten from 2006 to 2011 and to the methodology as recommended by the IEA-PVPS T12 (IEA-PVPS T12, 2011) report. We shall analyse below both of these references.

The second publication (Leccisi et al., 2016) simply makes reference to an analysis using non-validated life cycle inventory data (Frischknecht et al., 2015) and is based on the IEA methodology, which as explained in detail in Chapter 4 of our original publication (2016) is a frequent source of errors.

The above-stated method is derived from the report IEA – PVPS Task 12 report. It is based on the energy invested as primary energy compared to a theoretical displacement of fossil energy expressed itself as primary energy.

The theoretical conversion of secondary back to primary energy can give very different results depending on the protocol used and it can be a major source of errors. The paper (Giampietro and Sorman, 2013) outlines the main differences between the British Petroleum (BP) statistics protocol (used by the Energy Information Administration of the US and by the majority of energy analysts) and the IEA statistics protocol. As an example, on one hand, according to the BP protocol, in order to convert 1 kWh_e of hydroelectric energy, a secondary energy, into primary energy it is necessary to multiply by 2.65. I.e. 1 kWh_e secondary corresponds to 2.65 kWh primary energy. On the other hand, according to the IEA statistics protocol, to convert 1 unit of secondary hydroelectric energy into primary energy, it is necessary to multiply by 1. I.e. 1 kWh_e converts to 1 kWh of primary energy.

Concerning the work of M. de Wild-Scholten, it follows from her more recent paper (de Wild-Scholten, 2013) that the CED for a roof-mounted PV system, expressed as secondary energy, is 1204 kWh_e/m^2 (value from 2013), which is in line with our value of 1300 kWh_e/m^2. This value differs greatly from the CED of 290 kWh_e/m^2 quoted by Raugei et al. (2017), which is not substantiated by measured values from a module manufacturing plant or solar silicon producer and is very far from reality.

The third publication "Life cycle assessment of grid-connected power generation from crystalline silicon solar modules in China" (Hou et al., 2016) for multi-crystalline modules applies system boundaries currently used in LCA-analysis but not the system boundaries required for an $ERoEI_{EXT}$ analysis in order to calculate the benefits to society from a given energy source. The method used by Hou is called Process-Based Life Cycle Assessment.

Many energy contributions have obviously been excluded from the above calculation by Hou et al. (2016). Hou et al. considered only electricity but no other sources of energy outside the perimeter of manufacturing plants for metallurgical grade silicon, for solar grade silicon, for solar cells and PV modules. Not considered are materials or consumables: coal and lignite necessary for the reduction of quartz, principally fossil fuel for glass and aluminium production, the embodied energy of all materials such as metals, acid or basic chemicals, gases, cleaning agents, plastics and consumable materials like pure silicon carbide for the cell slicing, nitrogen, argon and compressed air. Hou et al. have also not considered transport of materials to the manufacturing plants as well as transport of conditioned solid wastes to a final repository. Note that modules are according to paragraph 3.1 of our original paper (2016) material-intensive and by consequence transport-intensive and transport of material needs to be considered.

Another recent article "A hybrid life-cycle inventory for multi-crystalline silicon PV module manufacturing in China" (Yao et al., 2014) presents a completely different picture of the cumulative energy demand for the manufacturing of a PV module. Note that the study considers a wafer thickness of 200 µm. In our calculations, we have assumed 300 µm thickness, concurring that the trend is towards 200 µm. However, this does not significantly change the cumulative energy demand as the result from Yao et al. (2014) indicates. The claim by Raugei et al. (2017) that reducing thickness and weight of a wafer will linearly reduce the CED cannot be accepted because no reference whatsoever is given to corroborate such a claim.

The input-output based hybrid method is widely regarded as the most appropriate approach to calculate the embodied energy in a complete manner, especially when reliable data are not openly available for many industrial sectors. This method is applied normally in the civil construction field. It was further developed by Treloar (1998), Crawford (2004) and Acquaye (2010).

The study of Yao et al. (2014) presents a hybrid life-cycle inventory (LCI) of Chinese multi-crystalline silicon PV modules. This hybrid LCI approach combines process-based LCI data for module and poly-silicon manufacturing plants with a 2007 China Input-Output - LCI model for production of raw material and fuel inputs to estimate the "cradle to gate" primary energy use.

Yao et al. (2014) separately outline the requirements for electricity at the PV module plant as well as the embodied primary energy for materials for the production of multi-crystalline silicon PV modules. These data have been collected at major PV module manufacturing plants in China, representing average Chinese industrial practice. Converting the values given in Table 2 of the paper by Yao et al. (2014) into secondary energy, through application of the BP-protocol, yields the value of 1180 kWh_e/m^2. According to Table 2, this value does not include the embodied energy for the supports and for the balance of plant equipment. In addition, the energy for the Czochralski process to obtain monocrystalline silicon is not considered at all because the focus of Yao et al. (2014) is only on multi-crystalline silicon. Therefore, a much higher estimation than our value of 1300 kWh_e/m^2 will result. Considering all supports, the balance of plant equipment and assuming that 50% of the multicrystalline material is refined to monocrystalline silicon a value of 1335 kWh_e/m^2 is obtained.

The methodology for the $ERoEI_{EXT}$ requires considering all relevant energy contributions as we have done in our published paper (2016), and as was largely the case in the recent paper by Yao et al. (2014). This requirement is not met in the references indicated by Raugei et al. (2017), which cannot be used to determine the $ERoEI_{EXT}$.

5. Energy demand for the integration of the intermittent PV-electricity into the existing grid

Solar generated electricity in regions of moderate insolation offers an extremely low yearly capacity factor of 9% or of 3% during the winter period instead of a range of 65–85% for other high-density energy sources such as fossil or nuclear power plants. The solar electricity supply does not align in general with the demand profile, and is stochastic, volatile, intermittent and non-dispatchable.

The control of the grid frequency within a certain range at high intermittent electricity penetration, is a highly complex task involving grid, storage, balancing, balancing reserve and curtailment. In our study, we have estimated the energy contributions for each of the above tasks with the exception of the curtailment.

That the integration of the intermittent PV-electricity into the existing grid is not only a question of storage, is shown in the following examples illustrating what happened in Germany. The Federal Republic of Germany has a level of intermittent electricity penetration (solar PV and wind) of about 18% of the electricity consumed, with about 40 GW of capacity for solar, and 46 GW for wind. During the summer working weeks, the capacity needed is about 70–80 GW, but the required capacity during the weekend can drop to 50–60 GW. The electrical distribution system is not yet in a position to master such a situation involving excess intermittent electricity, as has been evidenced by the continual rise in the number of redispatch interventions recorded by the Bundesnetzagentur (German Federal Network Agency) in Germany between 2010 and 2015 (Bundesnetzagentur, 2016). Therefore, the operator of the electrical network had to sell or dump during the second weekend of May 2016 the excess energy outside Germany paying in total 21.3 Million € or 0.06 € per kWh to a receiver for such an intermittent supply. According to a study by Energy Brainpool (2014), the German energy market experienced 97 h of negative electricity prices during the year 2014 – these 97 h costing about 90 Million €. In the year 2022 negative electricity prices are expected during 1200 h, since lignite or coal plants cannot be stopped for just a few hours a day during excess electricity supply from wind or photovoltaic power generation. German grid companies have reacted to the negative prices by asking wind turbine owners to curtail their electricity production, paying them up to 90% of the administered feed-in tariffs on their potential production (in 2015 this amounted to about 485 Million €). This means that in the event of excessive electricity supply, the consumer has to pay for generating energy and later on for annihilating it. To earn such an amount of money for a consumer implies a considerable additional use of energy that should be accounted for when calculating the $ERoEI_{EXT}$. This situation will become worse in future due to additional installation of PV and wind systems.

In our publication (Ferroni and Hopkirk, 2016) a scenario was developed in which approximately 25% of the produced solar electricity needs to be used for storage. The excess energy needs to be shifted either seasonally from summer to winter or on a daily/weekly basis. The tendency is to select pumped-storage hydroelectric systems for seasonal shifting and batteries, that have lower efficiencies, for shifting on a daily/weekly basis. The need to shift about 25% of the total photovoltaic production output is due to the fact that solar energy production in regions of moderate insolation like Switzerland or Germany during winter is only about 30% of the yearly total depending on weather conditions, but the consumption of electricity during the winter period is 20–25% higher with respect to the summer period. The ratio of the two storage facilities – pumped-storage or batteries - is not important for our calculation since we have assumed the higher efficiencies and we are not considering servicing the huge capital for the storage.

According to the study by the BFE (Swiss Federal Office for Energy) on storage facilities up to the year 2050 (BFE - Energiespeicherung in der Schweiz, 2013) the energy demand for storage after shutdown of the base load nuclear power plant, the objective of the energy transition, is also about 25% of the Swiss electricity consumption.

It was not the objective of our study to analyse the effects of the intermittency or volatility of renewable energy. We do not agree with the references given by Raugei et al. regarding storage/buffering. We do concur however, with the results of the new calculation by Sinn (2016). The main conclusion of this study is that without a massive investment in the construction of hydroelectric pumped- storages it will not be possible to have a share of anywhere near 100% of usable wind and solar power in the gross total electric power consumption. About 6400 pumped-storage plants would be needed in Germany, whereas at present the Federal Republic has only 35 such plants. The argumentation by Sinn (2016) above explains how it would be essential to use a portion of the solar-generated electricity for storage schemes due to the fact that the load-following capacity of solar energy is practically nil.

The estimated value of 25% for this is reasonable in order to create a PV system offering a realistic source of energy capable of replacing fossil or nuclear sources and is supported by the conclusion of the report on storage for Switzerland (BFE - Energiespeicherung in der Schweiz, 2013).

In addition, the cost due to a blackout in a region with high intermittent electricity penetration of about 50% such as happened in 2016 in South Australia (Australian Energy Market Operator: Preliminary Report, Blackout System Event in South Australia on 28 September, 2016), estimated at AUD 367 million (Heard et al., 2017), should also be considered.

6. Energy demand for labour

The standard ISO 14040 (ISO 0, 1404, 2006) does not require considering the labour. The authors (Ferroni and Hopkirk, 2016) are aware of this, but heavily disagree. We have provided proof that PV electricity is labour intensive and this must be accounted for. This is also underlined by the supporters (EPIA-Job Creation, 2012) of the energy transition towards a mixture of various renewable energy types. Therefore, it has to be considered as indicated in a general study on the embodied energy calculation regarding method and guidelines for a building and its constituent material (Dixit, 2013) and also by the European Committee for the Standardisation (CEN) from Technical Committee 350 “Sustainability of Construction Works”. In the Briefing Paper – Assessing the environmental impacts of construction - understanding European Standards and their implication (Briefing Paper, 2013) giving a summary of all applicable European standards, under Figure 3 it is clearly stated that for the *Life cycle stages – product, construction, use stage and end-of -life*, it is mandatory for a cradle to grave analysis to consider what we have defined in other terminology as energy invested for the labour (paragraph 5.3.2 of our original study).

Labour required for the manufacturing of modules, support and balance of plant equipment has not been taken into account in our study since their contribution to CED is negligible and, if relevant, should have been included in the life cycle stage we named “Manufacturing” or, according to the European standard terminology, “Product”. Our analysis considers the labour necessary after the manufacturing – that is to say: for installation, operation, maintenance and decommissioning or according to the European standard terminology “Construction, Use Stage and End-of-life". Therefore, no double counting as claimed by Raugei et al. has been incurred. The energy component of labour is calculated using the energy intensity for Switzerland expressed as a source of secondary energy including, of course, the energy imported from abroad. It should be clear that direct wages are only a portion of the energy demand for labour and therefore we have used the energy intensity of the charge rates used by the companies involved in the life cycle following manufacturing. Since PV electricity is also material-intensive this has an impact on the transport energy consumed. As already known, prices in Switzerland, including wages, are high, but energy intensity is low (paragraph 5.3.1 of our original study).

7. Energy demand for servicing the capital

It is important, when reading the present clarification, to avoid misunderstandings by distinguishing clearly between capital and servicing of capital. The energy contribution for the capital necessary for manufacturing is already included in the CED of the PV system. This corresponds to the life cycle stage called “Manufacturing”. In our published study (Chapter 5.3.3) the question of servicing the capital means essentially the payment of the total interest on the borrowed capital. It is also important to note that nearly all the investment for the PV system is an upfront energy debt, but the ERoEI is calculated over a 25-year life, a rather low lifetime in comparison with conventional electricity generating systems, and the PV electricity generation consequently is a capital-intensive debt investment. Therefore, it is necessary to include the energy contribution for servicing the required capital.

For the calculated case, an average interest rate of 5% is to be paid over an assumed amortization period of 25 years. Using the constant annuity approach and deducting 4% for amortization – that is to say 100 divided by the 25 years of lifetime, the annual figure of 3.1% of the total capital is required. Now, applying the energy intensity as determined in paragraph 5.3.1 of our published study (2016) one obtains the energy demand for the amount necessary for servicing the capital. The energy demand for the capital, i.e. the price for production of the PV system and the labour are already included under the heading of "Energy demand/invested for materials and labour". Thus no “double counting” error is incurred. This further clarification explains the differences – apparently not yet clear to Raugei et al. – between capital and servicing the capital. Regarding the value used for the capital costs of a PV system see below (Chapter 8).

Note that in our paper we have neglected the energy demand for servicing the capital for the integration of the intermittent PV-electricity into the grid. We judge our estimation for the energy invested in relation to the capital servicing to be very conservative.

8. Other arguments of the “comprehensive response”

Our published study has compared the material, labour and capital intensity of solar electricity to that of nuclear in order to quantify the differences between a very low power density source to one of high density. However, the results of the study referring to nuclear power plants have no influence on our central point, the $\mathrm{ERoEI_{EXT}}$ of solar electricity. Therefore, as indicated earlier, we are not discussing the comments of Raugei et al. regarding nuclear plants.

Raugei et al. have criticized our estimated cost of 6000 CHF/$\mathrm{kW_p}$ for an installed PV plant in Switzerland assuming 2/3 as roof-mounted and 1/3 as free-field-mounted. This value is in fact cited in the Swissolar brochure for the year 2014 on page 9 (Swissolar, 2013), indicating a range between 5000 and 7000 CHF/$\mathrm{kW_p}$. However, their estimate is valid only for roof-mounted PV-systems. Free-field PV systems may involve additional costs, as explained in the book of Prieto and Hall (2013).

Raugei et al. indicate, based on Table 9 of Hüsser's Survey Report for the IEA (Hüsser, 2016), an average price of 2800 CHF/$\mathrm{kW_p}$ or 475 CHF/$\mathrm{m^2}$ for roof-mounted PV-systems. However, this price is given without any supporting references but "based on offers…". Therefore, we cannot comment.

In their paper Raugei et al. proceed erroneously to use only the so-called "soft costs" of 800–1500 CHF/$\mathrm{kW_p}$ from the same IEA study (Hüsser, Table 9, 2016) thereby completely ignoring the fundamental difference between servicing the capital and the capital itself (see above).

Moreover, we cannot comment on the very low prices referenced in the brochure edited by Fraunhofer/ISE (2015) and based on data from BSW (Bundesverband Solarwirtschaft), a German association similar to Swissolar in Switzerland. According to their website BSW collects data from selected companies active in PV installation through surveys. Therefore, we are unable to verify the validity of the data from the providing companies whose reluctance to give out their proprietary data is an undisputable fact. Unfortunately, we are not aware of any data emanating from consumer organizations to cross-reference the provided numbers.

As shown in our introduction the Energy Transition (Energiewende) is very expensive, despite the very low prices of installed PV systems indicated for Germany. The present situation of the photovoltaic industry is characterized in general by a very high manufacturing overcapacity, module price dumping and, for most solar companies, negative net income. This has caused bankruptcy, insolvency, closure or acquisition of more than 100 companies (Greentech Media, 2015). This means that the current low module prices cannot cover costs, at least for the many companies that went into bankruptcy. Therefore, the capital destruction of the companies listed above should be added to the cost of the PV systems, thus involving additional invested energy. Similarly, the prices indicated by Fraunhofer/ISE (2015), simply cannot cover the total cost and more bankruptcies are expected.

Furthermore, one needs to bear in mind that the purchase prices of modules themselves are only a small factor and do not reflect the total energy invested. It is revealing to have, for instance, a closer look at the cost of the energy required for the manufacturing of the modules in China. According to Table 2 of the paper by Yao et al. (2014) it is possible to calculate, by using the correct conversion protocol, the quantity of coal needed per square meter of module (361 kg of coal) and also the cost, namely only 22 CHF/ m^2 module at the present cost of coal in China.

The total cost of the PV systems as part of the energy invested is only relevant for the energy demand for servicing the capital as explained in chapter 7.

We checked in our original paper (2016, chapter 5.3.2) the person-hours for installation and maintenance and multiplied it by Swiss hourly rates charged by the specialized companies engaged in this business.

9. Concluding remarks

Our methodology applied for the calculation of the Energy Return on Energy Invested called extended ERoEI ($\text{ERoEI}_{\text{EXT}}$) addresses the possible benefits or otherwise of photovoltaic generation to society. We show that the standardised methodology generally used for Life Cycle Assessment (LCA) of PV systems is inadequate for determining with due diligence the benefits to society of such systems in regions of moderate insolation like Switzerland and Germany. We are faced with this situation because important contributions to the energy invested in a PV plant are excluded in the LCA-analysis such as:

a) the energy invested in the labour for installation, operation, maintenance and decommissioning,
b) the energy necessary for the integration of an intermittent and stochastic electricity source into a wider electricity grid – as distinct from a non-intermittent, “dispatchable” energy source as needed by society, and
c) the energy invested for servicing the interest on the capital required.

The $\text{ERoEI}_{\text{EXT}}$ - methodology is similar to the methodology applied in the civil construction sector and reflects the concerns of economists like Paul L. Joskow of the Massachusetts Institute of Technology in the article “Comparing the Costs of Intermittent and Dispatchable Electricity Generating Technologies“ (Joskow, 2011). The paper by Joskow demonstrates that the approach normally utilized in the calculation of the energy cost named “levelized cost” is inappropriate for comparing intermittent generating technologies like wind and solar with dispatchable generating technologies like fossil or nuclear power plant. Levelized cost comparisons are misleading for comparing intermittent and dispatchable generating technologies because they fail to take into account important differences in their production profiles and the associated large variations in the market value of the electricity they supply. Levelized cost comparisons overvalue the importance of intermittent generating technologies compared to dispatchable base load generating technologies. Taking into account the differences in production profiles, the associated variations in the market value of the electricity supplied and the life-cycle costs associated with different generating technologies, it is necessary to establish realistic comparisons between them. The $\text{ERoEI}_{\text{EXT}}$ defined in our published paper (2016) considers the most relevant intermittent properties of PV electricity.

We have seen in Chapter 7 that the “*double counting*” errors as claimed by Raugei et al. (2017) do not in fact exist. We consider our calculation of the energy return in regions of moderate insolation as realistic and prudent. If the goal is to reach 100% substitution of fossil and nuclear fuels by renewable energies, then the energy invested for the storage/buffering could be much higher than our estimation, since the alternative storage concepts have lower efficiencies than the water pumped-storage concept. Countries having at present a penetration of intermittent electricity (wind and solar) higher than 15–20% of the total electricity generation have also much higher electricity prices. Furthermore, their grid reliability and stability are prone to fluctuations and thus more difficult to maintain. In other words, an energy system with 100% renewable generation is from an energetic point of view not feasible.

Our data for the cumulative energy demand (CED) for the manufacturing of PV-systems have been confirmed by a recent publication by Yao et al. (2014) based on the experience of plant operation for the production of solar silicon and modules in China. Improvements cannot be excluded, but we are not considering technologies at laboratory or prototype stage. Contrary to our value of 1300 kWh_e/m^2, the value indicated by Raugei et al. of 290 $\text{kWh}_e/\ \text{m}^2$ does not include all important energy contributions. Furthermore, we should like to add that the data banks used for the Life Cycle inventory have not been validated. It is well known how difficult it is to collect data from manufacturers, since information concerning energy requirements in production and the material quality is usually treated as proprietary.

The conclusions of our study, following the response of Raugei et al. remain unchanged. These are valid for regions of moderate insolation. Any attempt to adopt an Energy Transition strategy by substitution of intermittent for base load power generation in countries like Switzerland or further North will result in an unavoidable Net Energy Loss. This implies a severe depletion of resources. However, continued research and development should be encouraged.

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