Toward an Integrated Assessment of the Performance of Photovoltaic Power Stations for Electricity Generation

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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.

Keywords

Photovoltaics; Multi-scale integrated sustainability assessment; Energy system; Societal metabolism; Urban metabolism; Multi-criteria constraints.

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

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 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 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 [7–9] . 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 [6], 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].

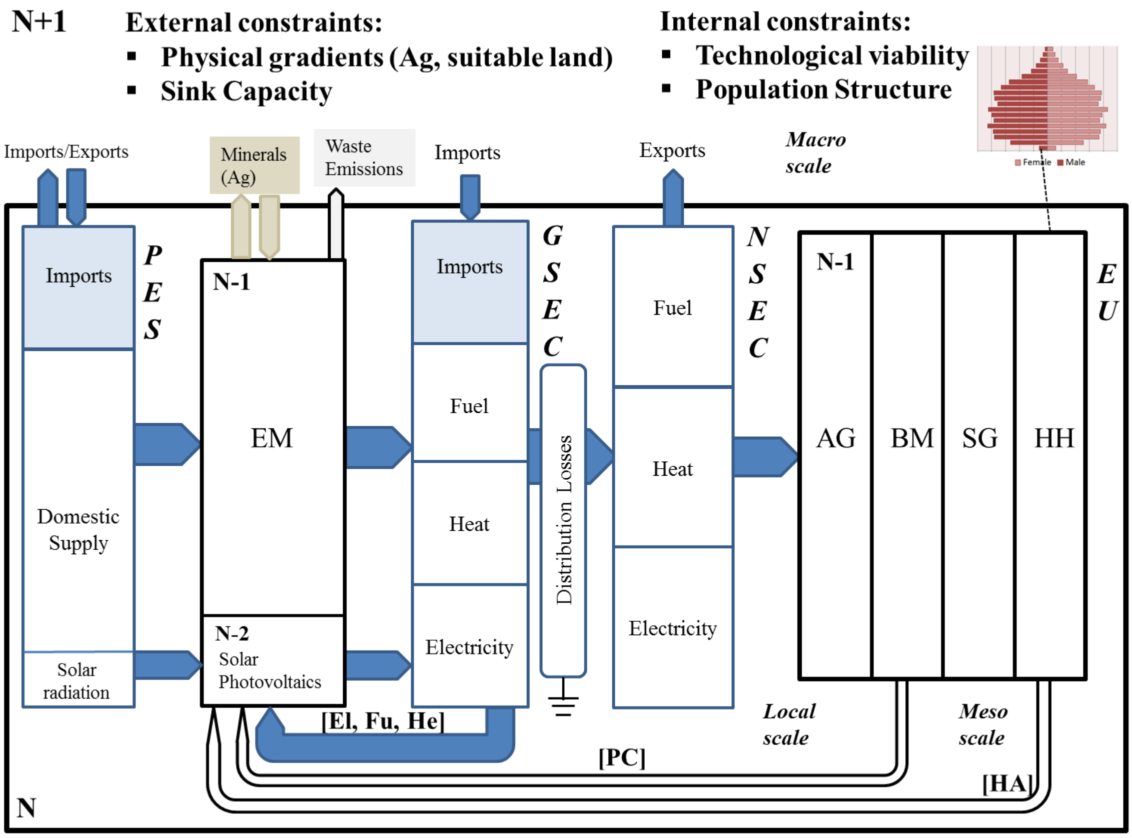
With respect to the assessment procedure of renewable alternative energy sources and technology, it is instructive to examine the nature of the *feasibility* and *viability* of energy transformation systems. The MuSIASEM scheme has already been successfully applied to several case studies assessing the 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, constrained and non-linear fashion. Figure 1 represents the hierarchical structure of the different economic sectors including the energy and mining sector.

Figure 1. around here

Figure 1. The hierarchical structural representation of the different economic sectors.

Figure 1 illustrates the role of the energy sector as a converter of primary energy sources (PES) into three energy carriers (EC) - electricity (El), fuel (Fu) and heat (He) - eventually required to meet the energy demand of a society (end use - EU). The Gross Supply of Energy Carriers (GSEC) results into a Net Supply of Energy Carriers (NSEC) equivalent to the societal demand after the self-consumption of the energy and mining sector and the distributional losses. The multi-scale perspective involves four different hierarchical levels: the N+1 level, outside of the societal system observed; the N level, the system corresponding to the latter; the N-1 level related to the societal sub-sectors: energy and mining (EM), agricultural (AG), building and manufacturing (BM), service and government (SG) and household (HH); finally, the N-2 level represents the “photovoltaics” sub-compartment (conversion of solar radiation PES into the electricity EC) within the EM sector. The required production factors for the conversion process are illustrated (El, Fu, He, PC as Power Capacity and Human Activity as HA) along their respective sector. The surrounding environment (dimension N+1) provides the requisite biophysical resources (i.a. minerals, silver specifically) and the waste emissions sink capacity. Moreover, it is possible also to import/export both PES and ECs ready for use. The constraints on the PES/EC conversion process are determined at various scales: the local scale (N-1/N-2 - availability of production factors, PC and ECs, that is to say converters and appropriate structures); the meso scale (N/N-1 - the demographic profile of the society, i.e. enough hours of human activity to be invested in the energy conversion process); the macro scale (N+1/N - the availability of biophysical gradients along sink capacity for the emissions).



In this paper, four dimensions of sustainable conditions within the MuSIASEM framework are proposed for use in identifying the limiting factors of PV systems within a given geographical region, typically a nation, a territory or an urban settlement. It should be noted that these four dimensions are not mutually exclusive, but for the sake of simplicity we individualize conditions that are most suitable for each dimension:

(1) *Energy and Material Accessibility* -- what amounts of resources are available under the condition of economic and technological accessibility? At the least, the set of variables employed for fueling the economy as well as for maintaining the social fabric has to be tackled; (i) primary energy sources (such as fossil fuels, solar energy, wind energy, etc.); (ii) energy carriers (energy forms such as fuels, process heat and electricity); (iii) material flows (mineral resources and other resources such as silver); and (iv) land-based resources such as water.

(2) *Environmental Health Desirability* -- how we monitor and keep the minimum standard of human and ecosystem health after the following processes of energy and material flow transformation; (i) acquisition; (ii) production; (iii) distribution; (iv)

consumption; and (v) assimilation. In a similar fashion to resource trade, these wastes could be traded if circumstances allowed;

(3) *Socioeconomic Acceptability* -- how do we guarantee *Energy and Material Accessibility* along with *Environmental Health Desirability*, based on the socially desirable material standard of living, industrial structures, and institutional settings associated with the population under assessment, by using the given *Technological Achievability*? In the literature, no author so far has benchmarked the performance of photovoltaics with the characteristic pattern of energy carrier production in the energy and mining sector.

(4) *Technological Achievability*---how do we satisfy Socioeconomic Acceptability based on the present technological level and the plausible future technological prospects?

The complete examination of these four condition dimensions useful for identifying the limiting factors of PV systems within the MuSIASEM framework is not fully attempted in this paper. Instead, a set of flow and fund elements that are, in the author's view, crucially important for the large-scale deployment of PV systems are picked. In particular, the requirement of direct and indirect flow and fund elements in photovoltaic power stations based on crystalline silicon wafer solar cells are selected. In our analysis we consider five energy and material flow elements (energy carriers in the form of electricity, fuel and heat; water; and silver) and two fund elements (labor and Ricardian land).

3. Data and methodology

In our accounting methodology we introduce the production factors mentioned in Section 2 into the two stages of *fund*-making, that is, the production of solar panels, and the subsequent generation of electricity (**Table 1**). The first stage consists of the following processes: (i) silica mining and refining; (ii) reduction and purification; (iii) wafer sawing; (iv) PV cell production; (v) PV panel production; (vi) transportation and installation and; (vii) final dismantling.

Table 1 around here

Table 1 A Flow-Fund Representation of the Present PV systems - The quantities are reported as intensive variables (per unity electricity produced).

	Physical quantity	**Specific direct requirement (fund)**	**Specific indirect requirement (flow)**

Funds		Human labor $(h\cdot GWh_{el}^{-1})$	HA_d	HA_i
		Land $(m^2\cdot GWh_{el}^{-1})$	L_d	L_i
		Power Capacity $(MW\cdot GWh_{el}^{-1})$	PC_d	PC_i
Flows		Water $(m^3\cdot GWh_{el}^{-1})$	W_d	W_i
	ECs	Electricity $(MWh_{el}\cdot GWh_{el}^{-1})$	El_d	El_i
		Heat $(GJ_{he}\cdot GWh_{el}^{-1})$	He_d	He_i
		Fuel $(GJ_{fu}\cdot GWh_{el}^{-1})$	Fu_d	Fu_i
		Silver $(kg\cdot GWh_{el}^{-1})$	Ag_d	Ag_i

We acknowledge the different quality of energy forms, refraining from aggregating in our accounting the various energy carriers – electricity, fuel and heat – due to the different qualities and characteristics of these energy forms. This kind of pre-analytical option is required due to the different uses and usefulness of different forms of ECs at performing specific functions in complex autopoietic systems (i.e. systems which replicate and generate themselves), such as societies [19]. Applying the MuSIASEM approach, we use a “semantically open” grammar. That is, a set of expected relations over semantic categories that can be formalized *a la carte*, depending on which questions are relevant for the social actors/stakeholders involved in the system representation [4,14]. Explicitly, we define a series of semantic and formal categories, e.g. “net supply of energy carriers” and “kWh of electricity”, physical quantities and their relative quantification in appropriate units, respectively.

In our analysis, we evaluated only utility-scale and ground-mounted, fixed-tilt solar power plants constituent of multicrystalline silicon wafer-based solar cells. The PV installations based on these first-generation solar cells still represents the most widely adopted technology worldwide, with a market share above 90% [20]. Indeed, in spite of the research that led to the development of second generation (thin-film) and third generation solar cells, the share of crystalline silicon wafer-based solar cells firmly predominates, with no apparent sign of decline.

In spite of the fact that the majority of photovoltaic installations worldwide are low small-scale rooftop, utility-scale plants constitute a very relevant fraction in terms of power capacity. For electricity production, an average solar radiation of 1700 kWh m^{-2} y^{-1} is assumed. A sensitivity analysis of the parameter was also performed, however, and a wide range of solar irradiations (850 – 2500 kWh m^{-2} y^{-1}) were considered, spanning from high-latitude low insolation to the highest values typical of deserts. A production factor of 0.7 was adopted to account for the conversion losses, including mismatch of modules, reduction of efficiency due to dust, transmission and grid losses, and so on [21,22]. An average efficiency of 16% is also assumed, with a PV panel lifetime of 30 years. The assumed solar panels power density is 160 W/m^2. All of these figures are typical for modern commercial technologies. From these data an average electricity production of 36 GWh_{el}/MW_p during the plant lifetime is estimated (with a range 18 – 53 GWh_{el}/MW_p dependent on solar insolation). The interval spanned could be even wider due to the different optimal packing factor at different latitudes [23]. The capacity factor assumed is 0.17 (i.e. the fraction of hours of the year during which the plant is actually producing), with a range of 0.10 – 0.26; this quantity can also be as low as 0.05 in particularly cloudy regions.

The data used for the accounting scheme is derived directly from measured experimental values. Models/extrapolations have been excluded from the accounting, privileging bottom-up data from technical documents over top-down statistics wherever possible. However, data is affected by a rather high amount of uncertainty, particularly for the quantities of human labor and water, due to the absence of systematic and accurate investigations in the literature.

The variables are expressed as intensive quantities - that is to say in relation to the electricity produced (per GWh_{el}). The intensive quantities (expressed per GWh_{el}) have been derived by dividing the unitary value of each item per MW_p installed by the lifetime production of electricity of the plant, expressed in GWh_{el}/MW_p. The values for human activity are taken from [24], multiplying the coefficient of jobs/MW_p (respectively, 21.44 and 1.65 persons $\cdot$ y $\cdot$ MW^{-1} for the fund-making and the flow-generation stage) by the number of hours worked per year (1,800 h) as well as the employed human factor in the mining and refining sector (equations (A.1) and (A.2) in the Appendix). The data represents the most accurate accounting in the literature and refers to the Spanish sector in the year 2012.

With regard to land use accounting, data refers to total occupied area and was taken from two publications related to PV solar power stations in the US [25,26]. Additionally, the average power density of 62 plants has been calculated to be 37 W m^{-2}. The specific direct land requirement has been calculated according to equation (A.3) in the Appendix.

The coefficients for water use and for energy carriers derive from several technical reports and life-cycle assessments [1,22,27–33]. The final indirect input figure has been obtained by summing each of the sub-process components (i.e. silica mining, silica reduction, metal grade silicon to solar grade silicon conversion, casting, wafer sawing, solar cells, panels production and final decommissioning - equations (A.4), (A.6), (A.7), (A.8), respectively). In contrast, direct requirement is related to employment in the operation and maintenance stages (equations (A.5), (A.9), (A.10), (A.11)). The data assumed for silver consumption per unit of installed power, 36 g/W_p, refers to the average of commercial technologies in 2014 [34] (equation (A.12)).

Finally, all of the quantities for the national case Study of Spain in the year 2013 (ECs of production and consumption, hours of labor, and so on), were retrieved from the Eurostat database (procedure details are described in the Appendix) [35].

4. Results and discussion

Specific intensive benchmarks for different levels of local solar radiation intensity are reported below in Table 2. The benchmarks are calculated relative to net electricity production. Electricity used in flow generation is negligible in relation to its production. On the contrary, electricity use is extremely relevant in the fund-making process. The first observational note is that of the majority of resources are allocated in the fund-making process, as is intuitive.

Table 2 around here

Table 2 Specific technical coefficients allocated in the direct (electricity generation) and indirect stage (fund making) - The quantities are reported as intensive variables, per unity of electricity produced in GWh_{el}

Solar insolation ($kWh\ m^{-2}\ y^{-1}$)	**1700**		**850**		**1250**		**2100**		**2500**	
	Specific direct	Specific indirect	Dir.	Indir.	Dir.	Indir.	Dir.	Indir.	Dir.	Indir.

	requirement (fund)	requirement (flow)								
Human labor ($h \cdot GWh_{el}^{-1}$)	1100	83	2200	170	1500	110	870	67	730	57
Land ($m^2 \cdot GWh_{el}^{-1}$)	760	N.A.	1500	N.A.	1000	N.A.	620	N.A.	520	N.A.
Water ($m^3 \cdot GWh_{el}^{-1}$)	420	10	840	21	570	14	340	8.3	280	7.0
Electricity ($MWh_{el} \cdot GWh_{el}^{-1}$)	38	0.15	75	0.30	51	0.20	31	0.12	26	0.10
Heat ($GJ_{he} \cdot GWh_{el}^{-1}$)	84	1.5	170	3.0	110	2.1	68	1.2	57	1.0
Fuel ($GJ_{fu} \cdot GWh_{el}^{-1}$)	9.8	1.5	20	3.0	13	2.0	8.0	1.2	6.7	1.0
Silver ($kg \cdot GWh_{el}^{-1}$)	1.0	N.A.	2.0	N.A.	1.4	N.A.	0.82	N.A.	0.69	N.A.

In contrast to this data, the specific input of production factors is seen to be definitively higher in the flows-generation stage in a published work on a similar grammar assessing the performances of power-plants based on nuclear energy and coal [14] (Table 3). For these types of power plants, direct requirements represent the quantity of production factors allocated during the flow-generation stage. These production factors include, for example, the mining and enriching/refining of primary energy sources, the operation and maintenance activities of thermal plants, and the handling of generated waste.

Table 3 around here

Table 3 Comparison of the performance of solar PV electricity generation relative to nuclear and coal-based electricity generation The quantities in Table 3 are reported as intensive variables, per unit of net electricity production in GWh_{el}**.** The amount of process heat and fuel used has been aggregated as “thermal energy carriers” for the sake of comparison. Abbreviation: IGCC - Integrated Gasification Combined Cycle.

Direct requirements (flow generation)

	Photovoltaics		Nuclear		IGCC (Coal)	
HA (h/GWh_{el})	83	57-170	480	N.A.	160	N.A.

El (MWh$_{el}$/GWh$_{el}$)	0.15	0.10-0.30	33	±0.4	32	N.A.
EC$_{th}$ (GJ$_{th}$/GWh$_{el}$)	3.0	2.0-6.0	250	±130	160	N.A.

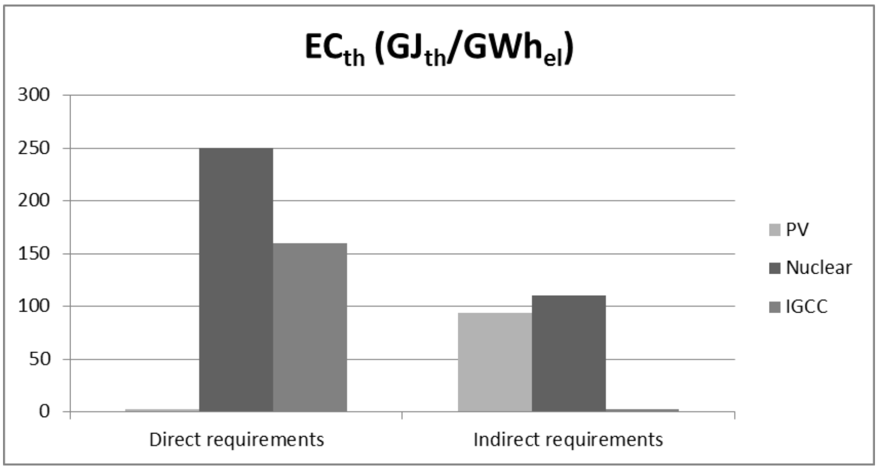
Indirect requirements (fund making)

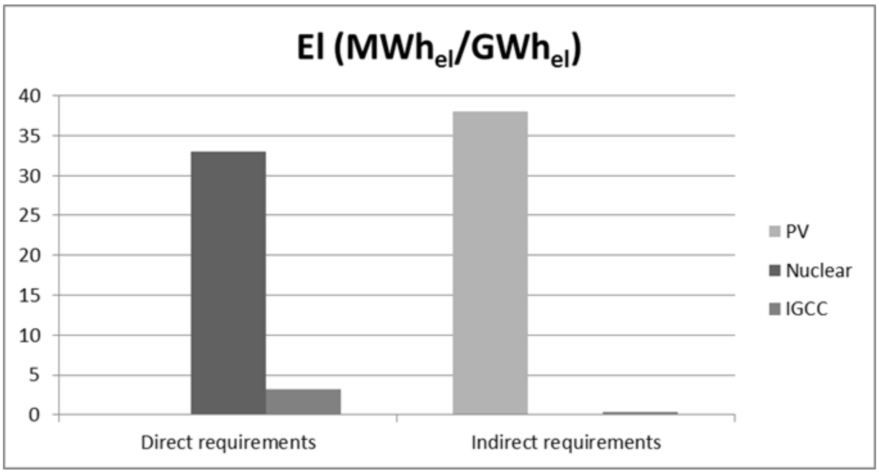
	Photovoltaics		Nuclear		IGCC (Coal)	
HA (h/GWh$_{el}$)	1100	730-2200	160	N.A.	15	N.A.
El (MWh$_{el}$/GWh$_{el}$)	38	26-75	N.A.	N.A.	0.32	N.A.
EC$_{th}$ (GJ$_{th}$/GWh$_{el}$)	94	74-190	110	±9	2.3	N.A.

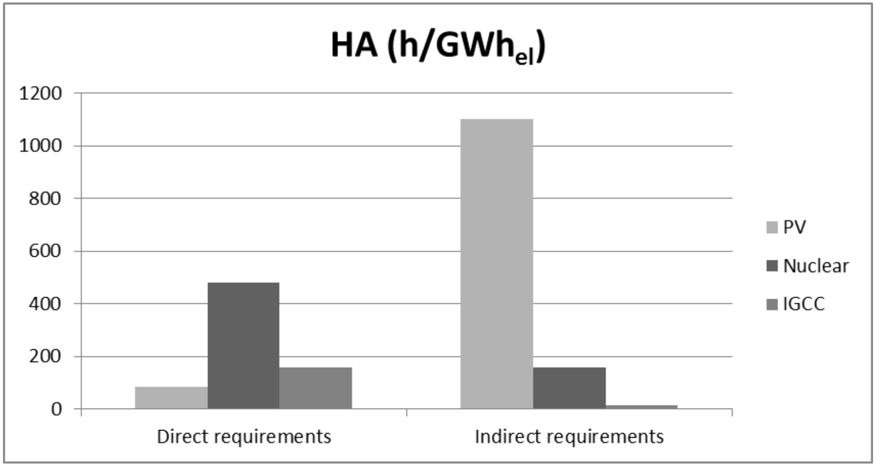
These differences in direct and indirect requirements derive from profound differences in the processes of electricity generation. In the case of PV, electricity generation is based on the photovoltaic effect, which does not require any particular input *per se*, except obviously sunlight (a physical gradient outside of human control) and some minor maintenance and operational activity to assure complete functionality of the plant. On the contrary, the electricity production in a thermal plant is much more demanding (Figure 2) in terms of production factors, starting from the supply of the primary energy source, whose provision must be guaranteed. Moreover, once the chemical energy stored in the PES is converted into thermal energy, a further transformation into mechanical energy is required to convert it into electrical energy. Hence, the complexity of this type of power-plant demands numerous inputs in order to assure effective energy conversion.

Figure 2 around here

Figure 2 Graphical representation of several allocated production factors (ECs and labor) of PV in comparison with nuclear power and coal-based power (IGCC) for electricity production Figure 2 stresses the different characteristics of the conversion processing and the different demand pattern for the fund-making and flow-generation stages.







With regard to biophysical constraint (*Energy and Material Accessibility*), the power of solar insolation does not represent a limit *per se,* with an average value of 174,000 $W \cdot y^{-1}$ reaching Earth of which 21,840 TW reach ice-free land surface. Should this last quantity be entirely converted into electrical energy, roughly one hour of supply would be enough to meet the current annual world electricity demand. On the other hand, a limiting factor of *Energy and Material Accessibility* may be the use of silver in PV cell manufacturing (silver is used in a specialized paste for the contact metallization of silicon wafer-based cells). Although the decrease of silver consumption per cell has been remarkable in recent years, down to 36 mg_{Ag}/W_p on average in commercial technologies in 2014 [34], in the case of a solar PV deployment large enough to cover 30% of the current yearly global electricity demand (4.6 TW of new installations), the total usage of the silver commodity could reach 33% of the currently estimated world reserves of the metal [36]. Other authors have tackled the issue, and have come to contrasting conclusions [37–39] on silver as well as other potentially more critical metals used in PV deployment [40]. In addition, as silver is mostly extracted as a companion metal, a heightened requirement of the commodity would also affect the mining of the host metals, i.e. copper and lead, influencing their prices as well as their general recycling rate [41]. In spite of the remarkable decreases recently achieved in the use of silver for the contact metallization of the cells both for the finger and the busbar parts, the employment of silver continues to play a central role. According to "contact-metallization" experts, alternative technologies, including the promising Ni/Cu plating one [42], do not seem to be in the position to replace silver, at least in the medium term [43]. Some supply of the metal could be provided for by using old scrap, though whether the metals from disposed solar panels will be recoverable, and to what extent, is still unclear. A recovery rate of 30-50% is reported in the literature [44], however the number of systematic studies on PV module recycling is entirely inadequate.

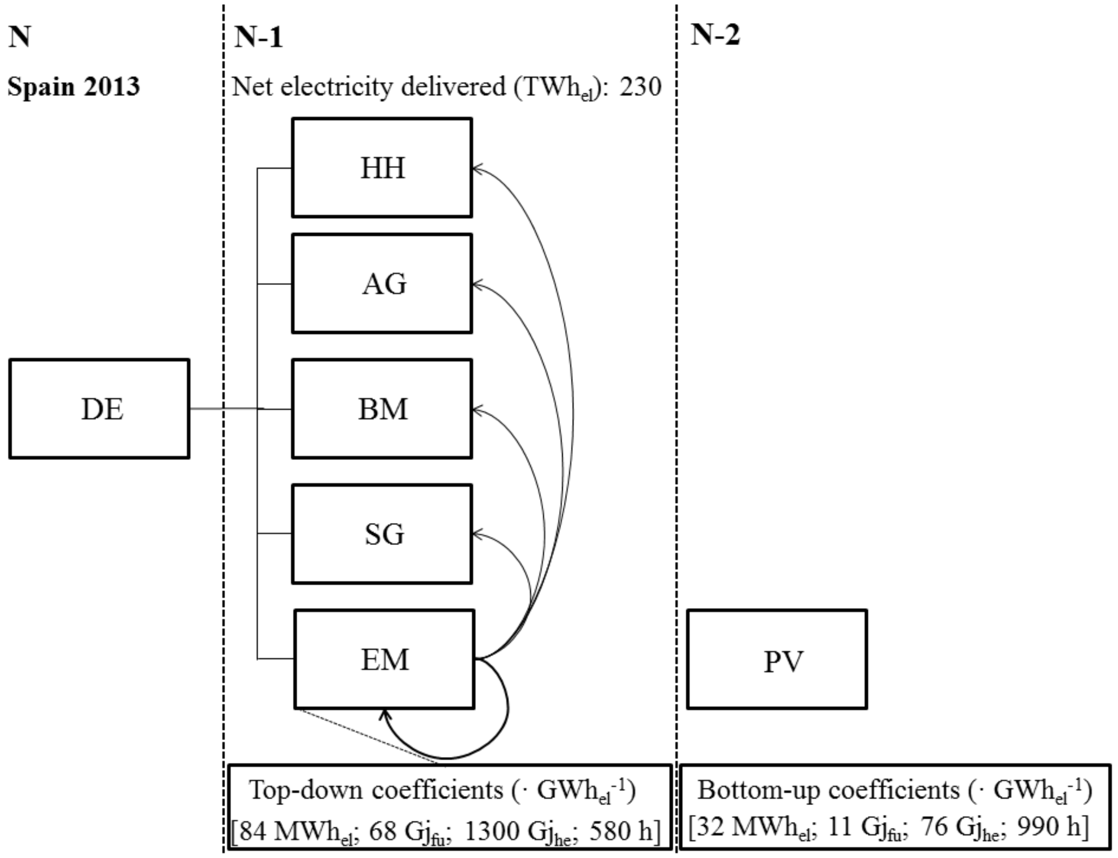
Conversely, water does not represent a limitation of *Environmental Health Desirability* in photovoltaics deployment: most of its use takes place in the production process. Generally, for this type of application high-value demineralized, if not deionized, water, is required. A small amount is also required for panel cleaning, with the number of washing cycles estimated to be between two and four per year [1,22]. In the flow-generation stage PV is not at all water-intensive, its use ranging between two-three orders of magnitude less than most other electricity generation technologies including fossil-fuels based ones [45] as well as nuclear and geothermal power [46]. The only less water-demanding technologies appear to be other renewables, wind and hydroelectric [46,47]. Although water consumption for cleansing does not quantitatively represent an issue, its local scarcity could be a limiting factor in very highly insolated, desert and arid areas, where utility scale PV power stations tend to be installed due to the favorable insolation conditions. However, water usage in these circumstances is reduced to the extreme in comparison with other solar techniques, such as concentrated solar thermal (CSP) where water plays a more prominent role in the cooling phase as it is involved in the condensation of vapor produced at the turbine outlet [48]. As a matter of fact, water consumption is two orders of magnitude higher for CSP in the flow-generation stage in comparison to photovoltaics [49]. This holds even for the innovative and promising dry-cooling technology, in spite of the fact that it is 77% less water intensive in comparison to water-cooling technology [48]. With regard to land use, 520 – 1500 m^2 are required to produce 1 GWh_{el} for PV solar power plants. This figure corresponds to an average power density of 37 W/m^2, though, in the literature, some authors estimate an entire order-of-magnitude lower [50,51]. In comparison, the supplied power density in fossil fuel power plants is at least one order of magnitude higher [52]. In the literature, however, it has also been argued that coal-based power plants are significantly land intensive, once one performs a thorough calculation of land transformation, e.g. that which occurs during the mining stage [26]. This is the case for thin-seam low-quality coal mines, such as some types of lignite mines, with an overall performance benchmarked on the same order of magnitude as photovoltaics [50]. Typical power densities for electricity consumption are between 20 - 100 W/m^2 for houses, with lower benchmarks in rural areas. On the contrary, in urban contexts the quantity can be orders of magnitude higher, ranging from 200 – 400 W/m^2 in the case of office edifices, and up to 3 kW/m^2 for high-rise buildings [52]. In spite of the fact that solar photovoltaics is the densest form of renewable energy, the mismatch between the high power density demandof urban systems is blatant. This “power dilution” could potentially drive a significant land rush as remarked in Scheidel and Sorman [53] in the case of a significant solar PV deployment.

In relation to technological and socioeconomic viability (*Technological Achievability and Socioeconomic Acceptability*), the highest share of energy carriers is used in fund-making, as already seen in Table 3. This is especially true for electricity, whose consumption is two orders of magnitude higher in the fund-making stage compared to the flows-generation stage (see the Appendix for details). Most electricity is consumed in the manufacturing process, especially during the purification of metallurgical-grade silicon and wafer sawing. Indeed, the purification of metallurgical-grade silicon consists of a carbothermic reduction, a process which takes place at very high temperatures.

On the socioeconomic desirability side (*Socioeconomic Acceptability*), modern societies are characterized by the allocation of a very limited fraction of human labor (paid work) in the agricultural, energy and mining sectors. This allows for the investment of large fractions of paid-work hours in the service and government sector, in addition to the availability of a significant quantity of time for leisure activities, where the resources produced or imported are consumed. That is to say, in order to allocate more time in consumptive activities, the production of resources has to be met with a certain minimal fraction of human labor. Following a protocol already applied in the literature, it is possible to check the viability of a certain power technology for the production of an EC benchmarking its performance with the characteristic value of the EM sector of a defined nation [54]. Confronting the top-down technical coefficients of the EM sector with the bottom-up ones of a specific technology, it is possible to test the implications of the introduction/spreading of the technology under assessment, as the example in Figure 3 depicts. In terms of ECs consumption, photovoltaic turns out to be much less intensive in comparison to the global Spanish EM sector. This result is not surprising, since the latter comprises several very demanding energy steps such as the mining of ores and other resources, as well as the refining of oil (a process especially intensive in terms of heat use). Therefore, in relation to EC use, there seems to be no constraint to a massive PV deployment. However, the allocation of human activity appears to be more critical, as the PV comes out to be roughly twice as labor intensive than the average of the EM sector. This aspect could have significant implications on the *Socioeconomic Acceptability* of PV.

Figure 3 around here

Figure 3 Assessment of the viability of PV for electricity production: In Figure 3, performance is benchmarked against the Energy and Mining Sector of Spain in the year 2013. Coefficients are reported as intensive variables (per net unit of electricity delivered to the rest of the society). For PV, the reported coefficients derive from the aggregation of the fund-making and flow-generation stages. A solar insolation of 2000 kWh m^{-2} y^{-1} has been assumed as average for Spain. Abbreviations: DE – domestic economy.



5. Conclusion

Our approach represents a first attempt at thoroughly analyzing the performances of solar power systems based on photovoltaic technology for electricity production. The potential criticalities with regard to a number of production factors have been identified. The biophysical viability of PV technology could be constrained by the availability of silver used during the PV-cell manufacturing stage. Furthermore, the low power density of photovoltaics installation could drive a remarkable land rush. The technology appears to be significantly less water intensive than other electricity generation technologies, nevertheless the local availability of water in desert areas could represent a challenge. In relation to technological viability, the most significant fraction of the energy carriers is consumed during the fund-making stage. Finally, with regard to socioeconomic viability, human labor indirectly allocated in the fund-making process could represent a serious constraint with respect to the metabolic requirements of modern societies. The uncertainty of some data and the extreme heterogeneity of the data sources would require a more systematic survey of the allocated production factors within a precise contextualization in a given national, regional or local system. A more circumstanced spatial scale would allow for the definition of a precise value for solar insolation, and the homogeneous identification of specific production factors for a certain industrial system. For example, it would be very interesting to apply the methodology at to China or Japan, the countries where the highest share of the solar photovoltaic power capacity is manufactured [31,55], and currently installed (with annual added capacities in 2014 of 10.6 and 9.7 GW_p, respectively [56]). Further work should include the adoption of a thorough accounting scheme [57] that will address also the sink side, i.e. emissions and generated waste in relation to the issue of biophysical constraints, in addition to required power capacity. Furthermore, the elaborated tool-kit could prove very useful to policy-makers as a decision making aid. For instance, the accounting tool can be used in order to address what production factors would be required as well as what would be needed in terms of jobs, land use, and so on, in order to realize a certain degree of penetration of photovoltaics into an electrical-grid system. Moreover, economic/monetary aspects could be integrated into the assessment in order to have a more complete evaluation. Finally, accounting for the typical daily pattern of electricity production would make it possible to concretely estimate what the actual possibilities of electricity-grid penetration and the relative volume of power storage required for the grid harmonization would be.

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