Applied Energy 186 (2017) 167–174

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# Toward an integrated assessment of the performance of photovoltaic power stations for electricity generation

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## HIGHLIGHTS

- The paper analyzes the performance of photovoltaic systems for electricity production.
- The performance is assessed relative to several dimensions and types of constraints.
- The availability of physical gradients for large-scale deployment of PV is analyzed.
- The required production factors for PV production and operation are addressed.
- The electricity generation from PV is evaluated in relation to socioeconomic needs.

## ARTICLE INFO

*Article history:*
Received 30 November 2015
Received in revised form 11 May 2016
Accepted 16 May 2016
Available online 24 May 2016

*Keywords:*
Photovoltaics
Multi-scale integrated sustainability assessment
Energy system
Societal metabolism
Urban metabolism
Multi-criteria constraints

## ABSTRACT

In this paper a photovoltaic (PV) technologies for electricity generation accounting scheme is proposed and applied. The adopted scheme aims to overcome limitations of conventional indicators such as EROI (Energy Return on Investment) and EPBT (Energy Payback Time) and to present a more comprehensive description of energy and material transformations. The proposed methodology is based on the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach. In this work, *four dimensions of sustainability* which should be addressed for the purpose of identifying the limiting factors of photovoltaic systems for electricity production are presented: Energy and Material Accessibility; Environmental Health Desirability; Technological Achievability; and Socioeconomic Acceptability. In relation to these four dimensions, the direct and indirect requirements of flow *and* fund elements (silver, energy carriers and water as flows; human time and land as funds) in photovoltaic power stations based on crystalline silicon wafer cells are evaluated and the implications of the overall performance and limitations of the present PV systems are discussed. These parameters are also compared with other electricity production technologies as well as benchmarked against the performance of the energy and mining sector of a modern country (Spain). It is concluded that the availability of silver could constrain photovoltaic cell manufacturing. Furthermore, the low power density of photovoltaic installations could drive a remarkable land rush. Finally, the human labor allocated in the fund-making process could represent a serious constraint in respect to the requirements of the metabolism of modern societies.



## 1. Introduction

Fossil fuel abundance over the past approximately two hundred years has boosted the current material affluence of modern societies. The depletion of easy recoverable fossil primary energy sources and the increasing volume of carbon dioxide emissions derived from their combustion are, however, two issues of primary importance. It is therefore imperative to evaluate the potential of alternative and renewable energy resources. One of the most promising of these resources is undoubtedly solar photovoltaics, a process by which solar radiation is converted directly into electricity. This technique has several advantages [1]: no greenhouse gas emissions once installed, no moving parts (which could, e.g., cause noise pollution during the operation), and easy scalability in respect of power needs (applications range from a few milliwatts, e.g. in wristwatches, to recently developed solar power plants with power capacities on the order of several hundreds of megawatts). Additionally, silicon is the second most abundant element in the Earth's crust and is nontoxic. On the other hand, some technical drawbacks, mainly in relation to the questionable ability

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http://dx.doi.org/10.1016/j.apenergy.2016.05.102
0306-2619/

of current electrical grids and societal patterns of consumption to adjust, raise warning flags. The main issue of photovoltaics is related to the fact that the production of electricity is concentrated within a limited fraction of hours, namely those corresponding to peak insolation. In general, these hours do not match the peaks in demand characteristic of diurnal activity cycles, especially in urban systems. Therefore, electricity generation from photovoltaic power plants could not be particularly effective at responding to peaks in demand. In countries where high-penetrations in the electric grids have already taken place, several cases of over-loading and over-voltaging have already been documented [2]. In addition, the low capacity utilization factor (i.e. the fraction of hours of the year where the converter is actually used) of PV plants in comparison to fossil fuel-based ones [3] implies the requirement of a much higher power capacity capital fund in order to generate the same amount of electricity.

EROI (Energy Return on Investment) and EPBT (Energy Payback Time) are two important indicators frequently used in assessment of primary energy quality and energy generation system performance. EROI is the ratio of the amount of net energy acquired from a primary energy source to the amount of energy expended, directly and indirectly, to obtain the net quantity acquired. Therefore, EROI can be used as a quality indicator of primary energy sources such as crude oil *in situ*. On the other hand, EPBT has been used in assessment of renewable energy generation systems. In the case of a PV module, EPBT is the ratio of the energy input during the module life cycle of a PV panel – including the energy requirement for manufacturing, installation, operation, and decommissioning – to the annual energy savings due to electricity generated by the PV module. These two indicators refer only to aspects of energy quality and quantity. Therefore, these indicators would not be satisfactory if one were to attempt to evaluate the overall energy *and* material balance associated with important aspects of the quality and quantity of alternative primary energy sources as well as their corresponding socioeconomic changes in terms of human time, land and capital utilization patterns. To this end, in this paper a general accounting scheme applied to photovoltaic technologies for electricity generation is proposed. The methodology adopted is based on the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach [4].

The rest of the paper is organized as follows. Section 2 explains the basic rational behind the MuSIASEM approach and introduces four dimensions of sustainability which should be addressed for the purpose of identifying the limiting factors of photovoltaic systems for electricity production: Energy and Material Accessibility; Environmental Health Desirability; Technological Achievability; and Socioeconomic Acceptability. Section 3 introduces the methodology used and the data source, explaining how the MuSIASEM approach has been applied to our case study along with the assumptions made. Section 4 shows and analyzes the findings obtained, comparing the performance of PV to other electricity generation technologies and the energy and mining sector of a modern country (Spain in the year 2013). Some conclusions are made in Section 5, potential further improvements of the accounting scheme are illustrated, and the potential criticalities of PV technology are stressed in relation to the four dimensions of sustainability.

## 2. Basic rationale of MuSIASEM and four dimensions of sustainable energy systems

MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) is an accounting scheme that is a combination of the following three pioneering works from various scientific disciplines: (1) Georgescu-Roegen's flow-fund representation of the production process [5]; (2) hypercycle and dissipative parts theory in nature [5,6]; (3) hierarchy theory and scale issues in ecology [7–10]. We briefly explain these three basic ideas behind the MuISASEM approach (a comprehensive description of the methodology and its theoretical pillars can be found in [4]).

Georgescu-Roegen's *flow-fund* scheme has been elaborated from his critique of the production function theory of standard economics, wherein smooth substitution among any factors (or elements) of production is assumed. Conversely, Georgescu-Roegen proposed a completely new representation of the production function where he distinguished between two types of production elements: flows and funds. Flow and fund elements play completely different roles in the production process. Flow elements are production factors that are produced or consumed during the production process. Fund elements are production agents that remain the same (in terms of production efficiency) over the duration of the production process. Fund elements are Ricardian land (i.e. land as indestructible pure space), labor and capital and they perform the transformation of input flows into output flows. In the analytical representation of contemporary energy analysis, these three fund elements are typically excluded. However, ever since the industrial revolution, due to the massive increase in energy use, land and labor use patterns as well as capital formation and utilization patterns have transformed dramatically. When omitting these fund elements from the analysis of energy transformation technologies embedded in socioeconomic systems, one certainly misses many critical aspects. MuSIASEM represents an attempt to explicitly include these crucial fund elements in an analytical representation of energy systems.

The hypercycle and dissipative parts theory has been developed by Ulanowicz [7], who acknowledged the fact that the network of matter and energy flows making up an ecosystem can be divided into these two parts. The hypercycle part is a net energy supplier for the rest of the ecosystem. In our representation, the energy and mining sector constitutes this role for the societal context. In contrast, the dissipative part comprises of all net energy degradative activities. In terms of energetic metabolism, cities represent almost exclusively a dissipative system. In the literature, the possibility of having a significant production of energy carriers such as electricity from PV systems in urban contexts has been thoroughly discussed [11], yet whether or not urban PV capacity could feasibly suffice local demands is still a matter of debate [3]. Some authors have suggested the adoption of façade-integrated PV panels, in addition to roof-top systems, in order to increase the conversion potential of multistory buildings [12]. Moreover, PV has a remarkable potential to increase electricity access in rural and isolated areas with off-grid systems (notably in developing country, where this issue is highly pressing) [13].

With respect to the assessment procedure of renewable alternative energy sources and technology, it is instructive to examine the nature of the *feasibility* and *viability* of energy transformation systems. The MuSIASEM scheme has already been successfully applied to several case studies assessing the performances of alternative energy sources [14–18]. To our knowledge, this paper represents the first contribution whereby such an approach (a multi-scale and integrated evaluation of the technology) is undertaken for photovoltaics.

The performance of a given power technology for the conversion of PES into EC affects the viable metabolic pattern of societies. This last one, in turn determines the availability of the production factors for the PES to EC conversion in an impredicative,[1] constrained and non-linear fashion. Fig. 1 represents the hierarchical

[1] From [19], p. 42: "When a set *M* and a particular object *m* are so defined that on the one hand *m* is a member of *M*, and on the other hand the definition of m depends on *M*, we say that the procedure is *impredicative*. An impredicative definition is circular, at least on its face, as what is defined participates in its own definition".