Article

Life-Cycle Land-Use Requirement for PV in Vietnam

Eleonora Riva Sanseverino [1], Maurizio Cellura [1], Le Quyen Luu [1,2,*], Maria Anna Cusenza [1], Ninh Nguyen Quang [2] and **Nam Hoai Nguyen [2]**

[1] Department of Engineering, University of Palermo, Viale delle Scienze Ed.9, 90128 Palermo, Italy; eleonora.rivasanseverino@unipa.it (E.R.S.); maurizio.cellura@unipa.it (M.C.); mariaanna.cusenza@unipa.it (M.A.C.)

[2] Institute of Energy Science, Vietnam Academy of Science and Technology, Hanoi 10072, Vietnam; nqninh@ies.vast.vn (N.N.Q.); nhnam@ies.vast.vn (N.H.N.)

* Correspondence: lequyen.luu@community.unipa.it

Abstract: Over the last 15 years, photovoltaics (PV) in Vietnam has experienced development. The increased installed capacity of PV requires more land for installation sites as well as for manufacturing the plants' component and waste treatment during the plants' decommissioning. As a developing country, in which more than 80% of the population's livelihood depends on agriculture, there are concerns about the competition of land for agriculture and solar development. This paper estimates the life-cycle land-use requirement for PV development in Vietnam, to provide the scientific-based evidence for policy makers on the quantity of land required, so that the land budget can be suitably allocated. The direct land-use requirement for PV ranges from 3.7 to 6.7 m^2 MWh^{-1} year, and the total fenced area is 7.18 to 8.16 m^2 MWh^{-1} year. Regarding the life-cycle land use, the land occupation is 241.85 m^2a and land transformation is 16.17 m^2 per MWh. Most of the required land area is for the installation of the PV infrastructure, while the indirect land use of the background process is inconsiderable.

Keywords: land use; life cycle thinking and photovoltaic system

1. Introduction

The achievement of the international targets on climate change set during the Paris Climate Conference (COP21) will require a deep transition towards a decarbonized global energy sector [1]. Renewable energy resources (RESs) are recognised as one of the optimal options to reduce energy-related greenhouse gas (GHG) emissions [2]. According to the International Renewable Energy Agency (IRENA) projections, the share of renewable energy in the power sector would increase from 25% in 2017 up to 85% by 2050, mostly through growth in solar and wind power generation [2].

The strategies implemented in the energy sector in order to mitigate climate change could involve a trade-off among the economic sectors due to the competitive uses of limited natural resources [3]. This is the case of land availability and the competitive use between food and renewable energy production [4]. The exploitation of renewable energy systems, such as photovoltaics (PV), bioenergy, etc. will involve the expansion of land devoted to energy production [5–7].

Historically, land has been used for agriculture and food production. In line with socio-economic development and population growth, increased demand on food will drive the expansion of agricultural land use. According to the Food and Agriculture Organization (FAO), feeding the global population by 2050 will require a 60% increase in food production [7]. Food production security is a key pillar within the Sustainable Development Goal "Zero Hunger" (SDG 2) set by the 2030 Agenda of Sustainable Development of the United Nations which aims to end hunger and malnutrition by 2030.

Current resource use trajectories could compromise inclusiveness and sustainable development. In this framework, the water–energy–food nexus approach is emerging as a

systemic and integrated management of limited resources needed to achieve competing objectives [7]. In order to support stakeholders in the resources planning, the availability of reliable data on the resource demand in the different implemented strategies is of paramount importance [8].

In this context, this study aims at evaluating the nexus between a significant increase of PV energy and the land needed for the PV system installation. In order to give a reliable estimation of the needed land, the authors apply a life-cycle approach [9–11] to assess both direct and indirect land use related to the whole life cycle of the systems examined. The functional unit is one MWh of solar power. The studied system boundary covers different stages of PV life cycle from cradle (raw material extraction and PV components manufacture) to gate (operation of PV plant and generation of solar power electricity). The end of life phase has not been considered in this paper as the life cycle inventories of the end-of-life treatment of PV modules are weak [12].

The case study is the Vietnam energy sector in which PV will increase from the current 5000 MW_p up to 13 GW_p in the near future [13]. Moreover, the competition of land for agriculture and PV appears more strongly as the Vietnamese economy is growing. As in many fast-developing countries, the Vietnamese economy is changing its structure from an agriculture-based economy (46.3% of gross domestic product (GDP) in 1988 to 13.96% in 2019) to an industry-based (23.96% of GDP in 1988 to 34.49% in 2019) and a service-based (from 29.74% of GDP in 1988 to 41.64% in 2019) economy [14].

PV has been widely proved to contribute to the GHG emissions reduction, as it emits no carbon dioxide, methane and nitrous oxide during its operation stage [15]. Over the whole life cycle, the GHG emissions of PV are less than one-fourth of those from an oil-fired steam turbine plant and one-half of that from a gas-fired combined cycle plant [16]. However, PV impacts abiotic resource consumption, freshwater ecotoxicity and human toxicity significantly [17–19]. Considering the global expected diffusion of the PV energy system and the potential competition for land among different economic sectors, a deeper insight into life-cycle land use is required to support policy makers in land resource allocation.

Several papers have studied land use for PV installation. In detail, Pimentel et al. reported that the land requirement for PV was at 28 m^2 for one MWh [20]. However, the authors did not follow a life-cycle approach and only the land requirement for PV system installation was accounted for and the indirect land use was not clearly mentioned.

Fthenakis and Kim conducted a review on life-cycle land requirements of different energy generation technologies: coal, natural gas, hydroelectric, PV, wind and biomass [21]. In this study, the studied PV structures were constructed in the area with solar irradiance of 1.7–$2.5 \text{ MWh m}^{-2} \text{ year}^{-1}$, 9.5–20.2% solar to electricity efficiency (module efficiency times performance ratio). In terms of land transformation, solar power transformed a land area of 0.2 to $0.5 \text{ m}^2 \text{ MWh}^{-1}$ [21]. A solar PV plant (SPP) with $2.4 \text{ MWh m}^{-2} \text{ year}^{-1}$ of solar irradiance, at 13% module efficiency and 8% performance ratio occupied $9.9 \text{ m}^2 \text{ MWh}^{-1}$ year [21]. Besides, indirect land impacts related to PV modules and balance-of-system (BOS), such as inverter, transformer, mounting structures and energy for PV (e.g., fuels consumed during transportation of the PV plants' components), are negligible, between 22.5 and $25.9 \text{ m}^2 \text{ GWh}^{-1}$, compared to direct land use [21].

Later on, in 2015, Aman et al. reviewed technical and environmental aspects of solar systems, e.g., concentrating solar power (CSP) and PV [22]. In the paper, the land transformation and land occupation were compared among different types of power technologies, including coal and PV. Authors followed a life cycle approach and based the assessment on the life cycle land use for PV system obtained by Fthenakis and Kim ($9.9 \text{ m}^2 \text{ MWh}^{-1}$ year) [21]. In general, the land use of PV ranges from high to low, depending on the location where the PV modules are mounted [22], for example considering low to high solar irradiance of the installation sites. While the direct land disturbed by the solar infrastructures was estimated at 5.9 acres per MW for small PV and 7.2 acres per MW

for large PV [22], it was not clear what was the exact amount of indirect land use due to background processes, for example Si material extraction.

Bukhary et al. estimated and harmonized water and land use for CSP and PV technologies. The reviewed results are then incorporated into a system dynamic model to analyze water and land availability and usage, and relevant carbon emission reduction in six states in the USA based on their renewable portfolio standard (RPS) during 2015–2030 [23]. In term of land use, it was indicated that SPPs require an area of 18.1×10^6 m^2 for 750 MW [23]. The land use for PV system was not assessed in a life cycle perspective since its computation was based on data inferred from [24] which estimated land requirement for PV system by including only land use for facility installation.

From the literature analysis, it was clear that only a few studies are available on the land requirements of PV systems and that most of them did not follow a life-cycle approach. Their focus was on the direct land use and neglected the indirect land use requirement, except for the work of Fthenakis and Kim [21] who performed a life cycle assessment (LCA) on a specific SPP. In addition, it is controversial on land requirements of PV, ranging among 45 m^2 MWh^{-1} [25]; 28 m^2 MWh^{-1} [20]; 9.9 m^2 MWh^{-1} year [21]; 5.9–7.2 acres per MW [22]; and 18.1×10^6 m^2 for 750 MW [23]. Considering that the land-use requirement for PV depends on the solar irradiance and the technology efficiency, the disagreement of land-use requirements in these studies may originate from the different solar irradiance in the studied installation sites, as well as the applied technologies. Moreover, it should be noted that there is a difference on approaches and scopes of the studies, for example the inclusion of indirect land use and to what extent it is included, in both upstream (panels and BOS manufacturing) and downstream processes (end-of-life treatment of the plants' infrastructure). The difference on approaches and scopes of the studies would contribute to the various results obtained.

In this context, this study will contribute to the state of the art by applying a life-cycle approach for quantifying land use requirement of PV development by including all the devices and all the processes needed for a PV system to deliver its function. Although the study will provide a quantitative calculation of land area used for PV for Vietnam, it can be used as a comparative basis of life-cycle land use requirement for PV globally. The estimated land-use requirement for PV will support strategic land use planning, in which the land resources are balanced and suitably allocated to sustainably exploit the land budget and avoid the competition on land use for different socio-economic-industrial activities including agricultural and energy production. The preliminary estimation of the land needed for the installation of PV can be useful to identify the most suitable site for the best layout of the plant in order to increase its efficiency and reduce costs [26]. The obtained results would not only limit for Vietnamese government but also benefit the global policy making process in sustainably allocated limited land resources, and PV investors and developers in economically financing the PV projects.

2. Methods and Data

2.1. Methods

The most common life-cycle approach applied for environmental impacts is LCA methodology, which is clarified in the international standards of ISO 14040, ISO 14044 [9,10]. Life-cycle thinking (LCT) covers environmental, social and economic impacts of a product (or service) from the natural resource extraction to the end-of-life of the product [11]. As a pillar of LCT, "LCA examines and evaluates all inputs, outputs and potential environmental impacts of a product system over its life cycle" [10]. It is a holistic approach, extending the traditional boundary of production stages to include upstream and downstream stages of material extraction and waste management along the product's value chain. LCA, consequently, considers the limited capacity of natural resources including land, to meet increasing demand of human socio-economic activities, and avoids shifting the environmental burden of one stage into other stages during the whole value chain of the product. Examples of this approach are the inclusion of land use for mining coal for

thermal electricity production or the consideration of land use for growing feedstock for biofuels for energy production.

In this study, the life-cycle approach is applied by considering both the direct land use for SPP installation and operation as well as indirect land use during background stages e.g., raw material extraction and component production. As the rooftop solar systems are installed on the roof of buildings, they require almost no land during installation and operation. Moreover, the share of rooftop solar systems' installed capacity in Vietnam is small compared to that of SPP [13], therefore, the focus is on SPP life-cycle land use requirements.

For direct land use requirement calculation, the study followed the method of Bukhary et al. [23]. First, the direct land use estimate (*L*) of each SPP is calculated based on the following Equation (1):

$$L = \frac{P}{I \times SE} \tag{1}$$

in which:

L: Direct land use estimate. It is the direct land area occupied by solar structure, measured in m^2 MWh^{-1} year.

P: packing factor (unitless). It is the ratio of land cover by the array, including land area for the shading, to the actual land cover of the modules [23].

I: solar irradiance, measured in MWh m^{-2} $year^{-1}$.

SE: solar to electricity efficiency (unitless). It is a product of performance ratio and module efficiency [23].

Then, Equation (2) below is used to harmonize land use estimate of different SPPs in Vietnam by adjusting several technical characteristics such as solar irradiance, module efficiency, performance ratio and lifetime of the plant. Due to the differences in the solar irradiance of the installation sites as well as the applied technologies of PV plants, the direct land-use estimates are different among plants. The harmonized land use estimate will provide a generalized result of land use requirement for PV in Vietnam, regardless the technical characteristics. The harmonized solar irradiance, module efficiency and performance ratio are assumed based on literature [23,27] and the mean value of the actual situation in Vietnam. While the published features (land-use estimate, solar irradiance, module efficiency and performance ratio) are the actual data of different SPPs in Vietnam. Details of required data are discussed in the following parts.

$$Ni_{harm} = \frac{Ni_{pub} \; I_{pub} \times ME_{pub} \times PR_{pub} \times LT_{pub}}{I_{harm} \times ME_{harm} \times PR_{harm} \times LT_{harm}} \tag{2}$$

in which:

Ni_{harm}: harmonized land use estimate (m^2 MWh^{-1} year).

Ni_{pub}: land use estimate of all studied SPPs in Vietnam (m^2 MWh^{-1} year).

I_{pub}: solar irradiance in installation sites (MWh m^{-2} $year^{-1}$).

I_{harm}: harmonized solar irradiance, at 1.9 MWh m^{-2} $year^{-1}$, which is the average solar irradiance of installation sites.

ME_{pub}: module efficiency of studied SPPs (unitless).

ME_{harm}: harmonized module efficiency, at 0.18, which is the mean value of actual modules' efficiency in Vietnam.

PR_{pub}: performance ratio of studied SPPs (unitless).

PR_{harm}: harmonized performance ratio (unitless), at 0.8, which is based on [23].

LT_{pub}: lifetime of studied SPPs (year).

LT_{harm}: harmonized lifetime (year), at 30 years, which is based on [23].

The indirect land-use requirement is calculated on the basis of the secondary data for production of components, e.g., modules and balance-of-system, and transportation of the components to the construction sites of the PV plants, extracted from Ecoinvent 3.6 database [28]. The technologies considered include PV panels 330 kW, Inverter 100 kW, Transformer 4500 kVA; Transformer 63 MVA; Transformer 100 kVA; Sea transportation

by tanker, for dry goods; Road transportation >32 metric tons; and Electrical installation of all components. The inventory data are the global average values, except for Road transportation. The vehicle technology standard for Road transportation is Euro 4, which is the same for the standard of road vehicle in Vietnam.

2.2. Solar Irradiance in Vietnam

The territory of Vietnam is long and narrow from the 8th to 23rd latitude of the Northern hemisphere, within the tropical region. Consequently, the solar energy potential in Vietnam is quite large, and feasibly exploited for the socio-economic and industrial development of the country. However, due to the shape of the territory, the exploitation potential of solar energy is different among regions. The national average solar irradiance is around 4–5 kWh m^{-2} day^{-1}, but it is quite low in the North and high in the South of Vietnam [29]. From 17th latitude towards the South of Vietnam, the solar irradiance is high and stable throughout the whole year, with difference at about 20% between the dry and rainy seasons. The duration of sunlight is more than 12 h during days from vernal equinox to autumnal equinox, and less than 12 h during days from autumnal equinox to vernal equinox. The average sunny hours are between 1800–2600 h annually [29].

In general, the amount of solar radiation in Vietnam is thus relatively good. In particular, in the Central Highlands, Southern Central and South regions, the amount of solar irradiance is very good for developing PV systems. Table 1 presents the annual irradiance of some provinces in Vietnam.

Table 1. Annual solar irradiance of some provinces in Vietnam. Reproduced from [30], The World Bank Group: 2020.

Region	Provinces	Average Solar Irradiance (MWh m^{-2} year^{-1})
Central Highland	Kon Tum	1.74
	Gia Lai	1.78
	Dak Lak	1.79
	Dak Nong	1.81
	Lam Dong	1.80
Southern Central	Quang Ngai	1.70
	Binh Dinh	1.90
	Phu Yen	1.86
	Khanh Hoa	1.98
	Ninh Thuan	2.0
	Binh Thuan	2.0
South	Vung Tau	1.86
	Tay Ninh	1.91
	An Giang	1.9
Average		1.9

2.3. Technical Characteristics of Photovoltaics (PV)

Solar to electricity efficiency depends on the technology and surrounding environment. It is proportional to the performance ratio and modules' efficiency. Performance ratio is the ratio of alternating current electricity generated by the PV modules, taking into account system loss, to the calculated electricity based on direct current module's efficiency and solar irradiance [27]. The review on the performance ratio of PV was determined to be around 0.8 [23], which is the assumed value for harmonized SE parameter in Equation (2). In this study, the published performance ratio is the actual figures of different SPPs in Vietnam, ranging from 0.79 to 0.85.

Module efficiency is the percentage of solar energy converted into direct current electricity by the modules. Module efficiency depends on the surrounding environment, e.g., dust covered on the panel and in the atmosphere in forms of smog or air pollution. The accumulation of dust results in efficiency loss [31,32]. It was also pointed out by

Maghami et al. that the dust accumulation on the panel decreases both current and voltage output, while dust in the atmosphere decreases the current output only [33]. The global average module efficiency is around 0.19 [23]. In this study, the module efficiency are the actual figures of different SPPs in Vietnam. These numbers range from 0.17 to 0.19. The harmonized module efficiency is the mean value of the actual module efficiency in Vietnam, at 0.18, which is lower than the global average.

The typical lifetime of SPP is between 30 and 60 years [16]. Review of LCA of PV plants and solar rooftop systems assumed the lifetime to be 25 to 30 years [27]. Most of the panels' manufacturers guarantee an efficiency of 25 years. After 25 years, the panel efficiency reduces quickly. Therefore, the lifetime of 30 years is selected for both harmonized and published values.

Packing factor is the ratio of the total land to the actual land cover [23]. The total land is the area covered by the array, including the area provided to avoid shading and maintenance activities. The actual land is the area covered by panels or mirrors [23]. The work in [21] used different packing factors for solar power technologies, ranging from 2.1 to 5. For mono-crystalline (mono-Si) PV, the packing factor of 2.5 has been applied. In this study, packing factors are actual figures of different SPPs in Vietnam. The packing factors of the studied SPPs range from 1 to 1.8.

The studied SPPs include 11 SPPs in the Central Highland, 14 SPPs in the Southern Central and seven SPPs in the South of Vietnam. They comprise commercialized SPPs and SPPs that were approved for being connected to the grid. The total installed capacity of these SPP is 2335 MW, most of them have an installed capacity of (or being larger than) 50 MW; 28 out of 33 SPPs utilized the poly-crystalline (multi-Si) solar modules, with installed capacity 1949 MW, accounting for 84% of the total installed capacity of studied SPPs. Among the studied SPPs, there are only two SPPs installing the tracking system. Information about the studied SPPs and applied technologies can be found in Table S1.

2.4. Inventory Data

The land-use inventories are described in land occupation and land transformation. Land occupation describes the delay of land recovery over time, and is measured in m^2a [34], which means m^2 over 30 years in this study. Land transformation describes the change in land use, consequently causing changes in the ecosystem quality, and is measured in m^2 [34]. Land-use inventory data of the foreground process is based on the total land use by the SPPs, or the fenced area of the power plants. This land area includes the land occupied by the infrastructure within 30 years, and the land transformed from other land use purposes into areas for plants' infrastructure, internal road and green covers within the fenced area of the power plants.

The inventory data for background processes are extracted from Ecoinvent 3.6 database [28]. The process of manufacturing PV panels is scaled from the data for 1 m^2 of panel into a piece of panel. The process of manufacturing inverter is scaled down from the data for one piece of a 500 kW inverter into a 100 kW inverter. For the processes of manufacturing transformers low voltage and high voltage, the data are directly taken from Ecoinvent. For the process of manufacturing medium voltage transformer, the data is scaled from average value of high voltage and low voltage transformer. Transportation processes include sea transportation from the manufacturer sites (China) to the international ports of Vietnam, and road transportation from the international ports of Vietnam to the installation sites. Sea transportation is the global average data for transporting dry goods by tankers. Road transportation is the European average data for transporting goods by lorry according to the Euro 4 standard and at more than 32 metric tons. The distances of transportation are assumed to be 3300 km for sea transportation and 200 km for road transportation. Data of 3 kWp electrical installation is scaled up to 50 MWp electrical installation. The inventory data for background processes are specified in Table 2.

Table 2. Inventory data for background processes. Reproduced from [28], Ecoinvent: 2019.

Process	Land Occupation (m^{2}a)	Land Transformation (m^2)
Manufacturing of one piece of photovoltaic (PV) panel 330 kW	2.92×10^1	9.87
Manufacturing of one piece of inverter 100 kW	2.47×10^2	2.46×10^1
Manufacturing of one piece of transformer medium voltage 4500 kVA	3.46×10^{-3}	7.66×10^{-3}
Manufacturing of one piece of transformer high voltage 63 MVA	2.48×10^{-3}	5.37×10^{-3}
Manufacturing of one piece of transformer low voltage 100 kVA	3.16×10^{-3}	6.84×10^{-3}
Electrical installation 3 kWp	1.62×10^1	5.43×10^{-1}
Sea transportation (tkm)	5.33×10^{-5}	1.53×10^{-5}
Road transportation (tkm)	9.88×10^{-3}	1.90×10^{-4}

3. Results and Discussion

3.1. Direct Land Use of PV in Vietnam

The direct land use estimates range from 3.7 to 7 m^2 MWh^{-1} year. After harmonization, the land use estimates range from 3.7 to 6.7 m^2 MWh^{-1} year. The median value is 6.01 m^2 MWh^{-1} year.

There is not much difference between the direct land-use requirement among various silicon-based PV technologies, including mono-crystalline (mono-Si), poly-crystalline (multi-Si) and panels with tracking system. The harmonized land-use estimates for PV plants with mono-Si and multi-Si panels are around 5.6 m^2 MWh^{-1} year. This may originate from the increasing module efficiency of multi-Si panels, which becomes closer to that of mono-Si ones. The harmonized land-use estimates for PV plants with tracking systems is slightly higher than those without tracking systems, at 5.9 m^2 MWh^{-1} year.

The average land use efficiency for the fenced area of the PV plants ranges from 7.18 to 8.26 m^2 MWh^{-1} year, which is lower than the average land use of PV, at 9.4 to 10.6 m^2 MWh^{-1} year obtained by [23]. Table 3 presents the results obtained on the land-use estimate of the SPPs in Vietnam.

Table 3. Harmonized land use estimates of the solar PV plants (SPPs) in Vietnam.

Technology	Direct Land Use (m^2 MWh^{-1} year)				Average Land Efficiency (Fenced Area) (m^2 MWh^{-1} year)
	Mean	Median	Min	Max	
mono-Si	5.68	6.14	3.69	6.67	7.18
multi-Si	5.63	6.01	3.81	6.53	8.04
Panels with tracking system	5.92	N/A [1]	N/A	N/A	8.26

[1] Not available.

3.2. Life-Cycle Land-Use Requirement

The life-cycle land-use requirement for PV in Vietnam includes 241.85 m^{2}a of land occupation and 16.17 m^2 of land transformation for one MWh of solar power over 30 years.

Most of the land area is required for the foreground process of SPPs' infrastructure. The indirect land use for the background of manufacturing and transportation of panels, inverters and other components of the SPPs infrastructure to the installation sites are inconsiderable. The contribution of different processes to the life-cycle land-use requirement is specified in Figure 1. As a matter of fact, most of panels and BOS utilized in SPPs in Vietnam are imported from China, the indirect land use impacts from the manufacturing and transporting of these components do not pose any environmental impacts on the local land budget.
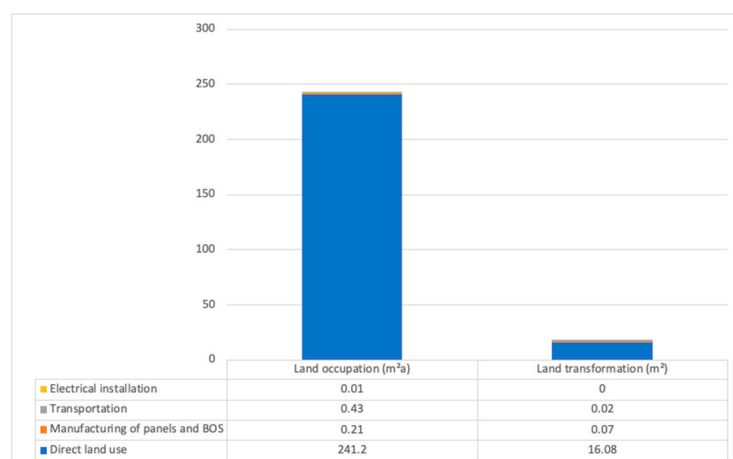
Figure 1. Life-cycle land-use requirement for SPPs in Vietnam by processes.

The land occupation of 241.85 m^{2}a represents the area of land occupied by the solar infrastructure to generate one MWh of solar power within 30 years of operation. The land transformation of 16.17 m^2 represent the area of land needed to be transformed from the previous situation into other purposes, e.g., constructing the SPP, manufacturing panels and BOS, etc. As previously stated, the land occupation delays recovery whereas land transformation causes a change in ecosystem quality. The land-use impact assessment requires identifying the type of land use, the spatial extent, the temporal extent, and the geographical location [34]. At the same time, other key elements need to be considered such as function of the land, ownership of the land (co-benefits of the land for different land use purposes), assumption on future or alternative land use and land recovery capacity [35]. This paper focuses on the land-use requirement of PV, therefore, only land areas with specific types of land are presented (see Table 4). The land-use impact assessment is excluded from the scope of this paper.

Table 4. Life-cycle land occupation and transformation of PV in Vietnam.

Land Use Flows	Unit	Value
Occupation, dump site	m^{2}a	2.03×10^{-2}
Occupation, forest, intensive	m^{2}a	1.94×10^{-1}
Occupation, industrial area	m^{2}a	1.50×10^{-2}
Occupation, mineral extraction site	m^{2}a	1.69×10^{-2}
Occupation, traffic area, rail/road embankment	m^{2}a	6.38×10^{-2}
Occupation, traffic area, road network	m^{2}a	2.94×10^{-1}
Occupation, unknown	m^{2}a	2.41×10^{2}
Occupation, water bodies, artificial	m^{2}a	2.68×10^{-2}
Transformation, from annual crop, non-irrigated	m^2	1.13×10^{-2}
Transformation, from unknown	m^2	8.05
Transformation, to industrial area	m^2	8.04

3.3. Limitations and Future Research

The water–food–energy nexus, which aims to secure the supply of these resources by strengthening synergies and reducing trade-offs among these sectors, is vital to aim towards sustainable developments paths. The land-use estimation of PV based on a life-cycle perspective would avoid unnecessary land-use exploitation at global scale or continental scale. The life-cycle perspective allows the matter to be investigated on a larger scale than the mere national perspective.

The study sets the system boundary from cradle to gate, while the end-of-life treatment of the PV has not been considered due to the limited availability of inventory data. The missing evaluation of the PV end-of-life treatments is a weak point of this study as the

waste treatment of panels and other components, either by landfilling, incineration or recycle, would require a substantial area of land [36]. Different end-of-life management options could involve different life-cycle land-use values [36]. This would open up future research on inventory data for the end-of-life stage of PV.

The results of the study are replicable to verify the LCT approach as well as the quantitative inventory of life cycle land use for PV. Although the case study limits the assessment to the Vietnamese context (mainly for the use phase), the available datasets that describe the life-cycle inventory of the PV systems and all the devices needed for a PV system to deliver its function are valid globally, that makes it a representative and illustrative example for LCA study on PV land use. Therefore, it can be used for supporting the land-use strategic planning for PV in Vietnam as well as other countries with economic and climatic characteristics similar to those of Vietnam, with an order of magnitude of the land-use impact associated with a significant increase in ground-mounted PV plant installation.

4. Conclusions

The increasing demands on land for both agriculture and renewable energy development require a clever strategy of land allocation. In this paper, a life-cycle approach was applied to evaluate the land-use requirement for PV development in Vietnam. It is identified that the direct land use for PV is 3.7 to 6.7 m^2 MWh^{-1} year. The total fenced area of a SPP would require 7.18 to 8.16 m^2 MWh^{-1} year.

When the indirect land-use is included, the life-cycle land-use requirement includes 241.85 m^2a of land occupation and 16.17 m^2 of land transformation per MWh over 30 years of lifetime. Both life-cycle land occupation and transformation mainly come from the construction and operation processes whereas the indirect land use of background processes is negligible.

Currently, the land budget for energy development in Vietnam is about 146.07 thousand ha, which is mainly used for large hydropower plants, thermal power plants, distribution and transmission network [37]. There is no available information on the land budget for developing PV in particular. However, considering the land area required for one MWh of PV is 8.04 m^2 MWh^{-1} year, the land area needed for about 5000 MWp or 4800 GWh of PV by 2019 is about 3800 ha, accounting for 3% of the total land budget for energy development. As the government has no plan to degrow other types of power, it is obvious that the land for PV development in the future would be transformed from land for other purposes. The competition in land use for alternative purposes would potentially limit the exploitation of PV in Vietnam in the near future.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. UN. Paris Agreement. 2015. Available online: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (accessed on 25 January 2021).
2. IRENA. *Global Energy Transformation: A Roadmap to 2050*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2018; Available online: https://www.irena.org/publications (accessed on 25 January 2021).
3. Cremades, R.; Mitter, H.; Tudose, N.C.; Sanchez-Plaza, A.; Graves, A.; Broekman, A.; Bender, S.; Giupponi, C.; Koundouri, P.; Bahri, M.; et al. Ten principles to integrate the water-energy-land nexus with climate services for co-producing local and regional integrated assessments. *Sci. Total Environ.* **2019**, *693*, 133662. [CrossRef]
4. Cobuloglu, H.I.; Büyüktahtakın, İ.E. Food vs. biofuel: An optimization approach to the spatio-temporal analysis of land-use competition and environmental impacts. *Appl. Energy* **2015**, *140*, 418–434. [CrossRef]
5. Konadu, D.D.; Mourão, Z.S.; Allwood, J.M.; Richards, K.S.; Kopec, G.; McMahon, R.; Fenner, R. Land use implications of future energy system trajectories—The case of the UK 2050 Carbon Plan. *Energy Policy* **2015**, *86*, 328–337. [CrossRef]
6. Fritsche, U.R.; Sims, R.E.H.; Monti, A. Direct and indirect land-use competition issues for energy crops and their sustainable production—An overview. *Biofuels Bioprod. Biorefining* **2010**, *4*, 692–704. [CrossRef]
7. FAO. *The Water-Energy-Food Nexus: A New Approach in Support of Food Security and Sustainable Agriculture*; FAO: Rome, Italy, 2014.
8. Mancini, F.; Nastasi, B. Solar Energy Data Analytics: PV Deployment and Land Use. *Energies* **2020**, *13*, 417. [CrossRef]
9. ISO. *Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; ISO 14044:2006; International Organization for Standardization: Geneva, Switzerland, 2006.
10. ISO. *Environmental Management—Life Cycle Assessment—Principles and Framework*; ISO 14040:2006; International Organization for Standardization: Geneva, Switzerland, 2006.
11. UNEP. *Greening the Economy throug Life Cycle Thinking*; UNEP SETAC Life Cycle Initiative: Nairobi, Kenya, 2012.
12. Stolz, P.; Frischknecht, R.; Wambach, K.; Sinha, P.; Heath, G. *Life Cycle Assessment of Current Photovoltaic Module Recycling, IEA PVPS Task 12*; International Energy Agency Power Systems Programme: Paris, France, 2017.
13. Sanseverino, E.R.; Le, T.T.H.; Pham, M.-H.; Silvestre, M.L.D.; Nguyen, Q.N.; Favuzza, S. Review of Potential and Actual Penetration of Solar Power in Vietnam. *Energies* **2020**, *13*, 2529. [CrossRef]
14. WB. Value Added in the Services Sector as Percent of GDP in Asia. 2019. Available online: https://www.theglobaleconomy.com/rankings/Share_of_services/Asia/#Vietnam (accessed on 30 November 2020).
15. Hosenuzzaman, M.; Rahim, N.A.; Selvaraj, J.; Hasanuzzaman, M.; Malek, A.B.M.A.; Nahar, A. Global prospects, progress, policies, and environmental impact of solar photovoltaic power generation. *Renew. Sustain. Energy Rev.* **2015**, *41*, 284–297. [CrossRef]
16. Kannan, R.; Leong, K.C.; Osman, R.; Ho, H.K.; Tso, C.P. Life cycle assessment study of solar PV systems: An example of a 2.7 kWp distributed solar PV system in Singapore. *Sol. Energy* **2006**, *80*, 555–563. [CrossRef]
17. Fu, Y.; Liu, X.; Yuan, Z. Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China. *J. Clean. Prod.* **2015**, *86*, 180–190. [CrossRef]
18. Cusenza, M.A.; Guarino, F.; Longo, S.; Mistretta, M.; Cellura, M. Environmental assessment of 2030 electricity generation scenarios in Sicily: An integrated approach. *Renew. Energy* **2020**, *160*, 1148–1159. [CrossRef]
19. Muteri, V.; Cellura, M.; Curto, D.; Franzitta, V.; Longo, S.; Mistretta, M.; Parisi, M.L. Review on Life Cycle Assessment of Solar Photovoltaic Panels. *Energies* **2020**, *13*, 252. [CrossRef]
20. Pimentel, D.; Herz, M.; Glickstein, M.; Zimmerman, M.; Allen, R.; Becker, K.; Evans, J.; Hussain, B.; Sarsfeld, R.; Grosfeld, A.; et al. Renewable energy: Current and potential issues. *Bioscience* **2002**, *52*, 1111–1119. [CrossRef]
21. Fthenakis, V.; Kim, H.C. Land use and electricity generation: A life-cycle analysis. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1465–1474. [CrossRef]
22. Aman, M.M.; Solangi, K.H.; Hossain, M.S.; Badarudin, A.; Jasmon, G.B.; Mokhlis, H.; Bakar, A.H.A.; Kazi, S.N. A review of Safety, Health and Environmental (SHE) issues of solar energy system. *Renew. Sustain. Energy Rev.* **2015**, *41*, 1190–1204. [CrossRef]
23. Bukhary, S.; Ahmad, S.; Batista, J. Analyzing land and water requirements for solar deployment in the Southwestern United States. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3288–3305. [CrossRef]
24. Horner, R.M.; Clark, C.E. Characterizing variability and reducing uncertainty in estimates of solar land use energy intensity. *Renew. Sustain. Energy Rev.* **2013**, *23*, 129–137. [CrossRef]
25. Gagnon, L.; Bélanger, C.; Uchiyama, Y. Life-cycle assessment of electricity generation options: The status of research in year 2001. *Energy Policy* **2002**, *30*, 1267–1278. [CrossRef]
26. Cumpston, J.; Pye, J. Shading and land use in regularly-spaced sun-tracking collectors. *Sol. Energy* **2014**, *108*, 199–209. [CrossRef]
27. Hsu, D.D.; O'Donoughue, P.; Fthenakis, V.; Heath, G.A.; Kim, H.C.; Sawyer, P.; Choi, J.K.; Turney, D.E. Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation Systematic Review and Harmonization. *J. Ind. Ecol.* **2012**, *16*, S122–S135. [CrossRef]
28. Ecoinvent Database Version 3.6. Available online: https://www.ecoinvent.org/database/older-versions/ecoinvent-36/ecoinvent-36.html (accessed on 17 December 2020).

29. Nguyễn, Đ.Q.; Vũ, X.Đ. Final Report on Research to Improve the Realiability of Supply and Energy Efficiency in K9 Area. In *Vietnamese: Báo Cáo Tổng kết Nghiên Cứu Giải Pháp Nâng Cao độ tin Cậy Cung Cấp và sử Dụng Tiết Kiệm, Hiệu quả năng Lượng Điện và Nhiệt tại Khu di Tích K9*; Institute of Energy Science, Vietnam Academy of Science and Technology and Center for Application of Science, Technology and Environment, Mangement Unit of Ho Chi Minh Mausoleum: Hanoi, Vietnam, 2014.

30. ESMAP. Global Solar Atlas. Available online: https://globalsolaratlas.info/map (accessed on 3 November 2020).

31. Saidan, M.; Albaali, A.; Alasis, E.; Kaldellis, J. Experimental study on the effect of dust deposition on solar photovoltaic panels in desert environment. *Renew Energy* **2016**, *92*, 499–505. [CrossRef]

32. Costa, S.; Diniz, A.; Kazmerski, L. Dust and soiling issues and impacts relating to solar energy systems: Literature review update for 2012–2015. *Renew. Sustain. Energy Rev.* **2016**, *63*, 33–61. [CrossRef]

33. Maghami, M.R.; Hizam, H.; Gomes, C.; Radzi, M.A.; Rezadad, M.I.; Hajighorbani, S. Power loss due to soiling on solar panel: A review. *Renew Sustain Energy Rev* **2016**, *59*, 1307–1316. [CrossRef]

34. Koellner, T.; Baan, L.D.; Beck, T.; Brandao, M.; Civit, B.; Goedkoop, M.; Margni, M.; Canals, L.M.I.; Müller-Wenk, R.; Weidema, B.; et al. Principles for life cycle inventories of land use on a global scale. *Int. J. Life Cycle Assess.* **2013**, *18*, 1203–1215. [CrossRef]

35. i Canals, L.M.; Bauer, C.; Depestele, J.; Dubreuil, A.; Knuchel, R.F.; Gaillard, G.; Michelsen, O.; Müller-Wenk, R.; Rydgren, B. Key elements in a framework for land use impact assessment within LCA. *Int. J. Life Cycle Assess.* **2007**, *12*, 5–15. [CrossRef]

36. Beccali, G.; Cellura, M.; Mistretta, M. Managing municipal solid waste: Energetic and environmental comparison among different management options. *Int. J. Life Cycle Assess.* **2001**, *6*, 243–249. [CrossRef]

37. MONRE. Land Use Planning for Energy Development, Renewable Energy Development. Available online: http://www.monre.gov.vn/Pages/quy-hoach-su-dung-dat-cho-phat-trien-dien-luc,-quy-hoach-nang-luong-moi,-nang-luong-tai-tao.aspx (accessed on 3 November 2020).