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

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ABSTRACT

A recent paper by Ferroni and Hopkirk (2016) asserts that the ERoEI (also referred to as EROI) of photovoltaic (PV) systems is so low that they actually act as net energy sinks, rather than delivering energy to society. Such claim, if accurate, would call into question many energy investment decisions. In the same paper, a comparison is also drawn between PV and nuclear electricity. We have carefully analysed this paper, and found methodological inconsistencies and calculation errors that, in combination, render its conclusions not scientifically sound. Ferroni and Hopkirk adopt 'extended' boundaries for their analysis of PV without acknowledging that such choice of boundaries makes their results incompatible with those for all other technologies that have been analysed using more conventional boundaries, including nuclear energy with which the authors engage in multiple inconsistent comparisons. In addition, they use out-dated information, make invalid assumptions on PV specifications and other key parameters, and conduct calculation errors, including double counting. We herein provide revised EROI calculations for PV electricity in Switzerland, adopting both conventional and 'extended' system boundaries, to contrast with their results, which points to an order-of-magnitude underestimate of the EROI of PV in Switzerland by Ferroni and Hopkirk.

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1. Introduction

Net energy analysis, whose principal metric is the Energy Return on Energy Invested (ERoEI), hereinafter referred to by the alternative and more common acronym EROI, provides an insightful approach to comparing alternative energy options (Carbajales-Dale et al., 2014), especially if used alongside other complementary methods (Raugei et al., 2016; Raugei and Leccisi, 2016; Leccisi et al., 2016; Jones et al., 2017). Getting the numbers right in public discourse when discussing alternative energy systems is extremely important (Koomey et al., 2002), as distorted facts can lead to erroneous energy policy decisions that can have long-term impacts (Davis et al., 2010). In spite of the simple nature of the EROI formula as the ratio of the energy 'returned' by a system to the energy 'invested' to deliver that return, there are many possible methodological and numerical caveats that may lead to major divergences in the calculated EROI values for even the same technology (Carbajales-Dale et al., 2015). Indeed, there is a long history of methodological problems within the net energy literature dating back (at least) to a series of conferences in the mid-1970s (Connolly and Spraul, 1975; IFIAS, 1978), which were held in large part to discuss how to conduct net energy analysis properly.

We provide a further contribution to this discussion by offering a comprehensive response to an article by Ferroni and Hopkirk (2016) recently published in Energy Policy. We focus on three key aspects of that paper:

- *Inappropriate comparisons* of results from their 'extended' system boundary analysis to those of other differently bounded analyses of conventional energy systems;
- *Utilization of incorrect data* (either because it is out-date or simply wrong) for determination of PV system parameters (including annual electricity yield)
- *Several incidents of double-counting* energy contributions (e.g., adding contributions that are already included in the embodied energy of materials).

2. Extending the EROI boundaries – how, whither and wherefore?

Net energy analyses may be conducted using a variety of boundaries and assumptions, all of which, in principle at least, may be considered valid. In general terms, it is well established that the wider the boundaries of the analysis, the lower the resulting EROI values (Mulder and Hagens, 2008; Hall et al., 2009, 2014; Dale et al., 2011; Murphy et al., 2011; Brandt and Dale, 2011; Brandt, 2011; Brandt et al., 2013; Raugei and Leccisi, 2016). Nonetheless, opting for wider boundaries can produce meaningful results, as doing so allows the inclusion of more of the indirect and often 'hidden' energy costs that contribute to reducing the ultimate 'net' energy return available to the end user. At the same time, though, it is crucial to recognize that extending the EROI boundaries beyond the inclusion of the physical inputs required for the production and operation of one unit of energy output from the analysed energy system also gradually shifts the goal of the analysis from the (comparative) assessment of its intrinsic net energy performance (*vs*. that of a similar functional unit of alternative technologies), to the assessment of the ability of the analysed system to support the entire societal demand for the type of energy carrier it produces, or sometimes even for all forms of net energy (Carbajales-Dale et al., 2015).

In order to avoid confusion and remain meaningful for energy policy, EROI calculations should therefore always be associated with an explicit objective. For example, are they conducted to inform a choice between renewable energy options? Are they conducted to assess the rate of decline in net energy availability from a given fossil fuel operation? Do they examine a marginal addition to the existing fossil-dominated energy system or a complete substitution of it by the studied technology?

In their paper, Ferroni and Hopkirk adopt 'extended' boundaries but fail to explicitly state a goal for their analysis. They also make repeated direct and indirect comparisons between PV and nuclear electricity without adjusting the analysis to ensure consistent boundaries. For example, they add an unreasonably extended storage requirement to PV but not to nuclear, ignoring that PV primarily serves peak loads while nuclear only serves base loads and both of them (not only PV) would require storage in order to satisfy total demand loads. This is problematic because the way in which the analyses are presented to the reader implies that any differences in the reported EROIs are due to data inputs – i.e., something inherent to the technologies or resources under investigation – and not an artefact emerging from methodological inconsistences between the studies being compared. The latter is actually the case here.

Along those same lines, Ferroni and Hopkirk's adoption of 'extended' boundaries makes their analysis inconsistent with (and therefore not directly comparable to) not only the recommendations provided by the International Energy Agency on the life cycle assessment and net energy analysis of PV systems (Frischknecht et al., 2016; Raugei et al., 2016), but also, critically, the vast majority of the previously published literature analysing the EROI of PVs (see review article by Bhandari et al. (2015)) as well as of virtually all other energy technologies, (e.g., Kubiszewski et al., 2010; Freise, 2011; Hu et al., 2013).

Specifically, Ferroni and Hopkirk included the following energy 'costs' as part of the EROI denominator via boundary expansion:

1. Energy cost of energy storage requirement for integration of PV-generated electricity into the grid;
2. Energy cost of labour and 'capital'.

In the following sub-sections, we shall address each of these system boundary extensions and discuss the methodological issues that they entail.

2.1. Energy storage

As discussed elsewhere (Carbajales-Dale et al., 2015; Raugei et al., 2016), the inclusion of large amounts of energy storage in the analysis of an individual grid-connected electricity production system (in this case, PV) implicitly shifts the goal of the study from the assessment of its intrinsic net energy performance to the assessment of its ability to, *by itself*, support the entire societal demand for electricity. Specifically, if the goal of the study is the calculation of EROI for an additional PV installation in current Swiss conditions, the inclusion of battery storage is unnecessary – to date no battery storage is required for grid-connected PV plants in Switzerland or anywhere in the world.

However, if one were to adopt the broader goal, then to do so effectively for a technology yet to be deployed at such scale one should carefully simulate the new system's configuration and the ways that the demand curve can respond to the supply change. Many other electricity generation technologies, if deployed on their own, would be equally incapable of continuously meeting society's highly variable demand for electricity without some form of energy storage or large amounts of wasted energy. Specifically, large base-load generators, such as nuclear power plants (which is the technology against which PV is compared by Ferroni and Hopkirk), would also need additional infrastructure, either in the form of storage or partially used large built-in over capacity, if they were to meet peak-loads in addition to the base loads they currently serve. Since there are no studies, to our knowledge, that analyse the EROI of nuclear with this same boundary (and Ferrroni and Hopkirk do not cite any), *comparing the EROI of 'PV + storage' as calculated by Ferroni and Hopkirk to that of nuclear power, as they define it, is inconsistent*. Furthermore, the amount of storage required for "smoothening" the solar output may be moderated by geographical diversity, by combining solar and wind generation, or demand response aspects that were not considered by Ferroni and Hopkirk, and in any case should be the result of a careful high temporal resolution analysis (see Section 3.2).

2.2. Labour and capital

In Section 5.3 of Ferroni and Hopkirk, the authors outline how they include the energy cost of labour and capital by multiplying the financial cost of those items by a regionally defined energy intensity ratio, thereby converting monetary expenditures into energy expenditures. There are two issues with this analysis: since "Wages [...] represent an allocation of energy surplus, not an energy consumption on-site, and including capital expenditures causes double counting of embodied material and direct energy costs in manufacturing of solar-PV" (Koppelaar, 2016). In other words, the energy equivalent of the assumed cost of installation in labour and capital terms is already accounted for by the estimated CED. One should either use a bottom-up energetic analysis or an input-output analysis of the economic impacts, but not the two concurrently for the same input. Ferroni and Hopkirk's comparison of jobs per MW between the nuclear and the PV cycles is also problematic, in that their numbers for PV are based primarily on residential roof-top installations instead of large solar farms that are more suitable for comparison with nuclear power plants.

3. Problematic determination of system parameters and calculation errors

The paper by Ferroni and Hopkirk presents multiple data quality issues, which will be discussed in detail in this section. One fundamental point that is at the root of several of such issues is that for a technology that is advancing rapidly such as PV, the use of historical data (even a decade old) implies that the resulting estimate has validity only as referring to the past, and not as a forward-looking policy instrument. We observe this in several key areas in the Ferroni and Hopkirk paper, i.e., in their estimation of capacity factors, embodied energy or cumulative energy demand (CED), expected lifetime, and system damage/replacement rates.

3.1. Parameters affecting the EROI numerator (energy 'returned' by the PV system)

Ferroni and Hopkirk state that the average annual electricity production of a panel in Switzerland is 88.1 $kWh_{el}/(m^2\ yr)$. They arrive at this number by starting with a value of 106 $kWh_{el}/(m^2\ yr)$, which is reported as representing the average output over the last 10 years from "relatively new" modules actually deployed within Switzerland (Swiss Federal Office of Energy, 2015a), and then subtracting what the authors call "performance degradations" (1% per year) and "operational downtime" (5% each year).

There are two issues with this calculation, though.

Firstly, using a 10-year average for a rapidly improving technology introduces an invalid approximation which is unnecessary because annual data are readily available from the same source (Table 1). By using a 10-year average for the performance per m^2 of PV, Ferroni and Hopkirk ignore the well documented fact that the PV efficiencies and environmental profiles have been steadily improving during the last decade (Louwen et al., 2016). In fact, as shown in Table 1, according to a recent reputable study (Fraunhofer ISE, 2016), the weighted (for the mixture of Switzerland installations) PV system efficiencies have increased from 12% to 16% during the last 10 years. We therefore ran a linear regression on all the actual reported values for the last 10 years, and arrived at a more representative estimate of 120 $kWh_{el}/(m^2\ yr)$ for current PV operation in Switzerland (Fig. 1).

Secondly, detracting performance degradation and operational downtime from reported cumulative output values constitutes partial double counting. Also, the most recent comprehensive study on PV system degradation (Jordan and Kurtz, 2013) reported significantly lower average degradation rates for post-year 2000 systems (i.e., respectively 0.23% for sc-Si PV and 0.59% for mc-Si PV). Again, the data used by Ferroni and Hopkirk is out of date. In fact, a degradation value of 0.2%/yr for Swiss conditions has also been specifically reported in another publication (Chianese et al., 2003).

Based on the evidence presented, when starting with the revised yield of 120 $kWh_{el}/(m^2{\cdot}yr)$ mentioned above, and conservatively applying a degradation rate of 0.5%/yr (i.e., notwithstanding the fact that some degradation is already included in the yield estimate for the initial four years) to a conservative lifetime of 25 years (i.e., the same value used in Ferroni and Hopkirk's calculations, and lower than the 30 years recommended by the IEA guidelines), an arguably more accurate estimate of 2827 kWh_{el}/m^2 is obtained for the total energy 'returned' by a modern PV system in Switzerland.

3.2. Parameters affecting the EROI denominator (energy 'invested' in the PV system)

In Section 5 of Ferroni and Hopkirk the energy invested in the PV system is derived. The assumed cumulative energy demand (CED)[1] is quoted as 1300 kWh_{el}/m^2, based on the literature sources provided in their Table 2 (most of which are between 18 and 6 years old, the only two more recent ones being a Master thesis by a University of Uppsala student, and a PowerPoint presentation by Ferroni himself) and does not differentiate between the type of PV technology (mono-crystalline, poly-crystalline, thin-film etc.) which makes a difference in the estimate of the CED.

It is interesting to note that a recent independent meta-analysis of the net energy of PV also assigned the lowest possible score of 1 (on a 1–5 scale) to Ferroni and Hopkirk's work under the 'reliability' and 'data age' criteria, respectively because "the data could only be traced via a secondary grey literature publication of the authors" and "the studies cite older studies which again cite older studies" (Koppelaar, 2016).

For illustration of the issue of technology improvement, we note that one of the studies that Ferroni and Hopkirk refer to (Nawaz and Tiwari, 2006) assumes 350 µm-thick Si wafers and losses of 300 µm from slicing the Si ingot, which represents the single most energy intensive input of the PV system. This assumption corresponds to Si ingot use of around 16 g/W_p. Since 2013 the average value for PV production has been below 6 g/W_p (Fraunhofer ISE, 2016, p. 30), which implies that the same weight of ingot material input would generate 2.7 times more output today than assumed in the Ferroni and Hopkirk reference. In terms of numbers, this aspect alone reduces the calculated CED by 416 kWh_{el}/m^2 or 30%.

Such reductions are confirmed in the literature. In a peer-reviewed study published this year (Görig and Breyer, 2016) the CED for the current market-based mix of PV systems was found to be 3.8 GJ/m^2 (for ground-mounted systems) and 2.7 GJ/m^2 (for rooftop systems). It should also be noted that Ferroni and Hopkirk's assumption that one third of the Swiss PV systems are ground-mounted is incorrect; the vast majority of Swiss PV installations actually consists of rooftop systems (Hüsser, 2016). Converting Görig and Breyer's up-to-date CED figures to 'equivalent electrical energy' as Ferroni and Hopkirk do by using a 38% efficiency factor, and assuming 95% rooftop and 5% ground-mounted systems,[2] yields CED≈2.76 GJ/m^2=1.05 GJ_{el}/m^2=290 $kWh_{el}/$

[1] For consistency and clarity, throughout this paper we use the subscript 'el' to indicate units of electrical energy (e.g., MJ_{el}, kWh_{el}), and no subscript at all for units of primary or thermal energy (e.g., MJ, kWh).

[2] Table 4a of Hüsser (2016) reports 290 ground-mounted PV systems over a total of 49844, which equates to 0.58% in system number share. However, since ground-mounted systems are typically much larger, a way to estimate the relative capacity shares is required. Unfortunately, the report stops tracking the difference between the two types

Table 1
Swiss PV Installed Capacity, PV system efficiency, and calculated average specific yield per year, 2005–2015.

	Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
C_i=cumulative installed capacity in year i[a]	[MW_p]	28	30	37	49	79	125	223	437	756	1,061	1,394
Out_i=total electricity output in year i[a]	[MWh_{el}]	20,740	23,770	28,550	36,730	54,390	93,640	168,050	299,470	500,470	841,570	1,118,550
Average specific yield	[kWh_{el}/ kW_p]	733	790	764	744	684	747	754	686	662	793	802
$\eta_{new,\ i}$=mean efficiency of new PV in year i[b]	[%]	12%	12.5%	13%	13.5%	14%	14.5%	15%	15.5%	16%	16.5%	17%
$\eta_{avg,\ i}$=calculated weighted average efficiency of installed PV capacity in year i[c]	[%]	12%	12%	12.2%	12.5%	13.1%	13.6%	14.2%	14.8%	15.3%	15.7%	16.0%
Calculated PV surface area based on $\eta_{avg,\ i}$	[m^2]	235,833	250,210	305,845	393,865	607,317	921,413	1,568,128	2,940,750	4,927,983	6,769,171	8,719,543
Specific yield per surface area based on $\eta_{avg,\ i}$	[kW h_{el}/ m^2]	87.9	95	93.3	93.3	89.6	101.6	107.2	101.8	101.6	124.3	128.3

[a] Swiss Federal Office of Energy, 2016.
[b] Fraunhofer ISE, 2016.
[c] $\eta_{avg,i}$=[$\eta_{avg,i-1}$·C_{i-1}+$\eta_{new,i}$·(C_i - C_{i-1})]/C_i

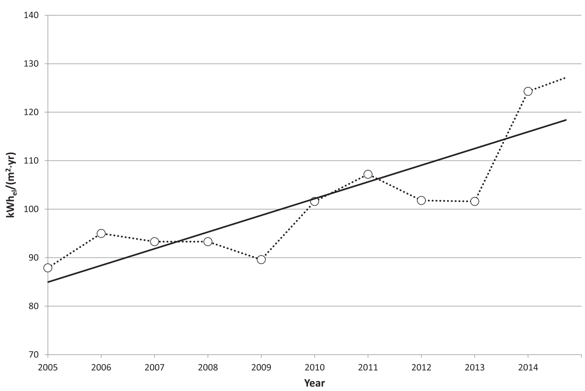

Fig. 1. Average specific PV yield per year in Switzerland, for years 2005–2015, and associated linear regression line.

m^2, which is 78% lower than the value used by Ferroni and Hopkirk. It is also noteworthy that two more equally recent peer-reviewed LCAs of ground-mounted mc-Si PV systems, respectively by Leccisi et al. (2016) and Hou et al. (2016), independently arrived at very similar results. Specifically, Leccisi et al. reported CED≈20 GJ/kW_p, based on the latest available life cycle inventory data (Frischknecht et al., 2015a) and current input electric grid mixtures; given their assumed module efficiency of 16%, this translates to 3.2 GJ/m^2=1.22 GJ_{el}/m^2=338 kWh_{el}/m^2. Hou et al. reported ≈1.9 kWh_{el}/Wp, which, under their 17% efficiency assumption, corresponds to 323 kWh_{el}/m^2. Such improvements over time are also further confirmed by a recent re-assessment of the net energy production of PVs reporting “a downward trend of CED versus installed capacity, with learning rates of 12.6 ± 0.85% and 11.9 ± 1.04% for poly and mono-Si systems” (Louwen et al., 2016).

The much lower CED value also directly affects the estimate for the additional energy required to replace faulty modules and inverters, which Ferroni and Hopkirk estimated at 90 kWh_{el}/m^2=6.9% of their assumed CED. This assumption is also subject to significant change – the incidence of PV systems failing to meet present standards in the field has decreased by 86% from 2002 to 2013 (TÜV Rheinland, 2014). Be that as it may, even when accepting this unsupported estimate of Ferroni and Hopkirk's in relative terms, the revised energy investment would then be 6.9% of 290 kWh_{el}/m^2≈20 kWh_{el}/m^2.

Ferroni and Hopkirk then assume, without any reference or attempt at simulation, that 25% of the generated PV electricity needs to be stored. We have already explained in Section 2.1 how by including energy storage in their assessment, the authors implicitly changed the goal of their study and made its results inconsistent and incomparable with those previously reported for other electricity generation technologies, including nuclear and coal. The impact on EROI of changing the amount of electricity output that is passed through storage was discussed in more detail elsewhere (Barnhart et al., 2013).

Even so, Ferroni and Hopkirk's choice of 25% is unsupported. Firstly, such a high storage requirement fails to take into account the potential synergy of combining PV with wind (Nikolakakis and Fthenakis, 2011), the drastic smoothening of PV fluctuations by considering geographical diversity (Perez and Fthenakis, 2015), and the optimization/minimization of storage requirements for load-following and ramp-rate control duties (van Haaren et al., 2015). Secondly, energy storage would be more fittingly addressed as part of an analysis of a country's whole energy system. Palzer and Henning (2014a, 2014b) showed that, for the case of Germany, about 8% of the generated electricity would have to be stored for an 87% renewable energy system, and a similarly low percentage was estimated for the UK (Gross et al., 2006). Also, the National Renewable Energy Laboratory estimated that high penetration (> 80%) of renewables would be possible in the USA with only ~5 times current storage capacity, which is currently at a comparatively low ~20 GW (Hand et al., 2012). Bogdanov and Breyer (2016) indicate an electricity storage demand of less than 15% for Northeast Asia for a 100% renewable energy system with a limited level of integration in other energy sectors. More specifically, given the high share of reservoir hydropower in the Swiss grid mix - producing 31.7% of total electricity (Swiss Federal Office of Energy, 2015b) - it seems plausible that the already-available hydro dams could often be used for flexible generation on demand, thereby significantly reducing the need for additional energy storage.

Finally, Ferroni and Hopkirk add in to the computation of the total energy investment two large contributions calculated on the basis of estimated economic inputs, i.e., “energy invested for the labour” (505 kWh_{el}/m^2) and “energy invested necessary for the capital” (420 kWh_{el}/m^2). Both of these values are either assumed or “based upon the authors’ experiences” (but still otherwise unsupported). We have already explained in Section 2.2 how, from a methodological perspective, the inclusion of these contributions result in lack of consistency with most previous studies of PVs and other technologies, as well as in at least partial double counting.

(*footnote continued*)
of installations by capacity after the year 2010, in which the ground-mounted capacity share was 2.31% (Table 5). We chose to assume a share of 5% ground-mounted PV systems for our revised calculations, which refers to the capacity of all PV systems connected to the medium voltage network (Table 4); this share also includes the larger roof-top systems, and is therefore a conservatively large estimate.

Table 2
EROI and $\mathbf{EROI_{EXT}}$ of PV electricity in Switzerland, respectively according to Ferroni and Hopkirk (2016) and to the revised calculations presented in this paper.

		Ferroni and Hopkirk (2016)	*Notes and references*	*This work*	*Notes and references*
Calculation of energy 'return' (R)	*Specific yield per surface area* [$kWh_{el}/(m^2 \cdot yr)$]	106	Claimed to be the average output over the last 10 years from "relatively new" modules in Switzerland, based on (Swiss Federal Office of Energy, 2015a).	120	Calculated by linear regression using the actual reported yearly outputs (Swiss Federal Office of Energy, 2016) and efficiencies (Fraunhofer ISE, 2016).
	Lifetime [yr]	25	Assumption.	25	Adopting the same assumption as in Ferroni and Hopkirk (conservatively based on typical manufacturer warranties).
	Operational downtime	5%	Source of double counting (should already have been included in the initial yield estimate).	0%	Already included in the initial yield estimate.
	Yearly degradation rate	1%	Incorrect citing of data from reference (Jordan and Kurtz, 2013).	0.5%	After (Jordan and Kurtz, 2013). It is a conservative estimate as some degradation is already accounted for in the historical values used to estimate the specific yield.
	R=Energy produced by PV system [$\mathbf{kWh_{el}/m^2}$]	**2203**		**2827**	
Energy 'investments' ($\mathbf{I_i}$) [$\mathbf{kWh_{el}/m^2}$][a]	$\mathbf{I_1}$**=CED of PV system**	**1300**	Based on old and/or unreliable studies (seven references, of which two are > 10 year-old, and two are 'grey literature')	**290**	Based on the latest and most up-to-date peer-reviewed literature (Görig and Breyer, 2016; Leccisi et al., 2016; Hou et al., 2016.)
	$\mathbf{I_2}$**=Faulty equipment**	**90**	Unsupported assumption	**2.9–20**[b]	Upper limit=Ferroni and Hopkirk's assumption (i.e., 6.9% of CED) Lower limit based on reported 86% reduction in PV system failures from 2002 to 2013 (TUV Rheinland, 2014)
	$\mathbf{I_3}$**=Energy storage**	**349**	Based on invalid assumption that 25% of the produced electricity must be stored. Inclusion of energy storage changes the goal of the study and, if inconsistently done for PV only, prevents comparability with other energy technologies (including nuclear which will require storage to provide peak power).	–	Energy storage not included in order to prevent goal shifting, and to maintain comparability with other technologies. It should be noted that no energy storage has historically been built in association with grid-connected PV installations in Switzerland.
	$\mathbf{I_4}$**=Labour and Capital**	**505+420=925**	Unsupported economic estimates ("based on the authors' experiences"); energy/currency ratio based on (Swiss Federal Office of the Environment, 2013) and "assuming that the net energy imported is proportional to the net CO_2-emissions"	**54–100**	Economic estimate range after (Hüsser, 2016); energy/currency ratio after (Frischknecht et al. 2015b)
	$\mathbf{EROI=R/(I_1+I_2)}$	**1.7**		**9.1–9.7**	
	$\mathbf{EROI_{EXT}=R/(\sum_i I_i)}$	**0.8**		**6.9–8.1**	

[a] Assuming a primary-to-electrical energy efficiency factor of 38%.
[b] Assuming the same relative contribution as in Ferroni and Hopkirk (2016).

But even when included, service inputs quantified in monetary inputs (i.e., 'soft' costs including installation, contracting, 'project management' and insurance) should be expected to have a small to negligible contribution to the total energy expenditure when converted into energy units (Loerincik and Jolliet, 2006), because service sectors have low energy intensities per turnover or value added. Using the actual documented range of such 'soft' costs in Switzerland =800~1500 CHF per kW_p (Hüsser, 2016, Table 9) and applying an energy intensity of construction services of 4 MJ/CHF (similar to the 0.43 kWh_{el}/CHF value adopted by Ferroni and Hopkirk, and consistent with the latest environmentally extended input output table of Switzerland (Frischknecht et al., 2015b)), the energy costs of service inputs actually amount to 3200–6000 MJ/kW_p, which corresponds to 54–100 kWh_{el}/m^2 (i.e., just 1.7–3.2% of the total electricity produced by the PV system as correctly quantified in Section 3.1).

3.3. Revised EROI calculations for PV electricity in Switzerland

Table 2 presents a summary of the values used by Ferroni and Hopkirk for their estimation of the EROI of PV electricity in Switzerland, with accompanying commentary notes and references, contrasted with those resulting from our revised calculations detailed in Sections 3.1 and 3.2 above, with corresponding notes and references. Both conventional and 'extended' system boundary calculations are included in the same table (the latter including economic inputs).

4. Critical issues with Ferroni and Hopkirk's claims and related estimates

Ferroni and Hopkirk's calculation of the $EROI_{ext}$ of PV electricity in Switzerland is interspersed with a large number of digressions and unsupported claims, which we shall briefly analyse and discuss in this section.

A first significant issue, which affects the CED calculations, is present in the estimates of capital intensity. Ferroni and Hopkirk claim from "personal experience" that the cost for installed PV is 6000 CHF/kW_p. While the authors offer no reference for this estimation, we cross-check this datum with the actual reported costs of current German and Swiss installations. The average, all-inclusive, system price for small rooftop PV systems in Germany was 1300 EUR/kW_p (≈1400 CHF/kW_p) in the first quarter (Q1) of 2015 (Fraunhofer ISE, 2015, Figure 3), i.e., over four times lower than claimed by Ferroni and Hopkirk. One would actually need to go back to Q2 2006 in order to reach a system cost approaching 5000 EUR/kW_p≈5400 CHF/kW_p. The reported average all-inclusive cost for residential PV systems in Switzerland, while higher than the German one at 2800 CHF/kW_p (Hüsser, 2016, Table 9), which is still less than half of that claimed by Ferroni and Hopkirk. This difference also directly affects the estimated labour and administrative cost discussed in Section 3.2.

Also, Section 2 of Ferroni and Hopkirk starts by stating that the average insolation in Switzerland is 1000–1400 kWh/(m^2 yr). However, they then confusingly discuss a much lower value of 400 kWh/(m^2 yr) based on the output of thermal collectors. Admittedly, this latter datum is not actually used by the authors in their analysis; however it is also *irrelevant* as it omits the fact that thermal collectors – a completely different technology *vs.* PV – have their own optical and thermal losses.

Ferroni and Hopkirk then write that the average lifetime of a PV system "could be said to be nearer to 17 than 30 years", based on data for PV waste processed in Germany and transforming the weight values to capacity values in order to estimate the amount of decommissioned plants since installations begun. Two major issues with this approach, however, are that: (i) the decommissioning estimates come from an era (1980–1998) in PV deployment that was essentially a pilot program, and (ii) there were incentives during this period for early decommissioning so that modern high efficiency modules could replace early technology (further supporting the domestic demand for PV in Germany). The practice of early replacement of modules was a one-time effort and no longer occurs in Germany, nor do we have any information about this applying to Switzerland. In fact, the first grid-connected Swiss PV plant was installed in 1982 and, in the 20-year analysis of its performance, it was found that the annual degradation rate had been 0.2%/year and it was concluded that despite visual issues "all plant modules … are still working in a very satisfactory manner" (Chianese et al., 2003). The actual reported decommissioning of PV modules in Switzerland was zero in 2015 (Hüsser, 2016). Finally, the tangible quality improvements in PV manufacturing are captured by TUV's report of a single panel failing performance tests in the assessed plants by TUV from 54% in 2002 to 7% in 2014.

Throughout their text, Ferroni and Hopkirk also make several comparisons of PV *vs.* nuclear without regard to the assumed boundaries. Section 3 of their paper presents a largely inconsistent estimate of the material, labour and capital intensities of PV compared to nuclear energy. The authors do not use any recognized rigorous standard of life cycle assessment nor equivalent published research on the topic but instead rely on 'back of the envelope' calculations. For example, in Section 3.1 they write, referring to nuclear electricity, "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 photovoltaic technology is at least 64 times that of nuclear energy." The first sentence in the quote simply lists the data input they use for nuclear electricity, but the second one draws a comparison to PV directly, and as we have been stating throughout this document, whenever a comparison is made, it always implies that, among other things, the boundaries of the analysis are consistent. Yet, unfortunately, there is no way of knowing whether that is the case in this example, and hence this is another instance of drawing inappropriate conclusions.

Lastly, Ferroni and Hopkirk claim that a large share of PV production currently takes place in China "due to elevated costs and local environmental restrictions". However, nowhere in their study do the authors analyse the affordability or environmental impacts of PV, nor do they provide any references on the second part of their assertion.

5. Conclusions

Our revised EROI and $EROI_{EXT}$ values for PV systems in Switzerland,[3] calculated according to the formula adopted by Ferroni and Hopkirk (i.e., as the ratio of the total electrical output to the 'equivalent electrical energy' investment), but based on the arguments and numbers presented in this paper are, respectively, EROI≈9–10 (when adhering to widely adopted 'conventional' system boundaries as recommended by the IEA (Raugei et al., 2016)) and $EROI_{EXT}$≈7–8 (when instead adopting 'extended' system boundaries that also include the energy investments for service inputs such as 'project management' and insurance). It is especially noteworthy that even the latter $EROI_{EXT}$ range is one order of magnitude higher than 0.8 which was obtained by Ferroni and Hopkirk.

In the end, measuring the performance of energy technologies is a complex task that ought not to be approached by using a single metric, however relevant and important it might be. There are fundamental aspects of an energy system that EROI does not capture, i.e. the renewable or non-renewable nature of different energy resources, the associated environmental externalities, and the distribution of a system's energy output over time.

At its core, EROI is simply a measure of the marginal amount of

[3] It is worth noticing that, of course, the EROI of PV is a strong function of the irradiation available at the region of deployment and that the calculations presented and discussed in this paper are only valid for Switzerland; EROIs as high as 60 are reported for high irradiation regions (Leccisi et al., 2016).

additional energy that a certain technology can provide to society for a given energy investment. The importance of using up-to-date and reliable data and parameter estimates cannot be overemphasised, especially in the case of rapidly evolving technologies such as PVs. But perhaps even more importantly, comparative EROI assessments – just like life cycle assessments and all other scientific studies – must be based on shared standards and protocols in order to ensure comparability itself (examples of such standards are those put forth by ISO (2006a,b) and the IEA (Alsema et al.,2009; Fthenakis et al., 2011; Frischknecht et al., 2016; Raugei et al., 2016). If such standards are not adhered to – especially in regard to goal definition and system boundary – then an individual analysis may still of course be potentially informative in and of itself (provided, of course, that it is based on sound assumptions and calculations), but its results should not be presented as intrinsically 'more correct', nor should they be directly compared to those ensuing from other studies that adopt different boundaries. Failing to recognize this fact leads to erroneous comparisons and risks poorly-derived energy policies. Also, extending the boundaries of the EROI calculations in order to estimate the ability of a certain technology to support the present civilization tends to stretch the value of this measurement beyond its initial intended purpose, and the vast uncertainties involved in doing so make it a risky enterprise that might easily lead to wrong policy choices.

It may sometimes be difficult for policy makers and for the public at large to unravel the methodological and numerical intricacies of these calculations in the way that we have done in this paper, and therein lies the risk that methodologically inconsistent and poorly-derived results such as Ferroni and Hopkirk's may be taken in more consideration than they deserve.

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