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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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A R T I C L E I N F O

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A B S T R A C T

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