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Combined land use of solar infrastructure and agriculture for socioeconomic and environmental co-benefits in the tropics

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ABSTRACT

Solar photovoltaics (PV) are on the rise even in areas of low solar insolation. However, in developing countries with limited capital, land scarcity, or with geographically isolated agrarian communities, large solar infrastructures are often impractical. In these cases, implementation of low-density PV over existing crops may be required to integrate renewable energy services into rural communities. Here, using Indonesia as a model system, we investigated the land use, energy, greenhouse gas emissions, economic feasibility, and the environmental co-benefits associated with off-grid solar PV when combined with high value crop cultivation. The life cycle analyses indicate that small-scale dual land-use systems are economically viable in certain configurations and have the potential to provide several co-benefits including rural electrification, retrofitting diesel electricity generation, and electricity for processing agricultural products locally. A hypothetical full-density off-grid solar PV for a model village in Indonesia shows that electricity output (1907.5 GJ yr^{-1}) is much higher than the total residential consumption (678 GJ yr^{-1}), highlighting the opportunity to downscale the PV infrastructure by half to lower capital cost, to co-locate crops, and to support secondary income generating activities. Economic analysis shows that the 30-year net present cost of electricity from the half-density co-located PV system (12,257 million IDR) is significantly lower than that of the flat cost of diesel required to generate equivalent electricity (14,702 million IDR). Our analysis provides insights for smarter energy planning by optimizing the efficiency of land use and limiting conversion of agricultural and forested areas for energy production.

1. Introduction

Competition for land and water resources between the energy and agriculture sectors may undermine sustainable developmental goals including mitigating climate change, controlling deforestation, and improving the quality of life [1–3]. More than a billion people around the world still lack access to electricity, and this remains a roadblock to eliminating poverty and human well-being in rural areas [4,5]. Often these populations are geographically distant from fossil fuel resources or are in areas with land scarcity, so the extension of electrical grids to these populations is impractical and requires additional land transformation for local energy resource exploration and installations [6]. On the other hand, a multitude of integrated assessment models of future climate mitigation pathways stress the need for the deployment of economically-viable renewable energy technologies to meet the growing energy demand in the developing world, since these countries will be among the most vulnerable to climate change impacts [4,7]. Given this context, the ease of deployment, modularity, and scalability [8–11] make solar photovoltaics (PV) technology a key component in microgrid or off-grid systems that can energize homes, micro and small enterprises [12], post-harvest processing, and irrigation practices that will save water and maximize agricultural yield [13,14].

Abbreviations: BOS, Balance of system; CapEx, Capital expenditure; CED, Cumulative energy demand; EOL, End-of-life FiT Feed-in tariff gCO2-eq Grams of carbon dioxide equivalent; GHG, Greenhouse gas; IDR, Indonesian Rupiah; kWh, Kilowatt-hour; kWp, Kilowatt peak; LCA, Life cycle analysis; LCOE, Levelized cost of energy; NPV, Net present value; PV, Photovoltaics.

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Solar PV is rapidly deploying across the globe, fueled by a combination of decreasing costs and increasing policy support [15–17]. Although direct solar energy has the potential to meet large portion of the global primary energy demand [18], solar PV's historically prohibitive costs and its fluctuating power output reduce the economic activities that it can support [19, 20]. Further, solar PV is land-intensive and the large-scale non-integrated deployment of solar PV has negative impacts on local soil and vegetation [19, 21]. However, co-location of solar PV with vegetation or crop production has the potential to provide mutual benefits, including increased PV efficiency from the cooler microclimate induced by underlying vegetation, reduction in the solar PV installation and operation costs through the secondary income stream from the co-located crop, reduction in irrigation water use, and increased crop yields from pollinator services [22–25]. The most common approach to integrating solar energy and crop production are mostly "solar-centric" approaches in arid and semi-arid regions, intended to maximize electricity output and adhere as much as possible to the standard solar energy development practices. In developing countries with limited capital, land scarcity, or with geographically isolated agrarian communities, large solar infrastructures are often impractically expensive. In these cases, "agro-centric" approaches – implementation of low-density PV over existing crops or processing facilities – are required to integrate renewable energy services into rural communities. Indonesia provides a representative case study, as it encompasses the world's fourth largest population (258 million) with a developing economy and rapidly growing food and energy demands. Although the electrification rate is high for the five major islands that are occupied by the majority of the population, nearly 13,000 (16%) of 82,030 villages in remote areas of Indonesia were categorized as undeveloped in 2016 due to their lack of access to electricity [26]. The challenges to providing electricity to these areas are multifaceted: first, these areas are far from most conventional and renewable fuel sources [27,28]. Second, achieving cost recovery and adequate economies of scale may be unlikely due to low population density and low average energy consumption in these areas [28]. Third, even if the cost recovery and economies of scale were achievable in such cases, a large portion of Indonesia's state electricity company Perusahaan Listrik Negara's budget is already allocated to minimizing the deterioration of existing infrastructure [28].

Even though renewable sources such as hydropower and geothermal are available, their development is challenged by scalability issues for small populations and often these resources are located too far from demand centers or in protected forests [28]. Rapid deforestation and other forms of land use, land-use change and forestry account for more than half of Indonesia's total greenhouse gas (GHG) emissions, and the country is prompted to protect its remaining stock of forests [29–32]. On the other hand, Indonesia has high average annual insolation (1643–1862 kWh m^{-2} yr^{-1}) [28,33], and the non-electrified portion of the population are often scattered over hundreds of remote islands and communities with limited to no grid connection [33]. These circumstances present a unique opportunity to utilize an off-grid agro-centric crop-PV co-location configuration as an alternative or a supplement to diesel-based electrification, which is commonly used as a means of on-site generation in non-electrified rural areas [6].

A major constraint for designing an economically viable PV-agriculture co-location is identifying location-specific, physiologically and economically viable crops or other agricultural activities for co-location [14]. Patchouli (*Pogostemon cablin*), a perennial herb that is native to South and Southeast Asia [34], is highly valued for its aromatic essential oil that is used extensively in the fragrance industry [34]. As the most exported of all Indonesian essential oils by volume, patchouli is widely cultivated and processed in Indonesia on several islands, and Indonesian patchouli oil exports amount to 90% of annual global consumption [35–37]. Further, patchouli cultivation has several desirable attributes for co-location with solar, including shade tolerance, low maintenance, short growth stature (~1 m), long crop cycle (2–3 years), little to no mechanization, availability of local processing facilities and existing marketing chains, and high demand and price for the patchouli oil [34,38].

The co-location of high-value crops may make off-grid solar PV systems economically viable in certain configurations and could provide a sustainable solution to meet increasing food and energy demands, particularly in regions with limited agricultural land. To explore the logistic and economic feasibility of integrated solar PV - agricultural systems, detailed life cycle analyses (LCA) are needed. LCA is a concept that is often used to determine the environmental footprints, such as energy and GHG emissions and water and land usage throughout the life cycle of a technology [22,39,40]. LCA has been performed for large-scale co-located PV plants in arid regions [22], but literature is limited for such analysis of small-scale co-located systems in tropical areas with low insolation. To this end, we conducted an LCA for a hectare of solar PV at full density, a hectare of solar PV at half density, a hectare of patchouli cultivation and processing, and a hectare of hypothetical co-located land use to explore the tradeoffs and synergies (in the context of land use, energy and GHG emissions) between the emerging land uses in Indonesia. Further we examined the economic feasibility of these systems at different PV densities and the potential to supply the rural electricity demand and to support commercial and public infrastructures. The environmental and economic analyses of this study are designed to be a relatively simple framework in which policymakers and rural communities can test the viability for rural electrification via agrivoltaics. While this study focuses on the combination of PV and patchouli, the size of the PV system and the type of the co-located crop depend on the needs of the area of interest.

2. Materials and methods

The determination of feasibility and the estimation of expected benefits of co-location of solar power generation with crop production were based on the LCA of the four following 1-ha land use scenarios: an off-grid solar PV system with a full module density of 400 kW_p ha^{-1} [22], a rotating cultivation of patchouli (*P. cablin* Benth.) and yardlong beans and extraction of patchouli oil, a co-located land use of off-grid solar PV (400 kW_p) system and the rotating cultivation and patchouli oil distillation, and another co-located off-grid PV and rotating cultivation with half the module density (200 kW_p). Recently, Ravi et al. (2016) used an LCA modeling for a utility-scale solar PV installation with aloe vera cultivation and gel production in desert areas of Northwestern India [22]. However, the performance of a similar co-location strategy has not been modeled for off-grid systems in a tropical climate, such as that of Indonesia. The output of the LCA for the land use scenarios included annual energy consumption and GHG emissions, and the output of the LCA of land uses with a PV component (standalone PV land use and the two co-located land uses) also included annual electricity generation and the GHG offsets against the grid and diesel. The GHG offsets against grid and diesel were calculated as the difference between the annual GHG emission from solar electricity generation and the annual GHG emission of acquiring the same amount of electricity from diesel and from a typical Indonesian grid.

Water usage was not considered for any scenario because, unlike the typical solar installations in arid regions of the world, the performance of the co-located system in the tropics would not likely be constrained by the availability of water. The constraint for the input values of the LCA was derived from existing studies, or initially derived from existing studies then supplemented by location-specific data collected during field visits. All outputs were expressed on a per-hectare-per-year basis to address the land-use efficiency of each scenario. The LCA model was implemented in R (R. ver. 3.2.6). A summary of the four land use scenarios considered for the LCA, respective material flows, and the system boundaries are shown in Fig. 1. Patchouli cultivation and distillation process is shown in Fig. 2. The data used, list of assumptions and methodologies can be found in the supplementary material.

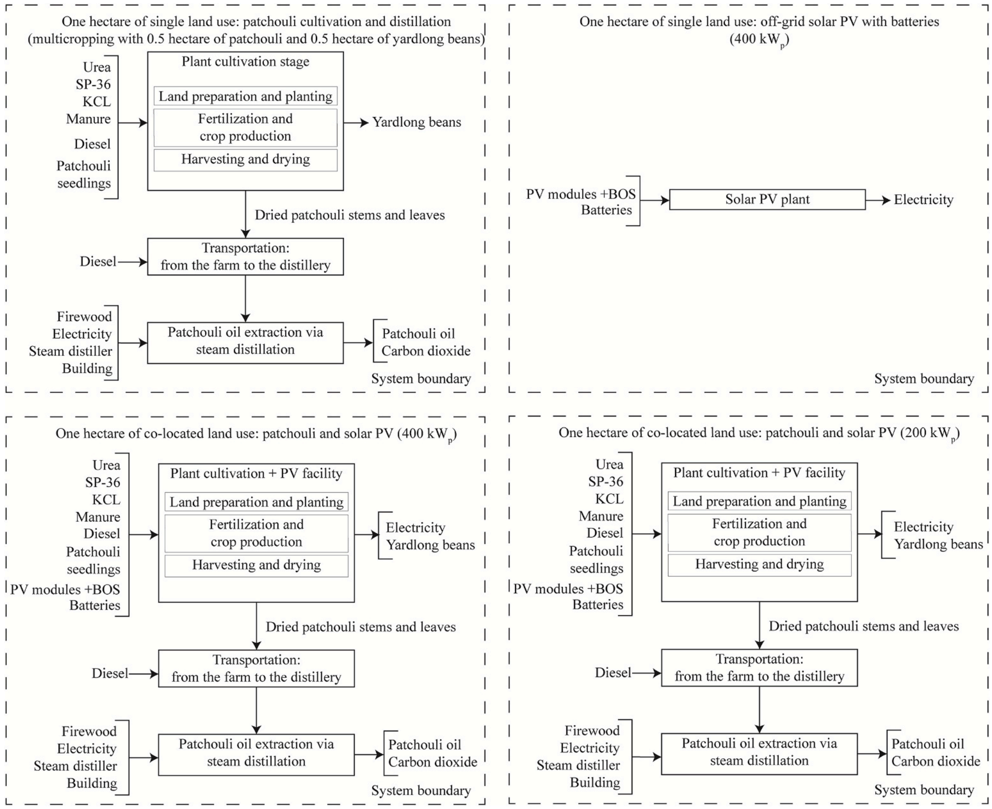

Fig. 1. Summary of the four land use scenarios considered for the LCA and their system boundaries.

2.1. *Life cycle analysis of solar photovoltaics*

The LCA of solar PV components use literature values from life cycle studies on rural microgrids and PV in other developing regions due to lack of Indonesia-specific data. For the purpose of co-location with crops, only solar PV was considered because PV is the dominant solar technology for current and proposed solar power installations for off-grid remote applications [22]. Multi-crystalline silicon PV technology was chosen over other PV technologies because of its high performance in a tropical setting, such as that of Indonesia [41,42]. Nominal capacity of each panel was 0.120 kW_p, and the area of each panel was 1 m^2 $module^{-1}$. Off-grid PV (400 kW_p ha^{-1}) and patchouli and full-density PV co-location (400 kW_p ha^{-1}) have 3333 PV modules ha^{-1}, and patchouli and half-density PV co-location (200 kW_p ha^{-1}) have 1660 PV modules ha^{-1}. The components of LCA for solar PV include (1) embodied energy (energy required for all stages of manufacturing of goods [43]) and GHG emissions of module and balance of system (BOS) components, (2) operation, (3) end-of-life (EOL) stage (decommission and treatment/disposal), and (4) transport of PV modules and BOS components.

Fig. 2. Patchouli cultivation and oil distillation in West Java, Indonesia.

The outputs of the LCA model of the solar PV system were lifetime GHG emission, land usage, energy intake, and energy output. Additionally, the lifetime GHG emission from the solar PV system was compared to the GHG emissions from using diesel generation or grid to obtain the same amount of energy as would be generated by the solar PV system over its lifetime. Then, all the outputs were divided over the system's assumed lifetime of 30 years to express them in a per-hectare-per-year basis (ha^{-1} yr^{-1}). Lifetime energy input and output of the solar PV system was first expressed in kWh per hectare (GJ ha^{-1} yr^{-1}). Lifetime energy input to the solar PV system is a sum of energy required for (1) manufacturing of the module and BOS components such as module frames, mounting structures, grid connectors, batteries, and concrete that are required for installing the module; (2) operation of the module; (3) end-of-life (EOL) stage; and (4) transport of PV modules and BOS components. Annual average energy demand of the PV facility was determined by multiplying a cumulative energy demand (CED) of 31.333 GJ kW_p^{-1} by the nominal capacity per hectare of the PV facility and then dividing by the project lifetime of 30 years [44]. While this CED was from a desert PV system with a standard BOS, this value was deemed appropriate for this study since the modeled standalone solar PV land use and the combined patchouli/PV land use would both use standard BOS with fixed-angle tilt, unlike some agrivoltaic systems whose BOS is constructed taller to provide clearance for agricultural machinery. Average annual output of a fixed-tilt PV system was estimated to be 1376 kWh kW_p^{-1}, which was a mean of average annual outputs calculated for eight locations in Indonesia [45]. A compound annual system degradation rate of 0.5% was applied over the PV system's assumed lifetime of 30 years [46]. Battery bank was sized as a ratio to the generation capacity, which was 3.08 kWh kW_p^{-1} [6]. The ratio was derived by dividing the size of the battery bank by the generation capacity of a standalone PV system from a techno-economic study on solar PV in Indonesian microgrids whose demand model was adopted for this study [6].

Lifetime GHG emission was expressed as a mass of carbon dioxide equivalents (kg CO_2-eq. ha^{-1} yr^{-1}). The lifetime GHG emissions from different life stages were calculated by multiplying an emission factor for off-grid solar of 79.7 g CO_2-eq. kWh^{-1} to lifetime electricity generation of PV (kWh) [47]. This value is from an LCA of standalone PV microgrids in Kenya, and it was deemed appropriate for this study because both this study and the Kenya study examine PV systems for small rural demands in an undeveloped region [47].

2.2. Life cycle analysis of patchouli cultivation and essential oils extraction

The LCA of patchouli cultivation used a modified version of the LCA framework described in Yan et al. (2011) [48] and Ravi et al. (2016) [18], which was based on the production pathway used in the tequila industry in Mexico and *Aloe vera* and solar co-location in India respectively. The data required for the LCA of patchouli cultivation and extraction of its essential oil were collected from site visits in Indonesia and supplemented with literature [34,37,38,49–53]. The components of the LCA of patchouli and their respective inputs are provided in the supplementary materials.

Patchouli grows well under warm and humid climates, and it can be grown successfully under a heavy and evenly distributed rainfall, from 150 to 300 cm yr^{-1} [54]. Even though Patchouli has an economic lifetime of 1.5–3 years [36,55], we chose a 2-year-crop cycle based on the local cultivation practices with a total of 15 crop cycles for the project period of 30 years.

The patchouli plants are generally established from seedlings that are placed in a nursery before being planted directly into the field [36]. The plants mature at seven months with a survival rate of 0.9 [36]. Planting density varies from 10,000 to 20,000 plants ha^{-1} depending on the fertility of the soil [36,56,57]. The first harvest occurs at maturity, and then subsequent harvests occur every 3–4 months. Each plant yields approximately 1 kg of fresh mass per harvest, which shrinks down to 0.25 kg (25% of its fresh mass) after being dried in the shade for several days [36]. Shade-drying on racks or on other flat surfaces with proper ventilation is recommended for maximal oil yield, as heating or direct sunlight may vaporize the oil from the dry mass [54,58].

The scope of the patchouli component of the LCA included the energy demand and the GHG emissions of manufacturing and transporting of agrochemicals from the factory to a farm, transporting the harvest from the farm to a distillery, and of distilling the oil from the harvest. Also included were the energy demand and the GHG emissions of the construction and operation of the distillation facility and the distiller. This component of the LCA excluded energy demand and the emissions of the production of the truck used in transporting the agrochemicals and the harvests, production of the farm equipment and the commute to and from the farm and the distillery.

The level of mechanization is very low for patchouli cultivation as the leaves and stems need to be harvested by hand [36], so diesel consumption only occurs during the transport of materials, such as fertilizers and dry yields. For the calculation of diesel consumption, the travel distance from the fertilizer factory to the farm and the travel distance from the farm to the distillation unit were assumed to be 100 km and 1 km, respectively.

Pesticide application was not considered for the model, as good agricultural practices of patchouli and the industry professionals advise against the use of pesticides in patchouli cultivation [36]. The application of manure and agrochemicals are dependent on the productivity of the soil, and the agrochemical application schedule used for our analysis is shown in Table 1.

We considered crop rotation with local nitrogen-fixing legumes (two years of patchouli and two years of yard-long beans), a recommended practice to remedy the decrease in patchouli yield caused by autotoxicity of patchouli, pest problems, and soil nutrient depletion [36,55,59]. In this crop rotation, patchouli would be cultivated on one half of the available land while yard-long beans were cultivated on the other half of the land for 2 years and then interchanged. To account for the GHG emissions from yard-long bean cultivation, a GHG emission factor of 624 kg CO_2-eq. ha^{-1} per harvest were added to the annual GHG emission of the patchouli land use [60]. Energy inputs and GHG emissions from the components of patchouli cultivation that last longer than the economic lifetime of patchouli (building and distillation unit) was first calculated on their lifetime-basis then divided by their lifetime to determine annual energy inputs and outputs.

2.3. Sensitivity and uncertainty analysis

Sensitivity analyses (one-at-a-time local sensitivity analysis) were performed for the patchouli land use. Input values that were 50% and 150% of the base case values were used. The results of the sensitivity analyses are shown in Tables 2 and 3. The variables that showed more than + - 10% difference in the total energy input and GHG emissions from the base case results were chosen for the uncertainty analysis. The range of variables that were used for the Monte Carlo simulations are listed next to the base case values of the respective variables in the supplementary material. Monte Carlo simulations were performed to obtain ranges for the outputs of the life cycle energy inputs/outputs, GHG emissions/offsets, and NPV of the two single land uses and the co-located land use. The simulation was iterated 10,000 times [22]. The input values for each iteration were drawn randomly from a triangular distribution of the input variables. The triangular distribution was used to acknowledge that common values and ranges for many variables were known while the actual distribution of the values for each variable was unknown. All the inputs varied for single land uses are also varied for the co-located land use. The results of the Monte Carlo simulations are shown in Figs. 3 and 4, and Table 2.

Table 1
Agrochemical application schedule, at planting density of 20,000 plants per hectare.

	Agrochemical dosage (kg ha^{-1})						
Timing	Initial planting	After first harvest	After second	After third	After fourth	After fifth	Two-year total
Plant age (months)	0	7	11	15	19	24	–
Urea	200	100	100	100	100	100	700
SP-36	100	50	50	50	50	50	350
KCl	150	100	100	100	100	100	650
Manure	10,000	10,000	10,000	10,000	10,000	10,000	60,000

Table 2
Tabulated results of the mean values from Monte Carlo simulations of the LCA of the CED/energy outputs and GHG emissions/offsets of the land uses. 10th and 90th percentiles in parentheses.

Land use	Co-located	Co-located	Solar PV	Patchouli		
	(200 kW_p ha^{-1})	(400 kW_p ha^{-1})	(400 kW_p ha^{-1})	Total	Cultivation stage	Distillation stage
Energy output	953.8	1907.5	1907.5	–	–	–
(GJ ha^{1} yr^{-1})	(837.8, 1065.5)	(1674.0, 2135.8)	(1674.0, 2135.8)	–	–	–
CED	241.1	435.8	389.9	45.8	11.6	34.2
(GJ ha^{-1} yr^{-1})	(218.5, 261.7)	(393.8, 470.3)	(350.0, 422.7)	(34.7, 58.5)	(11.6, 11.6)	(23.1, 46.9)
Gross GHG offsets against diesel	315.8	629.8	630.9	–	–	–
(Mg CO_2-eq. ha^{-1} yr^{-1})	(277.7, 353.4)	(552.7, 704.0)	(556.1, 704.7)	–	–	–
Gross GHG offsets against grid	186.3	371.6	372.2	–	–	–
(Mg CO_2-eq.ha^{-1} yr^{-1})	(163.9, 208.5)	(326.1, 415.4)	(328.1, 415.8)	–	–	–
GHG emissions	82.7	102.0	39.1	63.2	1.9	61.3
(Mg CO_2-eq. ha^{-1} yr^{-1})	(63.5, 104.4)	(82.3, 124.0)	(34.5, 43.7)	(44.0, 84.9)	(1.9, 1.9)	(42.1, 83.1)

Table 3
Results of the sensitivity analysis (CED).

Model Inputs	Energy input (GJ ha^{-1})			Output differential (%)	
	Low (50% of base input)	Moderate (100% of the base input)	High (150% of the base input)	Low-Moderate	High-Moderate
Months to maturity	122	102.2	82.5	19.3	−19.3
Fresh yield (kg $plant^{-1}$ $harvest^{-1}$)	57.9	102.2	146.5	−43.3	43.3
Fresh-to-dry mass ratio	57.9	102.2	146.5	−43.3	43.3
Distillation capacity (kg $distillation^{-1}$)	190.8	102.2	72.7	86.6	−28.9
Firewood consumption (kg $distillation^{-1}$)	59.2	102.2	145.3	−42.1	42.1
Firewood energy content (kWh kg^{-1})	59.2	102.2	145.3	−42.1	42.1

2.4. Economic analysis

The NPV of all four land uses were calculated for the standalone PV and the co-located PV-patchouli land uses over a 30-year period using annualized cash flow. The solar PV analyses assumed a default module density of 3333 modules per hectare, and a range of 2500–3500 modules ha^{-1} was used for the standalone PV land use. Unit costs of different system components were from an estimate for a small-scale system given by a local solar company. Then, each system component (battery bank, inverters, modules, etc.) was re-sized to the specification of the hypothetical PV systems used for this study. The total installation cost was then determined by multiplying the unit cost of system components by the size of each system components. The O&M costs were calculated on a per-kWp basis. The variables and the values for the calculation are listed in the supplementary data. The system was assumed to be off-grid, and thus the sole source of income in the standalone PV land use was assumed to be wholesale of electricity at the base case price of 0.149 USD per kWh, which was 85% of the mean average costs of electricity generation in all areas except for Sumatra and Java-Bali in 2018 [61]. The wholesale price of electricity as purchased by Indonesia's national utility PLN is declared by the Indonesian government based on the average cost of electricity production in the previous year, which includes heavily subsidized coal electricity [51].

The agricultural component of the economic analysis assumes a full crop density for standalone patchouli of 20,000 (15,000–30,000) plants ha^{-1}. Patchouli's economic life of two years is repeated 15 times over the project period of thirty years. Based on age to maturity and harvest intervals of patchouli, harvest occurs twice in the first year and three times in the second year, totaling five harvests over two years. This model assumes that all patchouli and all yard-long beans are harvested at the same time instead of following a staggered planting/harvest schedule for ensuring continuous harvest.

2.5. Uses for the energy output from the solar PV

The energy inputs and outputs of the standalone solar PV were compared to an annual electricity demand of a typical rural village in Indonesia. To calculate the annual electricity demand of the village, the daily grid load of a model village used in the techno-economic analysis by Blum et al. [6] was first converted to a lump sum of total daily demand and then converted to annual values. The village consisted of 450 households with identical demand profile, commerce, and social infrastructure. The annual total electricity demand is extrapolated from daily electrical demand profile that is described in detail in Blum et al. [6].

Rural Indonesia is characterized by population density less than 300 inhabitants km^{-2}, and more than 50% of the villages in these regions are comprised of less than 450 households occupied by less than 5000 people [62,63]. The electricity demand of this representative model community is the upper limit on the electricity from the PV system that has been used. In isolated villages, excess electrical generation/capacity would remain unused. Nevertheless, this community profile effectively accounts for a wide range of electricity demand by rural populations in

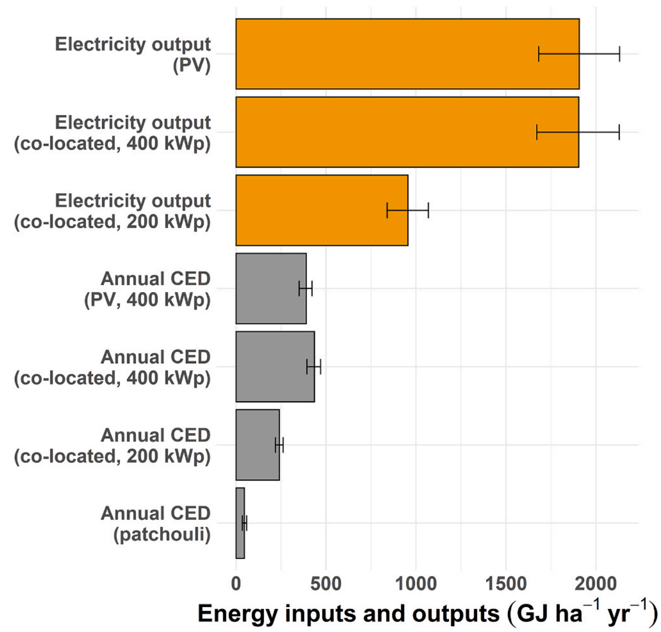

Fig. 3. Energy inputs and outputs from standalone solar PV land use, co-located land use with 400 kWp ha^{-1} module density, co-located land use with 200 kWp ha^{-1} module density; and energy input for patchouli cultivation and distillation. The yellow bars represent the energy produced by the PV component of the respective land uses (in parentheses), and the gray bars represent the energy requirement for each land uses. The error bars represent the 10th and the 90th percentile of the frequency distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

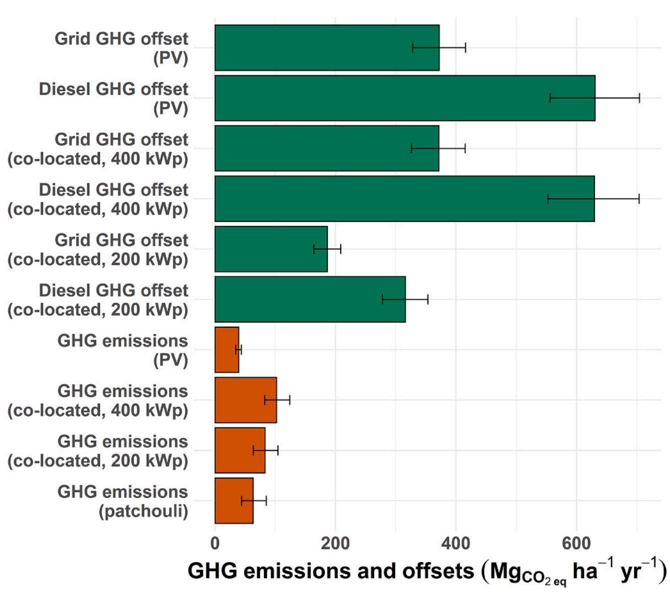

Fig. 4. GHG emissions and offsets from standalone solar PV land use, co-located land use with 400 kW_p ha^{-1} module density, co-located land use with 200 kW_p ha^{-1} module density; and GHG emissions for patchouli cultivation and distillation. The green bars represent the GHG gas offsets against diesel or grid by the PV component of the respective land uses (in parentheses), and the orange bars represent the GHG emissions from the respective land uses. The error bars represent the 10th and the 90th percentile of the frequency distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Indonesia. Thus, under limitations of this analysis, all electrical generation by the PV system is considered useful and is counted towards the GHG offsets.

3. Results and discussion

3.1. Lifetime energy flux and GHG emissions

The mean annual CED of the patchouli land use was 45.8 GJ ha^{-1} yr^{-1} with a 10th/90th percentile range of 34.7–58.5 GJ ha^{-1}, and the mean annual CED of standalone solar PV land use was 389.9 GJ ha^{-1} with a 10th/90th percentile range of 350.0–422.7 GJ ha^{-1} yr^{-1} (Fig. 3 and Table 2). The annual energy output is the same for the 400-kW_p co-located land use as it was for the PV land use because no loss of generation from agricultural practices were assumed to occur. Under this assumption, electricity output from a hectare of the co-located land use with the standard module density (400 kW_p ha^{-1}) far exceeds the energy requirement for the combined annual CED for solar PV and patchouli land uses (Fig. 3). Furthermore, comparing the annual electricity demand derived from Blum's demand model [6] shows that half of the standard module density (200 kW_p ha^{-1}) was sufficient to satisfy the annual demands of 450 households, commercial, and social electricity uses of a typical rural Indonesian village (Fig. 5).

While the annual CED of the standalone solar PV land use was almost a magnitude larger than that of the patchouli land use, the annual GHG emissions from a hectare of standalone PV (39.1 Mg ha^{-1} yr^{-1}) was smaller than those of the patchouli land use (63.2 Mg ha^{-1} yr^{-1}), 98.3% of which were caused by the patchouli distillation process (61.3 Mg ha^{-1} yr^{-1}) (Fig. 4). The PV land use generated 1907.5 GJ ha^{-1} yr^{-1} of electricity (Fig. 3), which translated 630.9 Mg ha^{-1} yr^{-1} offset against the GHG emissions from diesel electricity generation, and 372.2 Mg ha^{-1} yr^{-1} offset against the grid emissions (Fig. 4). However, the estimated GHG emissions from the PV land uses may vary by a magnitude in both directions based on the emission factor used for the calculation, whose reported values have varied as much as 9 g-CO_2 kWh^{-1} [44] to 104 g-CO_2 kWh^{-1} [64] for crystalline silicon PV. Using a more recent value of 487 g-CO_2 kWh^{-1} [65] would increase the estimated GHG emissions by five-fold and considerably decrease the GHG offsets against diesel and grid electricity. Furthermore, any portion of electricity generated by an off-grid system that exceeds the demand has no value to the end-users and has to be dumped [6]. While outside of the scope of this study, accounting only for the used electricity will result in higher specific GHG emissions and CED per unit electricity [65]. The contribution of the battery bank on the specific GHG emissions and CED depends on the PV

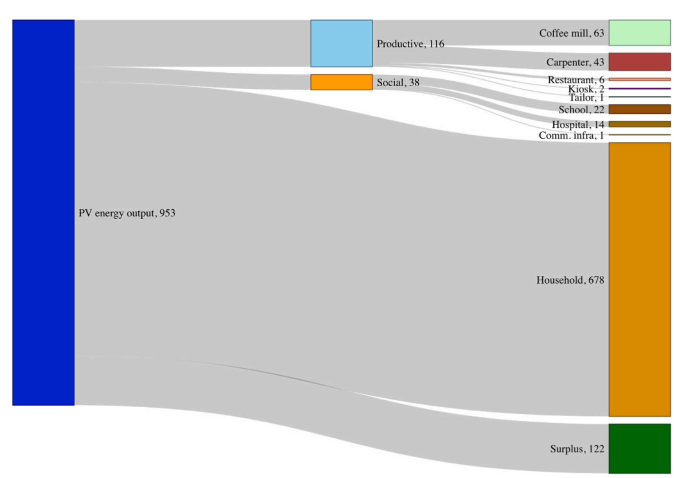

Fig. 5. Breakdown of the annual electricity production by a 200 kW_p system into different energy demands of a model village from Blum et al., 2013 [6]. Energy in GJ $year^{-1}$.

technology. For instance, crystalline PV modules require more embedded energy and GHG than other PV technologies, so battery bank's contribution to the total GHG and CED values are relatively small [65]. However, larger portion of the total GHG and CED can be attributed to the battery bank in PV systems with Cadmium telluride thin-film modules or other types since these modules require less embedded energy and GHG emissions to be manufactured [47,65]. Since the solar PV system analyzed for this study uses multi-crystalline PV modules, any realistic change in the size of the battery bank is unlikely to have any significant impact on the final GHG and CED values.

3.2. Sensitivity analysis

In the sensitivity analysis for the patchouli land use, both annual energy requirement per unit hectare (Table 3) and annual GHG emissions per unit hectare (Table 4) of patchouli cultivation and distillation land use showed more than 10% deviation from the base case outputs with 50% decrease or 50% increase to the following variables: the number of plants per hectare, fresh yield per plant per harvest, the ratio of unit mass of dry yield to fresh yield, the capacity of the distillation unit, and the firewood required per distillation.

The CED was also sensitive to the age of maturity of patchouli plants, and the effective heat of combustion of firewood. The GHG emissions were also sensitive to the size of the building, maximum number of distillations per year, and emissions per unit area of the building. However, both energy requirement and GHG emissions of the patchouli land use were less sensitive to the changes in the consumption of agrochemicals (Table 3).

Both energy requirement and GHG emissions of patchouli cultivation and distillation were sensitive to the variables that controlled the number of distillations per year, such as the number of plants per hectare, fresh yield per plant per harvest, and the ratio of unit mass of dry yield to fresh yield. Dry yield available for distillation is directly proportional to the number of distillations per year, and the large quantities of firewood used for distillation process incurs significant GHG emissions and energy consumption.

Supposing that there is a specific amount of heat required for distilling essential oil from a unit mass of the dry yield, the change in effective heat of combustion of firewood should have resulted in a change in firewood consumption per distillation. In practice, it was unclear how much heat is actually recovered from the combustion of firewood due to the lack of data on variables that the combustion depends on, such as the degree to which firewood is dried before being ignited. Since 98% of the lifetime GHG emission was attributed to the distillation process, accurate estimation of the GHG emission of the patchouli land use would require additional data related to the steam distillation process, such as the type of wood used for fuel, degree of combustion of fuel wood, heat efficiency of the oven, volume of water used for the steam distillation process, and a time series of the vapor pressure inside the chamber.

The annual CED and energy output of the standalone PV land use (389.9 and 1907.5 GJ ha^{-1} yr^{-1}, Table 2) were comparable to those of PV plants in other LCA studies [21,22,66]. Compared to the drylands where similar co-location studies took place, however, tropical Indonesia received less annual irradiation, which resulted in lower lifetime electricity output per CED [21,22,45]. The GHG emissions from the standalone PV land use (39.1 Mg CO_2-eq. ha^{-1} yr^{-1}) were also similar to those from the same land use in other co-location studies [21,22].

The large energy input and GHG emission of the patchouli cultivation were attributed to two factors: one, heightened usage of agrochemicals due to the high nutrient demand of patchouli cultivation, and two, usage of firewood during the steam distillation of patchouli. The energy input and the GHG emission could be mitigated in the cultivation stage by reducing the application of agrochemicals and increasing the use of organic fertilizer, and in the distillation stage by replacing the firewood combustion with a solar water boiler or other low-emission energy technology that could generate sufficient heat for the steam distillation process.

3.3. NPV

The mean 30-year NPV of patchouli land use was 418 million IDR with a 10th/90th percentile range of −69 million IDR to 971 million IDR, which showed that patchouli land use was profitable in most scenarios (Fig. 6a, **b)**. However, the mean 30-year NPV of the standalone PV land use with wholesale of electricity were −20,730 million IDR with a 10th/90th percentile range of −25,642 million to −16,182 million IDR, which showed that the standalone solar land use was highly unprofitable in all cases (Fig. 6a). The mean NPV of patchouli in its most profitable scenario (2593 million IDR) was still an order of magnitude less than that of the maximum NPV of the PV land use with wholesale of electricity (−10,182 million IDR). The mean NPV of the co-located land use with 200-kW_p solar PV array was −8404 million IDR (standard deviation of 1881 million IDR), which was a little less than half of the 400-kW_p co-located land use. The Monte Carlo simulations showed that the NPV of with PV components (standalone solar and the two co-located land uses) were less constrained than that of patchouli land use (Fig. 6a). The patchouli land use is far more profitable than both the standalone PV land use and the co-located crop-PV land use.

The large negative NPV of standalone PV land use was primarily attributed to the fact that a large portion of the cost of standalone PV land use was the sizeable investment capital required for installation [22]. The NPV of the co-located land use only had 50% of the module density of that of the standalone PV land use, and the shift of the NPV towards the positive in the co-located land use was attributed to the decrease in the investment cost of the PV component after reducing the module density to the half of the full module density. While the

Table 4
Results of the sensitivity analysis (GHG emissions).

Model Inputs	GHG emissions ($Mg\ ha^{-1}$)			Output differential (%)	
	Low (50% of base input)	Moderate (100% of the base input)	High (150% of the base input)	Low-Moderate	High-Moderate
Plants per hectare	13.1	24.6	36	−46.5	46.5
Months to maturity	29.4	24.6	19.7	19.6	−19.6
Fresh yield (kg $plant^{-1}$ $harvest^{-1}$)	13.3	24.6	35.8	−45.9	45.9
Fresh-to-dry mass ratio	13.3	24.6	35.8	−45.9	45.9
Building area (m^2)	12.4	24.6	44.8	−49.4	82.4
Maximum number of distillations per year	41.1	24.6	19	67.4	−22.5
Distillation capacity (kg $distillation^{-1}$)	47.1	24.6	17	91.7	−30.6
Firewood consumption (kg $distillation^{-1}$)	21.6	24.6	27.5	−12.2	12.2
Embodied emission per building area	16.5	24.6	32.6	−32.9	32.9
GHG emission per mass of firewood burnt	21.6	24.6	27.5	−12.2	12.2

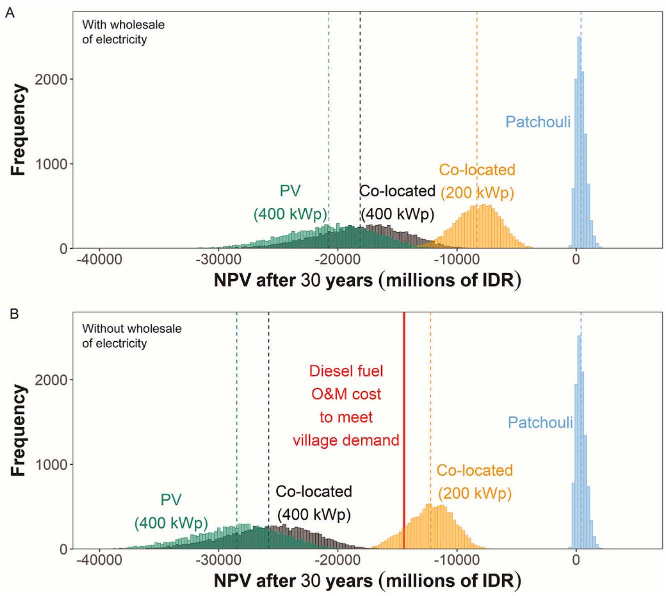

Fig. 6. Net present value (NPV) frequency distributions from Monte Carlo analysis (n = 10,000) where the x-axis represents NPV in Indonesian Rupiah (IDR). A. With wholesale of electricity. B. without wholesale of electricity. The dotted line at the center of each curve represents the mean NPV of the respective land uses. The red solid line represents the net present cost of the diesel fuel consumption and O&M costs for diesel electricity generation without accounting for the capital costs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

patchouli component increased the NPV of the co-located land uses, its impact on the NPV was barely noticeable as the positive NPV of the patchouli land uses is several magnitudes smaller than the negative NPV of the PV land use. In short, PV electricity generation for the wholesale of electricity was not a profitable land use in the current scenario.

When the wholesale of electricity is not considered, the NPV of the land uses with PV components can be defined as the net present cost (NPC) of electricity (Fig. 6b). In this case, the 30-year NPC of the electricity from 200-kWp co-located system (mean: −12,257 million IDR, standard deviation: 1864 million IDR) was smaller than the flat cost of diesel required to generate equivalent electricity (−14,702 million IDR) over the project lifetime, even without accounting for the capital expenditure for the diesel system. This finding is in agreement with previous techno-economic studies on off-grid solar PV in Indonesia: even though the installation cost of diesel generators is lower than that of solar PV, the LCOE of off-grid PV-storage systems was comparable or even cheaper than that of diesel due to the high transportation costs of diesel in rural areas [6,46]. Indonesian diesel price has been increasing, and this trend is likely to continue [6]. Therefore, we find that the co-located land use with low module density (200 kW_p ha^{-1}) for the direct consumption of electricity could reduce the cost of energy for the community without reducing the revenue from pre-existing agricultural venture.

In order to fully understand the implications of the NPV distribution, it is important to discuss several assumptions of the NPV model, First, this NPV model assumed that no subsidy exists for solar besides the government-mandated wholesale electricity price of $0.067 to $0.149 (Supplementary info). The Ministry of Energy and Mineral Resources regulation 50/2017 makes available a few different types of subsidy for renewable energy generation, such as Build, Own, Operate, and Transfer projects or a feed-in-tariff (FiT) as 85% of the local cost of generation for areas where the local cost of generation is higher than the national average, or as a business-to-business tariff pending governmental approval for areas with cost of generation lower than that of the national average [67,68]. This policy attempts to promote renewable energy development in rural areas with low electrification rates [67].

In practice, the average and regional costs of generation are brought down by cheap, subsidized coal generation which has resulted in a low cap on the wholesale price of electricity [67]. If the current subsidy structure were to be modified by either raising the cap on the tariff to accurately reflect the high cost of electricity generation, or by including the funding of the capital expenditure, NPV calculations for PV would improve. All other inputs staying the same, a decrease in the PV system cost by 65% or higher will result in the 30-year NPV of both 200-kW_p and 400-kW_p co-location land uses (Fig. 7) to be positive. Achieving this level of cost reduction in capital subsidy alone is unlikely. However, Indonesia's fuel subsidy has exceeded 17 billion USD (or 20% of Indonesia's total state expenditure) as of 2014, which was more than twice the money that the government spent on subsidizing electricity in that same year [69]. Diesel, whose retail price is set by the government to be 1000 IDR $litre^{-1}$ lower than the market price, has been between 4000 and 7000 IDR $litre^{-1}$, which means that the government has been subsidizing between 14% and 25% of diesel costs. Since diesel price is expected to increase in the coming decade, diverting the subsidy from diesel to other energy sources will ease the burden on the government's budget [9,69,70]. A subsidy for solar PV at the same scale as the current diesel subsidy would greatly reduce the impact of capital expenditure on the NPV. In addition to the capital subsidy, projected decrease in the cost of solar system components [71,72] may result in a positive NPV. Since the installation and operation of solar PV is loss-making with current policies, one may take full advantage of the projected decline in the PV costs by spreading out the capital expenditure via gradual purchase of PV components instead of taking out a loan for purchasing the entire system during the first year [71]. Such gradual expansion of solar infrastructure would also allow the interested rural communities to fully take advantage of any pre-existing diesel generators.

Another important assumption to discuss is that the NPV model does not consider the secondary benefits from electrification, such as the revenue generated by enterprises enabled by electrification or the avoidance of potential health costs of the local pollution due to firewood stoves and coal-fired or diesel power plants (e.g. hospital or municipal groundwater pumping) [73,74]. Furthermore, surplus electricity of is often used to produce more commercial or social goods [12,75–77].

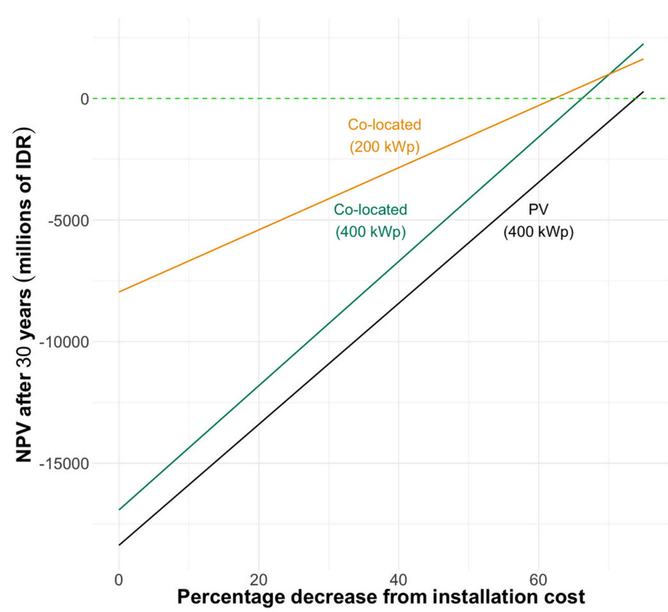

Fig. 7. Net present value of PV land uses with wholesale of electricity, as a function of decrease in the initial cost of solar PV deployment. The green dashed line represents 0 IDR, above which a land use would become profitable. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Using the excess energy to locally refine and diversify agricultural products may reduce the transportation cost from the site of raw material production to the processing facility and yield higher returns per hectare, provided that the processed agricultural product is more profitable than the raw agricultural material. the excess electricity could also provide relatively consistent pumping and more efficient means of irrigation, which may increase the crop yield per hectare [13,14,78]. In this way, small-scale PV systems that are co-located with agriculture may support the livelihood of smallholder farmers, reduce energy poverty, and bring positive effects on gender equality such as higher flexibility of time use for women [79]. However, these indirect economic benefits were not factored into the determination of the NPV. It is also worth noting that agricultural enterprises yield periodic revenue upon sale of the harvests, whereas electrical generation provides much shorter-term revenue generation. Therefore, the combination of solar PV electricity generation with agricultural enterprises may lead to a more stable local economy and less impact from the income variation owing to lean months or poor yields.

The high investment cost of solar PV and the capacity of a hectare of standalone PV land use could produce more than twice the typical village's electricity demand make a strong case for a vegetation-centric approach of PV-patchouli co-location rather than the energy-centric approach. Using the vegetation-centric approach, the PV array can be spread over several hectares of adjacent fields of patchouli. Satisfying the energy demand of the same model village would require one half of the modules required for a full-density PV land use, and the reduced number of modules could then be spread over 3 ha of adjacent patchouli cultivation for the module density per area one-ninth of the full module density, which may result in negligible loss in patchouli yield. Since the patchouli land use has a positive NPV, there exists a break-even density of PVs per hectare below which the NPV will be positive without any changes to the subsidies. A pilot-scale cultivation of lettuce, which is a shade-tolerant crop, under full-density PV operation showed negligible loss in yield, far out-performing the simulation of lettuce cultivation under full-density PV operation that estimated a 17% loss in fresh yield and a 20% loss in dry yield [80,81]. As another shade-tolerant crop, patchouli adapts to shaded conditions by increasing leaf area and pigment, so the cultivation of patchouli under the PV canopy may not suffer significant loss in oil yield [38]. To summarize, patchouli's adaptive features to low sunlight conditions, and the extremely low PV module density may eliminate yield loss altogether. However, a detailed simulation of distribution of solar irradiation under varying panel densities and measuring the potential changes in the crop yield in a pilot-scale co-location study are necessary verification steps.

3.4. Land use

In addition to capital, land occupation is another barrier to fully realizing the technical potential of solar energy. Just as Indonesia needs to increase its generation capacity and electrification rates without incurring further GHG emissions, it is also important that they do so with minimal land-transformation: Indonesia currently has one of the highest deforestation rates in the world, which has resulted in reduction in fundamental ecosystem services such as primary production and carbon sequestration [82,83]. Until now and for the foreseeable future, Indonesia's economy has been dependent on the cultivation of high-value crops (e.g. oil palm, patchouli, biofuel feedstocks) and coal power whose fuel sources often overlap with forested areas [84–87]. A more recent study in the energy transition scenario projects that as much as 750 TWh of Indonesia's electricity may come from solar PV by 2050 [88]. At mean power density of 400 kW ha^{-1} [22] and average annual electricity output of 1376 kWh/kW_p [45], PV generation of such scale would require approximately 1.4 million hectares (0.5% of Indonesia's total landmass, 2% of Indonesia's total agricultural land use, and 1% of Indonesia's forest cover). While this land footprint is small compared to the total land area of Indonesia, it may still contribute significantly to the overall impact of deforestation for a few reasons: 1) many of the environmental responses to the deforestation are non-linearly related to the extent of deforestation, and 2) separating the nonlinear responses from the linear responses is difficult [89]. 3) Furthermore, the indirect and regional effects due to the habitat fragmentation caused by conventional solar facilities are also difficult to quantify and mitigate, as repatriation and translocation programs have low success rates (<20%) [19]. The PV-patchouli co-location land use is designed to address this conundrum: based on the breakdown of the annual generation per hectare of standalone PV land use, only one half the number of modules (approximately 1660 modules ha^{-1} or 200 kW ha^{-1}) would be required to satisfy the energy demand of a village (Fig. 5). At worst, yield loss in a half-density agrivoltaic system is estimated to be 17% of the crop yield in the full sun [80]. At this loss rate, reaching 750 TWh of PV electricity by implementation of the co-location design in pre-existing farmlands would require 2.7 million hectares of crop-PV co-location, which would result in crop yield loss equivalent to 0.459 million hectares of loss in food production and no deforestation, compared to 1.4 million hectares of loss in farmlands and/or deforestation that would be caused by the conventional PV land use. To further reduce the crop yield loss caused by the shading from the solar panels, the solar PV density could be further reduced by spreading the PV array over adjacent farmlands. Doing so may also divide the burden of capital expenditure, which may be difficult for any single landowner to shoulder, over several landowners. Additionally, electrification via co-located crop-PV configuration enables implementation of solar-powered water pumps [78], water-efficient irrigation [14], and other energy-intensive agricultural activities that increase crop yields, thereby reducing energy poverty without incurring additional deforestation or land transformation for solar PV. However, the mitigated land-use change from the co-location design is calculated from a limited range of parameters and a single crop. While patchouli was chosen as the ideal crop to demonstrate the feasibility of the co-location scheme, Indonesia has wide climactic regimes, and patchouli-PV co-location may not be feasible in climates and soil conditions unsuitable for patchouli growth. Therefore, other plants that satisfy the following logistical and physiological requirements for their respective climate are equally worth investigating for the possibility of co-location. Overall, our analysis shows the potential of co-located PV-crop land use to replace or supplement diesel-based electrification with higher land-use efficiency and minimal land transformation. This finding is significant for Indonesia, which has one of the highest deforestation rates in the world that result from an over-reliance on abundant natural resources for food and energy production [90].

4. Conclusion

In this analysis we used a life cycle modeling framework to test the environmental and economic feasibility of a co-located solar PV – patchouli cultivation system. The annual energy production was enough to satisfy the energy demand of a model village three times over, which would in turn result in a significant offset of GHG emissions against either diesel electricity generation or grid supply of the same scale. However, the negative NPV of standalone PV land use also revealed that PV was very cost-prohibitive with no subsidies. Given the scale of solar PV's capital expenditure, the reduced panel density will not only minimize the loss of crop yield per unit area but also lower the cost of electricity than that of diesel-based electricity, while meeting the daily demands of a sizeable rural community. For PV to be profitable in the near future, owners of the PV system would need to take advantage of subsidies that offset high capital expenditures. In the long run, however, the downward trend in the cost of PV will likely shift the NPV in the positive direction. Indeed, the cost of generation has decreased significantly in the last decade to complement the Indonesian government's decision to increase the share of renewables [91]. An agro-centric crop-PV co-location configuration would be a plausible way of electrifying some of the remote Indonesian agrarian communities while minimizing the impact of PV systems' land and financial footprint. Further, the distributed solar PV infrastructure may be more resilient than the conventional grid to extreme events, which are predicted to occur more frequently in the future as it is easier to reestablish solar electricity micro-grids in rural areas affected by natural disasters [92,93].

Indonesia has experienced rapid population growth in the past four decades, creating additional demand for food, energy, and water resources [94] The constant pursuit for improving economic growth, calorie consumption, and energy accessibility has resulted in accelerated land use change and deforestation [90,95,96]. Moreover, Indonesia is already experiencing the impacts of climate change on agriculture and fisheries, further increasing the pressure on land and water resources [97]. Our analysis indicated that there is potential to establish small-scale co-located solar infrastructure and agriculture in geographically isolated rural areas with local participation, thus minimizing the socioeconomic and environmental issues resulting from additional land transformation or forest clearing for energy development or for cultivating high value non-food crops.

Credit author statement

Chong Seok Choi: Conceptualization, Data collection, Methodology, Analysis, Visualization, Writing, Original draft preparation. Sujith Ravi: Conceptualization, Methodology, Writing, Reviewing and Editing. Iskandar Z. Siregar: Data collection, Writing, Reviewing and Editing, Fifi Gus Dwiyanti: Data collection, Writing, Reviewing and Editing, Jordan Macknick; Conceptualization, Writing, Reviewing and Editing. Michael Elchinger; Methodology, Writing- Reviewing and Editing. and Nicholas Davatzes: Conceptualization, Methodology, Writing, Reviewing and Editing.

Data availability

Datasets related to this article and input files necessary to reproduce the figures are available in the supporting information.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.111610.

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