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RESUMEN

Según el séptimo objetivo de desarrollo sostenible (ODS) concluido por la Organización de las Naciones Unidas (ONU), la energía deberá ser limpia y accesible para todos en las próximas décadas. La energía limpia se utiliza a menudo como sinónimo de energía renovable (ER), sostenible o verde, palabras que se asocian con un concepto de tecnologías de bajo impacto ambiental (IA). Sin embargo, las ERs también tienen asociados IAs negativos, que pueden identificarse y evaluarse mediante instrumentos como la Evaluación de Impactos Ambientales (EIA) o el Análisis de ciclo de vida (ACV). Este artículo se centra en la revisión de los IAs documentados en diferentes ACV para sistemas de energía solar fotovoltaica (SEPV), el tipo más común de ERs modernas para satisfacer la demanda energética a nivel mundial.

Aunque diferentes estudios de ACV incluyen varias categorías ambientales de evaluación, para el análisis se seleccionaron 5 categorías, potencial de calentamiento global (GWP, por sus siglas en inglés), uso del suelo, pérdida de biodiversidad, salud humana y generación de residuos.

Los resultados muestran que los IAs de los SEPV documentados en ACVs dependen no solo de la tecnología, el contexto y la escala del proyecto, sino también del objetivo y alcance de cada estudio. Aun así, este artículo recoge valores orientativos para el GWP, el uso de suelo y los accidentes mortales de aves relacionados con SEPV. Además, la investigación revela la necesidad de enfoques complementarios como EIA o estudios de toxicidad para poder dimensionar impactos acerca de pérdida de biodiversidad y daños a la salud humana, así mismo concluye la falta de un sistema de gestión de residuos adecuado para las miles de toneladas que generarán estos sistemas a futuro.

Palabras clave: Energías Renovables, Energías Sostenibles, Energías Limpias, Energías Verdes, Impacto Ambiental, Sistemas de Energía Solar Fotovoltaica, Desarrollo Sostenible, ODS, Evaluación de Impactos Ambientales, Análisis de Ciclo de Vida.

Environmental impacts of solar photovoltaic systems: a revision from life cycle assessments and other studies

ABSTRACT

According to the 7th goal of sustainable development concluded by the United Nations (UN), energy should become clean and accessible for every human being on the planet in the upcoming decades. Clean energy is often used as a synonym for renewable, sustainable or green energy, words which are associated with a concept of low-impact technologies. However, renewable energies (REs) also have a set of negative environmental impacts (EIs), which can be identified and assessed through an EI Assessment (EIA) and/or a Life Cycle Assessment (LCA). This article focuses on the revision of EIs documented in LCA studies for solar photovoltaic (PV) systems (SPVSs), the most common type of modern REs to satisfy energy demand globally.

Although different LCA studies include various environmental assessment categories, five categories were selected for analysis, namely global warming potential (GWP), land use, biodiversity loss, human health (HH) and waste generation.

The results show that documented EIs of SPVSs from LCAs depend not only on the technology, context and scale of the project, but also on the objective and scope of each study. Still, this article summarizes orientational values for the GWP, land use and fatal bird accidents related to SPVSs. Further, the research reveals the need for complementary approaches such as EIAs or toxicity studies for the assessment of biodiversity loss as well as the impacts on HH, and the lack of an existing waste management system for the million tons of waste soon to be disposed.

Keywords: Renewable Energy, Sustainable Energy, Clean Energy, Green Energy, Environmental Impact, Photovoltaic, PV, Sustainable Development, SDGs, Environmental Impact Assessment, Life Cycle Assessment.

1. INTRODUCTION

For decades, the provision of clean energy has been recognized key for achieving SD by international organizations such as the World Health Organization, the International Union for Conservation of Nature and the Food and Agriculture Organization (FAO), among others. The UN (2021) estimated that energy accounts for 60% of greenhouse gas (GHG) emissions and governments around the world are directing their efforts towards reducing the environmental cost of energy through implementing REs. The Intergovernmental Panel on Climate Change (IPCC) identified the use of REs as a pillar for achieving SD, as the emission of GHGs associated to REs is deemed to be significantly lower compared to those related to fossil fuels (FFs), Edenhofer et al. (2012).

According to the IEA et al. (2019), modern REs also play a key role to respond to the fact that by 2019, 13% of the global population still lacked access to modern electricity (especially in low-income rural areas) and 44% lacked access to clean cooking fuels and technologies. This results in a significant threat to HH and the environment, as stated by the United Nations Statistics Division (2021).

The share of REs in the energy mix is considered a key indicator to assess the achievement of SD Goal (SDG) No. 7; specifically, Target 7.2 is *to increase substantially* *the share of renewable energy in the global energy mix*. However, experience with conventional REs has demonstrated that *renewable* is not a synonym for a lack of adverse EIs, as stated by Romero and Higinio (2021).

According to the SD Scenarios (SDS) carried out in the Energy Progress Report by the IEA et al. (2019), solar photovoltaic (PV) is the most relevant energy source to achieve SD and global power generation from solar PV is expected to increase over 350% from 2019 to 2030.

2. METHODOLOGY

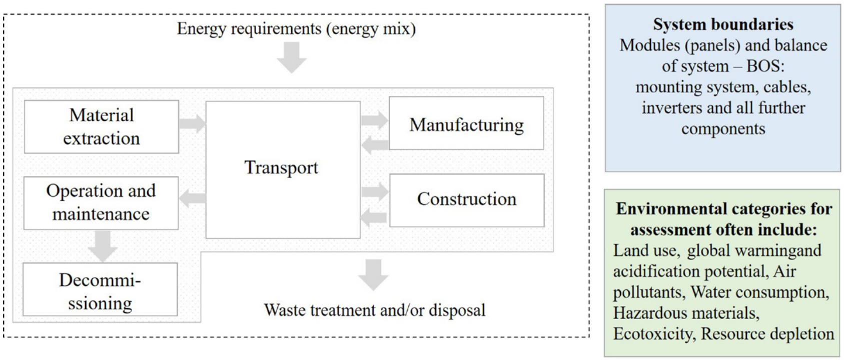
This article intends to analyze some of the adverse EIs that should be foreseen as we advance in the purpose of substantially increasing the share of solar PV in the global energy mix. The aim is to examine the EIs of utility-scale SPVSs for selected environmental categories, based on the revision of information gathered in recent LCA studies.

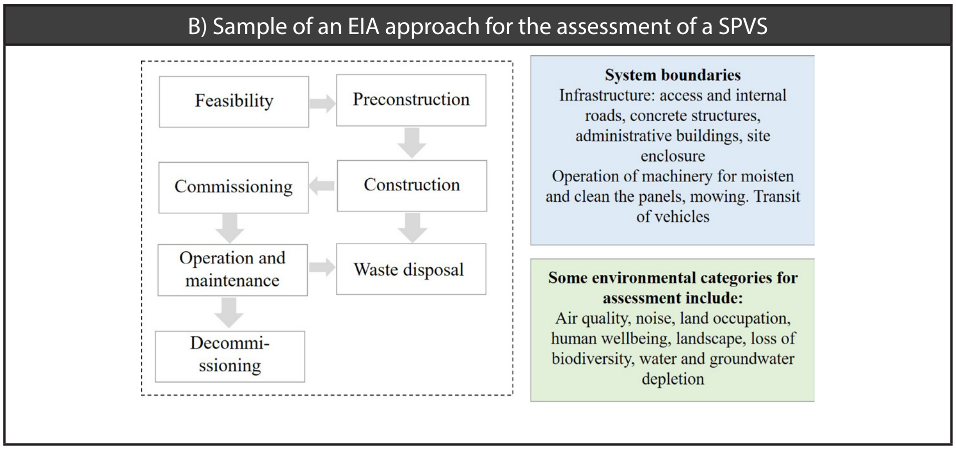
The global energy matrix was analyzed, in order to get an overview of the current use, scope and future trends of utility-scale SPVSs, including a revision of Total Final Consumption (TFC), electricity generation by source and the perspectives for future SDSs.

Different approaches provide tools for assessing the EIs of an activity, project, or technology. As described by Cornejo et al. (2005) and Fthenakis et al. (2011), an LCA, also known as a *cradle to grave* approach, allows estimating EIs covering the timeline from resource extraction up to final disposal of materials, analyzing each stage of the lifecycle involved in the study. An EIA is an instrument to foresee significant EIs of large-scale projects. It is often a mandatory instrument conversely to an LCA, and is carried out at the planning stage, allowing in advance the formulation of action plans to manage potential EIs. A monitoring and follow-up plan allows determining whether the EIs manifest as foreseen in the EIA.

System boundaries and environmental categories assessed through each of these approaches vary from study to study, depending on objectives and scope. A sample of system definition for each approach is shown in Figure 1.

Figure 1. A) Sample of an LCA approach for the assessment of a SPVS




B) Sample of an EIA approach for the assessment of a SPVS

Although this paper is centered on the revision of EIs documented in recent LCA studies, we found it relevant to complement the information regarding impacts on biodiversity loss and HH with other studies.

3. RESULTS

SPVSs

SPVSs transform direct energy from the sun into electricity, through an arrangement of multiple rectangular-shaped solar cells (solar modules), one or multiple inverters, charger controllers and wirings (conductors) to connect the system, and a surge protector to avoid electrical shocks. All mentioned components other than the panels are referred to as the Balance of System (BOS). The scale of SPVSs range from small rooftop units up to large-scale utility PV parks containing thousands or even millions of modules and extending over large areas.

The basic principle of SPVSs is the conversion of solar radiation to continuous current by a semiconductor being the solar cells, as described by Balfour et al. (2011). The material conventionally used for this semiconductor is Silicon (Si). Monocrystalline or single-crystalline Si (Mono-Si or sc-Si) and multi- or poly-crystalline Si (pc-Si) modules are described by Muteri et al (2020) as *first generation* PV cells. The Fraunhofer Institute for Solar Energy Systems ISE (2021) estimated that by 2020, 95% of cummulative production of solar PV modules were c-Si.

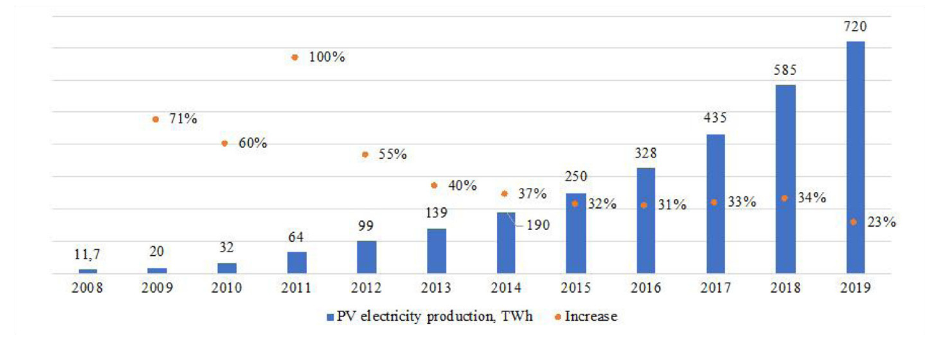
Second generation PV cells include amorphous Si (a-Si), Cadmium-Telluride (CdTe) and cadmium sulfide (CdS), while *third* or *next generation* PV cells include, among others, perovskite solar cells (PSC) and dye-sensitized solar cells (DSSC).

PV in the global energy mix

As described by Romero and Higinio (2021), although the global production of modern REs increased 8 times between 1990 and 2018, the scope of modern REs in the global mix contributes to 0,2% to the TFC. In their study they found that modern REs account for no more than 10% to the TFC of an economy, except for Iceland, due to their above-average use of geothermal sources.

According to the IEA database (2021), between 2009 and 2018, the electricity produced from solar PV increased nearly 50 times (Figure 2) and roughly 0,5% of global electricity in 2018 was produced with solar PV.

Figure 2. Electricity produced from solar PV, globally (TWh). Data: IEA, 2021.



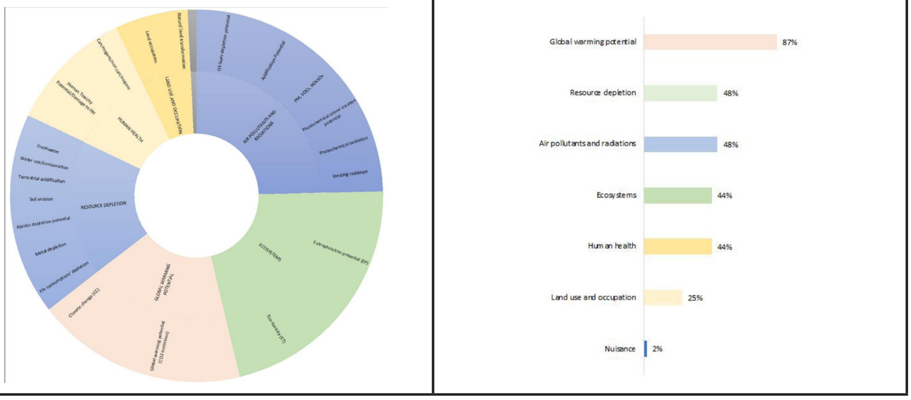
More PV power plants are being planned and constructed than any other modern energy technology project. IEA et al. (2019) suggested this is due to rapidly declining costs and an increase of supportive policies in leading countries. The SDS carried out by IEA et al. (2019) in the Energy Progress Report estimated that the production of electricity from solar PV in 2030 will be 3,268 TWh, roughly 5 times the amount in 2019. Irena (2019) estimated a total installed capacity of SPVSs of 2,840 GW by 2030.

EIs of SPVSs

EIs of SPVSs vary widely depending on scale, use (on-/off-grid), technology and location. The IEA´s Methodology Guidelines on LCA of Photovoltaic Electricity by Fthenakis et al. (2011) suggested that LCAs for SPVSs should assess GHG emissions, cumulative energy demand, acidification potential, ozone depletion potential, human toxicity, ecotoxicity and ionizing radiation. Environmental categories assessed, however, vary from study to study, depending on scope, purpose and methodology of each LCA. We gathered information from Muteri et al. (2020), who revised 39 LCAs of on-grid SPVSs, and added 12 LCA studies and revisions in order to identify environmental categories commonly analyzed, as resumed in Figure 3.

Figure 3. A) Share of environmental categories assessed and/or analyzed in 51 SPVS LCA studies.

B) Percentage of revised authors considering at least one indicator for each environmental category.



We decided to revise GWP from SPVSs, as this poses a global concern that has contributed to the development of modern REs; land use, as this is closely linked to potential EIs on biodiversity and an important territorial planning aspect; and impacts on ecosystems and HH. Although waste generated throughout the system boundaries is often used as an input in LCA studies, it is included in this analysis, as the authors are concerned with the amount of waste to be dealt with in the future resulting from SPVSs.

Global warming potential (GWP)

Energy, which often includes FFs in its origin, is required for manufacturing processes. According to Alsema and de Wild-Scholten (2007) emissions from SPVSs can be directly or indirectly accounted to process energy, either in the extraction and manufacturing of materials (*embedded* energy) or directly in transportation processes (*induced* energy).

GWP is often assessed by estimating GHG emissions in terms of carbon dioxide equivalencies (CO_2-eq). The values vary widely depending on the energy mix of the manufacturing country and the efficiency of the cells. Ludin et al. (2021) explained that GWP from SPVSs also depends on the scale and technology used, whether the system is on- or off-grid, the lifespan of the system and numerous other aspects that may vary from one LCA to another.

Information on GWP related to SPVSs was gathered from different authors (Table 1). All encountered LCAs include the GWP from energy for raw material extraction and the manufacturing of modules. However, estimations may or may not include the BOS, maintenance and end of life (EoL) of modules. Different authors, including Rao et al. (2021), Müller et al. (2021) and Anak et al. (2021) attributed 80 to 90% of GWP of SPVSs to material extraction and the manufacturing of PV modules. Rao et al. (2021) further estimated that the assembly stage and BOS alone account for 56% of GWP.

Fthenakis et al. (2011) suggested reporting 9 key parameters for each LCA study, namely irradiation level and location, module-rated efficiency, system performance ratio, time-frame of data, expected lifespan of modules and BOS, systems boundary and location of production; however, these are not always specified.

Table 1: Global warming potential of different SPVSs, power generation based

Author	Type of module	GWP, g-CO2-eq/ kWh
Müller et al. (2021)	sc-Si	13 to 30
Ludin et al. (2021). 25-year lifespan of SPVS	p-Si	12,1-569
	p-Si	
	p-Si	569
	a-Si	15,6-50
	sc-Si	29-671
Magrassi et al. (2018). 30-year lifespan of SPVS	sc-Si	43
Kim et al. (2013). 30-year lifespan of SPVS	sc-Si	41,8
	p-Si	31,5
Peng et al., 2013.	sc-Si	29-45
	p-Si	23-44
	a-Si	18-50
	CdTe	14-35
	DSSC	< 120
	CIS	10,5-46

From Table 1, GWP related to electricity produced with SPVSs ranges from 13 to 671 g CO2-eq/kWh. Still Rao et al. (2021) suggested that typical values for Si modules range around 50 g CO2-eq/kWh, which is relatively low compared to a global average of 440 g CO2-eq/kWh in 2020, from IEA (2019).

The lifespan duration of PV systems also influences the GWP estimations. Mérida García et al. (2019) estimated the GWP from off-grid SPVSs for rural irrigation, encountering that GHG emissions decrease by roughly 80% for a lifespan of 30 years compared to a duration of 5 years. Rao et al. (2021) suggested that the lifetime of cells is the most sensitive parameter for estimating GHG emissions, as the values are reduced with every increased year in lifespan. For their study with PSC they found that GHG emissions range from 122 to 300 g CO_2-eq/ kWh, for a lifespan of 5 and 2 years respectively, meaning a reduction of nearly 20% per year.

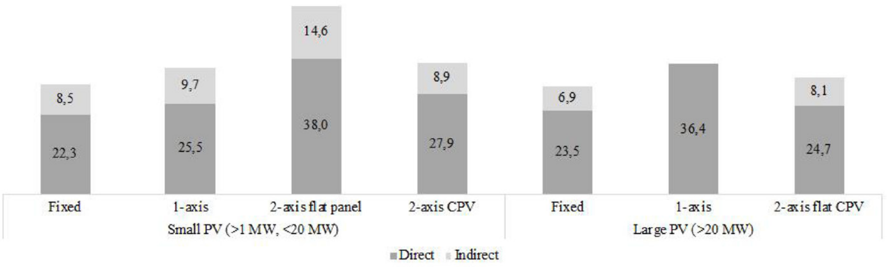
Regarding the *induced* energy, Müller et al. (2021) and Stamford and Azapagic (2018) estimated that transportation accounts for no more than 3% of the overall GWP. Dubey et al. (2013) suggested only 0,1 to 1% of GHG emissions are related to transport.

Land use

The increasing production of energy with solar PV comes along with the implementation of utility-scale ground-mounted SPVSs. Two parameters of evaluation are the *generation weighted* (km^2/GWh/yr) and *capacity weighted* land use (m^2/kW). The latter will further be referred to as the energy land-use intensity (ELUI).

Ong et al. (2013) studied the ELUI for US ground-mounted SPVSs as shown in Figure 4, including direct area use (land occupied by solar arrays, access roads, buildings and other infrastructure) and total area use, enclosed by the site boundary. According to this study, indirect land use adds 40% to direct ELUI for small-scale systems, and 30% for large-scale systems.

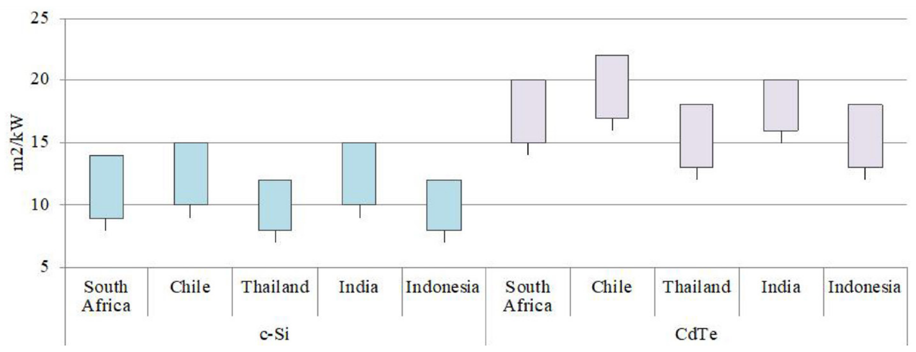
Figure 4. Direct and indirect land use for SPVSs, capacity weighted (m2/kW). Adapted from Ong et al., 2013.



CPV: concentrating PV

ELUI varies with scale, technology and location. Dhar et al. (2020) gathered information on land requirements for various SPVSs, encountering that direct ELUI ranges from 9 to 49 m^2/kW. The IFC (2015) also provided estimations for facilities in different countries (Figure 5), ranging from 8 to 22 m^2/kW. According to this source, ELUIs of c-Si (1st generation modules) are lower than those of CdTe. Even though the latter is considered a 2nd generation technology, CdTe thin-film modules have lower efficiencies.

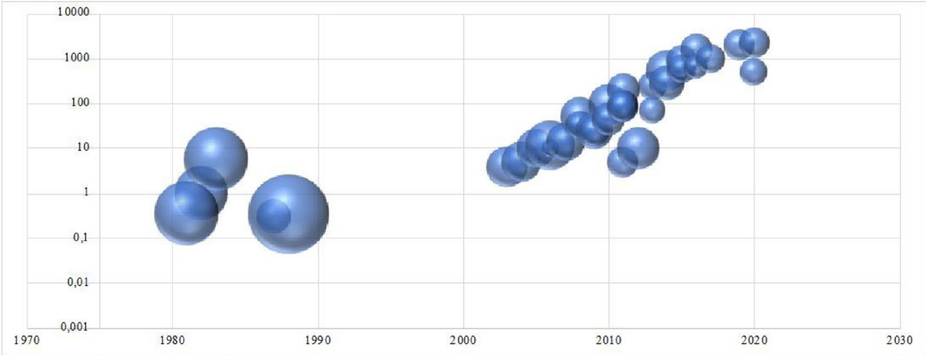
Figure 5. ELUI of c-Si and CdTe thin-film SPVSs in 5 countries. Data: IFC (2015)



Tawalbeh et al. (2021) stated that, although SPVSs have a high ELUI compared to other energy sources, ELUI of electricity produced from coal combined with coal sequestration is 5 to 13 times higher compared to that of SPVSs, due to lower efficiencies of thermal systems. They also concluded that wind power requires 10 times more land compared to SPVSs.

Figure 6 attempts to highlight trends of ELUI with information gathered from 35 utility-scale SPVSs worldwide. The size of the bubble represents the ELUI in m^2/kW, showing an average of 29 from 2010-2019, compared to an average of 37 from 2000 to 2009.

Figure 6. ELUI in m2/kW of 35 utility-scale SPVSs.



Biodiversity loss

Damage to ecosystems arises from complex chains of EIs on the abiotic components, including the infiltration of pollutants into the soil or erosion and transport of pollutants to water sources. Despite the fact that ecotoxicity (ET) or eutrophication potential (EP) can be assessed through an LCA as suggested by Fthenakis et al. (2011), an EIA allows further understanding of how the implementation of SPVSs contributes to biodiversity loss.

Land use and the release of toxic substances are closely linked to potential impacts on biodiversity. Da Pimentel Silva and Branco (2018) stated that the phase of construction is considered the most harmful for habitat and biodiversity loss, as it comes with potential removal of vegetation and the impact of heavy machinery. If pre-existing vegetation has to be removed, the impact on the soil and thus, the loss of habitat will be more extensive. In addition, a removal of vegetation may increase the danger of run-off and soil erosion, decreasing the soil quality.

Regarding the use of toxic materials, Antonanzas and Quinn (2021) concluded that the use of Copper (Cu), Aluminum (Al) and steel are the main contributors to eutrophication throughout the life cycle of SPVSs. During utilization stage, utility-scale SPVSs require the use of toxicants such as dust suppressants or rust inhibitors and solvents, used to clean the panels, with potential long-term impacts on ecosystems, as described by Hernandez et al. (2014) and da Pimentel Silva and Branco (2018),

Dhar et al. (2020) concluded that loss of biodiversity accounted to SPVSs is not a widely examined matter in the literature. Although some LCA authors are concerned with aspects such as habitat loss and fragmentation, microclimate disturbance and mortality of species, information on EIs is rather descriptive. The most quantified extinction of wildlife related to SPVSs is the loss of birds, occurring mostly due to a direct collision with the infrastructure of the facilities. None of the estimations, however, are made through an LCA approach. Visser et al. (2019) observed that the richness and density of bird species tends to be lower within the PV facility than in the boundary or the unaltered bordering zone. Dhar et al. (2020) estimated an annual bird mortality related to SPVSs ranging from 37,800 to 138,600 in the US, from previously documented data in southern California. They stated, however, that these numbers are much lower than those related to nuclear and FF energy plants.

Kosciuch et al. (2020) also performed a study on the revision of different sources in the US, concluding bird mortality associated to large-scale SPVSs varies between 2,7 and 9,9 mortalities/MW/year. Nonetheless, Loss (2016) and Loss et al. (2015) concluded that infrastructure such as highways, buildings, power lines or wind parks, are the biggest threats for avian collision and electrocution in the US and Canada.

Human health - HH

HH in LCAs for SPVSs is primarily discussed regarding possible ways to get in contact with toxic materials through air, soil or water. LCAs base their evaluation of impacts on HH on estimations regarding human toxicity potential, carcinogen/non carcinogen substances and respiratory organics/inorganics.

Human toxicity is often measured in 1,4-Dichlorobenzene-eq (1,4-DB-eq). Magrassi et al. (2018) found out that the production of components of a SPVSs has the highest contribution to 1,4-DB-eq (regarding a 100 kWp ground-mounted panel made of sc-Si).

Bakhiyi et al. (2014) and Sinha et al. (2019) stated that exposure to toxic materials for on-site workers can occur through dust, smoke, vapor inhalation, ingestion and dermal or eye contact. Bakhiyi et al. (2014) concluded that it is difficult to quantify the risks due to exposure, as they depend on the concentration and toxicity of the substances as well as the frequency and duration of the exposure.

Manufacture of modules: Antonanzas and Quinn (2021) compared PV panels manufactured and installed from 2000 to 2018 through an LCA approach and included several flexible parameters to determine their influence on the outcome. Their study concluded that Cu, Al and steel, often used in this industry, are the main contributors to human toxicity throughout the life-cycle of SPVSs. In every scenario and projection analyzed, the values of human toxicity ranged just below those of coal.

Regarding the category of HH in the manufacturing stage of CdTe modules, Rix et al (2015) monitored Cd levels in long-term workers, concluding no specific rise related to their occupation at the manufacturing plant.

The State University of North Carolina (2017) stated that the risks stemming from the exposure to hazardous substances within the manufacturing of PV panels is minimal, compared to those related to site contamination for most other lines of industry.

Use stage: Rix et al (2015) describe CdTe in their LCA study, as a *solid and stable compound, insoluble in water with a high melting point*, posing a low risk during extreme events. They state it is unlikely to have CdTe or CdS compounds released to the environment under normal circumstances.

For non-workers the highest risk of contamination as explained by Sinha et al. (2019) is the leakage of materials from broken cells into soil, air and ultimately the water cycle. Nonetheless, the same authors stated that even in the event of a leak due to module breakage, the values of contamination did not exceed the thresholds of the US Environmental Protection Agency (US-EPA) and therefore, are not deemed as a risk for HH. Rix et al. (2015) also considered that leakage of chemicals with intact panels is an unlikely event.

Robinson and Meindl (2019) documented a significant increase in levels of Selenium (Se), Lithium (Li), Strontium (Sr), Nickel (Ni) and Barium (Ba) in soils close to solar c-Si SPVSs, conversely to Lead (Pb) and Cadmium (Cd). The study suggests that metals leach from the system components (e.g., from the use of concrete) rather than the panels themselves. Although all metals were found below the US-EPA thresholds, they concluded the need for further study in order to better understand the impacts from construction and operation of SPVSs on ecosystems and HH.

Waste generation

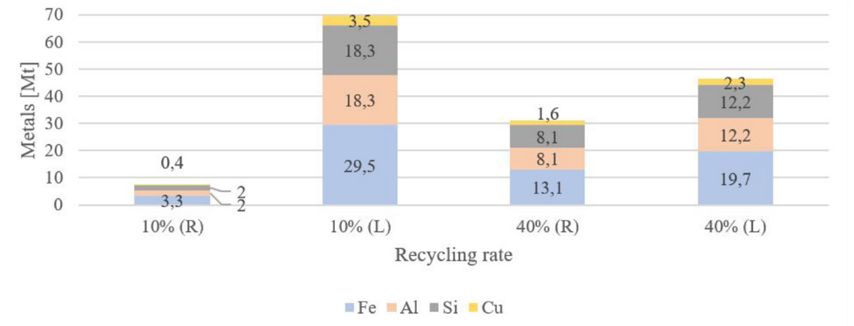
The authors consider the aspect of waste generation an important matter to analyse, as each utility-scale SPVS may be composed by hundreds of thousands, or even millions of PV units. With an average lifespan of 25 to 30 years for PV units, nowadays waste management for SPVSs is not yet considered an urgent issue.

Very few LCA authors document any concern with the amount of waste to be managed in a few years, stemming from SPVSs. Irena (2019) forecasts that significant streams of PV waste will have to be disposed globally from around 2030, and estimates 78 million tonnes of PV waste to be produced by 2050. Hong et al (2016) estimated that the production of 1 kWp with a p-Si PV cell generates 8,87 kg of waste to be landfilled, 23,7 kg to be incinerated and 402,7 kg to be recycled. These estimations exclude the required material at the stage of use and of disposal, meaning that the raw material consumption at these stages (RMC) also needs to be considered, when calculating the overall waste arising from the production of 1 kWp.

Up until now only the European Union (EU) has pushed forward policies and regulations concerning collection, recovery and recycling targets, in passing the directive of waste from electrical and electronic equipment (WEEE) in 2012, which includes PV systems, European Commission (2012). The Irena report (2019) suggestsed that the bigger the PV plant, the easier its recycling, as opposed to small rooftop systems, where adequate EoL management can add significant economic investments. Further, the additional cost of logistics for waste management in remote or rural areas is opposed to the advantageous implementation of solar PV in these regions.

The varierity of materials within one unit make the recycling of PV waste a challenging task. Irena (2019) stated that over 90% of mass of c-Si and thin-film panels is considered non-hazardous waste, while 4% of small c-Si panels and 2% of thin-film panels is potentially hazardous materials. Dominguez and Geyer (2017) estimated the share of the four main metals found in PV waste, namely Iron (Fe), Al, Si and Cu. Figure 7 compares the amount of potentially recovered (R) to lost (L) metals in the scenarios of 10-40% recycling rate, depicting minimum and maximum recovery values.

Figure 7: Comparison of recovered to lost materials in Mt depending on the recycling rate, adapted from Domínguez and Geyer (2017)



4. DISCUSSION

Information on EIs of SPVSs varies widely depending on various factors, including the characteristics of the systems and the environment, and also the purpose and scope of each LCA. However, some important elements from information contained in LCAs can be discussed.

GWP

Different authors attribute over 80% of GWP of SPVSs to materials, due to the use of FFs in the energy mix of manufacturing countries. Müller et al. (2021) suggested that the GWP of PV systems might be being overestimated, as life cycle inventories (LCI) of SPVSs are not rigorously upgraded with the increasing share of REs in the energy mix of manufacturing countries, nor with the current state of technologies. Rao et al. (2021) concluded that the assembly stage and BOS alone account for 56% of GWP, while emissions originating in transportation processes have only a low impact on the overall balance of GHG emissions.

Considering an average GWP value of 50 g CO2-eq/kWh related to electricity produced with SPVSs, and the projected SDS of an additional 2.548 TWh by 2030, 127 Mt of CO_2-eq are to be emitted, compared to 1,437 Mt if calculated with the average 440 g CO2-eq/kWh of electricity generated in 2020 globally, IEA (2020). Meaning a potential saving of emissions of around 90%.

GHG emissions associated with each unit of installed capacity progressively decrease with advances in technologies and also with the increase in the efficiency of systems, the lifespan of the modules, the capacity of facilities and the share of REs in energy mixes. Regarding the lifespan duration of modules alone, a reduction in terms of GWP of at least 20% per additional year can be observed from revised LCAs. Tawalbeh et al. (2021) estimated that GWP of SPVSs can be reduced up to 50% just through implementing novel materials and/or with the use of recycled Si.

Land use

Irena (2019) estimated that by 2050 large-scale SPVSs will account for 60% of total solar PV capacity, the analysis of land-use therefore resulting as a relevant issue. SPVSs are resource-intensive technologies in terms of land use; however, electricity produced from coal combined with coal sequestration and wind farms require 5 to 13 times more land than electricity produced with PV systems.

From the revision of 28 utility-scale SPVSs, the average ELUI was found at 29 m^2/kW for projects commissioned from 2010 to 2019, representing a reduction of 20% compared to the previous decade, suggesting that efficiency in terms of land use increased with the evolution of technologies and scale.

The efficiency of modules and the configuration of the systems also play an important role in land use. Various configuration strategies can help improving ELUI. Kafka and Miller (2020) proposed implementing dual-angle solar harvest systems, although efficiencies need to be tested for varied panel tilt-angles with various cloudy conditions. The implementation of floating SPVSs is also possible, as suggested by Da Pimentel Silva and Branco (2018).

As for potential multipurpose uses of land, sharing the land of SPVSs is often a challenge, as described by the Union of Concerned Scientists (2013). Some authors, however, suggest combining SPVSs and food crop harvesting, Da Pimentel Silva and Branco (2018), or establishing SPVSs in abandoned mines or sharing land with mining facilities, Dhar et al. (2020).

The versatile location of SPVSs is an advantage from an efficient land use perspective, compared to FFs, where the location is directly dependent on the possibility of banking coal or natural gas and the interference with the soil is more invasive. Here, not only the vegetation cover has to be removed (like at PV sites), but the soil also experiences continuous extraction of materials, Fthenakis and Kim (2009).

Biodiversity loss

Impacts on ecosystems in LCA studies for SPVSs are often assessed through estimations on ET and EP (see Figure 3). However, measuring impacts in terms of biodiversity loss poses a challenging task for an LCA approach, as it originates in the complex consequences related to the pressures on the abiotic factors. Kim et al. (2021) studied the projected habitat loss from large and medium PV systems in Japan and South Korea, concluding an urge to revise current SPVS site selection criteria, as the cost-benefit and efficiency for energy production are often prioritized over the loss of habitat.

EIAs are a desirable approach for reducing the impacts on ecosystems at the stage of planning. Electricity generated from solar PV in China, the US and Japan accounted for nearly 60% of global generation in 2019, from information of the IEA (2021). According to Schumacher (2019), EIAs for SPVSs are only required for an installed capacity over 10 MW in Japan; the US and the EU determine the need for an EIA for solar PV projects on a case-by-case basis.

According to the UNEP (2018), the requirement of an EIA is often perceived as a resource-intensive matter for project development and implementation. This may lead to underestimating the need for EIAs, when establishing incentives for modern REs. In Colombia, for instance, solar PV projects require an EIA from an installed capacity of 10 MW. By 2021, roughly 50% of the currently registered projects for electricity generation from SPVSs in Colombia have a nominal capacity below 10 MW.

Human health (HH)

An LCA allows estimating the performance of indicators related to potential damage to HH such as release of toxics and air pollutants to the environment. According to revised LCAs, the manufacture of components of a PV system has the highest contribution to the release of toxins to the environment.

However, different approaches such as toxicity studies and/or EIAs are needed in order to better understand the impacts on HH thoughout the lifecycle of SPVSs. Some important factors that determine the severity of potential damage caused by hazardous substances to HH include the concentration of pollutants in the environment and the frequency and duration of human exposure.

Figure 3 shows, nearly half of the examined LCA studies take into consideration the category of HH. Nonetheless, the actual damage to HH related to PV solar systems seems hard to quantify from an LCA point of view, as this approach does not seem to provide tools for correlating the release of toxicants to its impact on HH.

Some studies offer values in regard to the effect of specific chemicals for on-site workers, but overall the risks are presented descriptively. This is possibly linked to the complexity of the category, as an important number of factors need to be considered, including the amount and type of toxins, duration and frequency of exposure, direct exposure on-site and potential indirect exposure through soil or water contaminations, as well as the exposure to toxins outside the work realm (e.g. smokers).

Waste generation

Waste from PV systems is estimated to multiply by 300 from 2016 (0,25 Mt) to 2050 (78 Mt) and economic incentives for concepts such as closed loop recycling and circularity still need to be set. WEF (2019) stated that by 2019 only 20% of WEEE is being properly recycled, globally. Taking this proportion as a reference for PV waste, nearly 62 Mt of WEEE from SPVSs is expected to be landfilled, 8 Mt more than the total WEEE generated worldwide in 2019, Forti et al. (2020).

The recovery of metals from SPVSs not only prevents further metal depletion, but holds an important economic benefit. Mahmoudi et al. (2021) estimated a gross profit of materials recovered from PV waste to date of between 36 and 42 billion US dollar, only from OECD countries.

Although the importance of recycling SPVS parts is evident, Chowdhury et al. (2020) concluded that currently available tehnologies for recycling PV waste is rather limited. They explained that most waste management systems for PV waste are only for laboratory research and very few methods are comercially available.

5. Conclusions

- Estimations on GHG emissions of SPVSs vary within a wide range from dozens to hundreds of g CO2-eq/kWh, due to numerous aspects related to the system (such as technology and scale), and also substantiates the varied scopes of LCAs.

- Different authors attribute 80 to 90% of GWP of SPVSs to extraction of materials and manufacturing of the modules; GWP associated to transport throughout the LCA of utility-scale SPVSs is often deemed negligible.

- Typical values of GWP for c-Si modules range around 50 g CO2-eq/kWh, which is relatively low, compared to the average of 440 g CO2-eq/kWh of the global energy mix in 2020. Meaning with every installed capacity of solar PV replacing FF energy sources, up to 89% of emissions could be reduced.

- Impacts of SPVSs related to land use, lie mainly in the operational stage. However, considerations regarding land use should also be given to material extraction and disposal of solid waste.

- ELUIs of SPVSs vary widely depending on multiple factors. From the revision of 28 utility-scale SPVSs, the average ELUI from 2000 to 2009 was found to be 20% lower compared to the previous decade, suggesting that efficiency in terms of land use increase with the evolution of technologies and scale. Existing LCAs estimate that electricity produced from coal and wind requires 5 to 13 times the ELUI related to PV systems.

- ELUI of SPVSs can be further reduced by optimizing system arrays, prioritizing the use of efficient materials, and/or sharing land with other facilities.

- Although LCA studies often include estimations on EP or ET, biodiversity loss accounted to SPVSs is not a widely examined matter. Further study is needed in order to evaluate the relation between the existence of SPVSs and wildlife loss.

- EIAs are an advisable approach to foresee and reduce EIs on ecosystems from SPVSs at the planning stage. However, EIAs are not always required for utility-scale SPVSs and current site selection criteria prioritize cost-benefit and efficiency for energy production over the loss of habitat.

- According to revised LCAs, the manufacturing of components of a SPVSs have the highest contribution to the release of toxicants into the environment. However, complementary impact assessment approaches are needed in order to better understand the impacts to HH thoughout the lifecycle of SPVSs.

- The magnitude of current PV waste streams are not relevant enough to be considered a pressing issue, but the quantities of PV waste are expected to rise by the factor 300 until 2050.

- PV waste consists of hazardous and non-hazardous waste, resulting in a complex EoL management. The lack of an adjusted recycling plant results in low recovery and recycling rates and the loss of important revenues.

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