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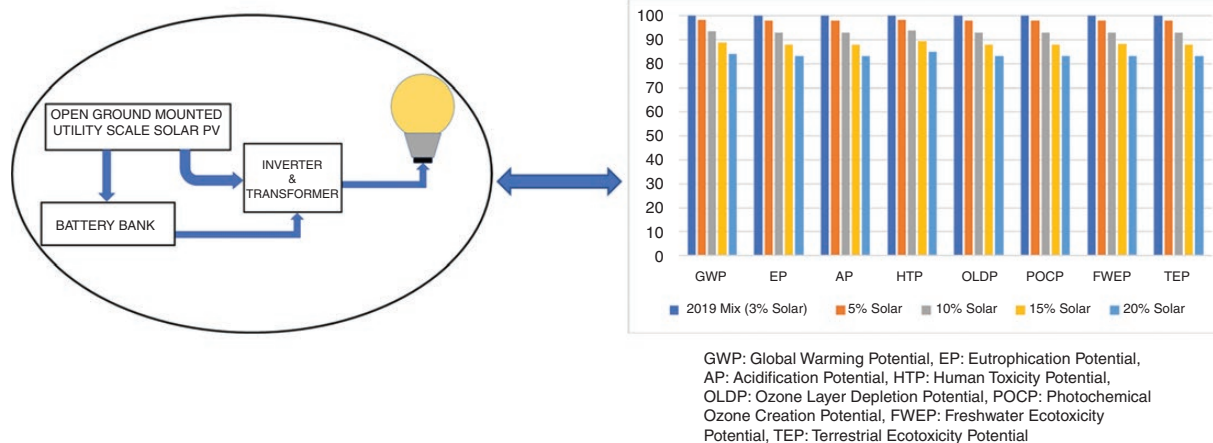
Role of solar power in shifting the Turkish electricity sector towards sustainability

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Abstract

This work covers a three-stage evaluation: cradle-to-grave life-cycle assessment (LCA) of polycrystalline silicon (pc-Si) and monocrystalline silicon (mc-Si) solar photovoltaics (PVs) as on-grid utility-scale energy options; environmental-impact distribution of pc-Si and mc-Si combinations under local conditions in Turkey; and assessment of the role of solar power in improving the environmental performance of the Turkish electricity mix. In LCA, mc-Si panels are found to have 4.47–9.16% higher environmental impacts than pc-Si panels in absolute terms. However, the higher efficiency and slower degradation rate of mc-Si panels make them have lower impacts on a kWh electricity basis. For the solar PV combination, the global-warming potential (GWP) and human-toxicity potential (HTP) results are found to be significantly lower than that of home-scale pc-Si systems (27.1–34.4 g versus 33.7–59.9 g CO₂ equivalent (eq)/kWh 30.6–38.9 g versus 65.9–117 g 1–4 dichlorobenzene (g 1–4 DB) eq/kWh) operating in Turkey due to the higher capacity and efficiency of the utility-scale system. This result reveals the advantage of utilizing solar power as a centralized energy option for the country. All of the eight impacts that we evaluated reduce increasingly with increasing solar percentage in the electricity mix. The general tendency is that each percentage increase in solar electricity in the mix reduces each impact by ~1.0%. With a conservative assumption, if the solar power ratio in the mix increases to 15% by 2030, a GWP reduction of 31.3 million tons can be achieved. This corresponds to 12.7% of the greenhouse-gas mitigation commitment (246 million tons CO₂ eq) made by Turkey under the United Nations Framework Convention on Climate Change. With the Turkish electricity sector being dominated by imported coal and natural gas, the obtained results reveal the potential of solar power in improving the environmental performance of the electricity mix in Turkey.

Graphical Abstract



Utility scale on-grid solar power improves environmental performance of Turkish electricity mix.

Keywords: solar PV life-cycle assessment; Turkish electricity-mix life-cycle impacts; environmental performance improvement with solar energy

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Introduction

Energy is the main driver of the economy and social life. However, energy-production-related environmental problems due to fossil-fuel use steer humanity towards renewable energy sources. As a functional energy form, electricity is a fundamental input in industry, in agriculture (electrical pumps and processing) and in the functioning of modern devices [1].

Having a growing population and a developing economy, Turkey has the highest increase rate in electricity demand (6–7% annually) among all Organisation for Economic Co-operation and Development countries and imports 74% of resources to meet her primary energy demand [2, 3]. In 2019, 56% of electricity was generated from fossil resources, mostly from imported hard coal and natural gas [4]. Under the United Nations Framework Convention on Climate Change and the 2015 United Nations Climate Change Conference (commonly referred to as COP 21), Turkey has committed to a 21% greenhouse-gas (GHG) emission reduction by 2030 that corresponds to 246 million tons of CO₂ equivalents. To achieve this commitment, Turkey aims to increase her solar capacity to 10 GW, wind capacity to 16 GW and to reduce transmission losses to 15% in the electricity sector [2].

1 Solar energy in Turkey

Solar energy is a promising local and renewable energy source for Turkey. The Solar Energy Atlas (SEA) of Turkey prepared by the General Directorate of Energy Affairs (GDEA) shows that the mean number of annual sunny hours is 2690 and the mean solar-insolation value per year is 1524 kWh/m², which reveals the high solar-energy potential of the country as shown in Fig. 1 [5].

The contribution of photovoltaics (PVs) to the electricity mix is new in Turkey. In 2015, the percentage of PVs in the mix was 0.23% and in 2019 it was 3.05% [4]. The PV industry showed a capacity growth of 213% in 2018; 249 MW of installed capacity in 2015 increased to 6700 MW in 2020 [4, 6]. The increase in the solar power share in the Turkish electricity mix is expected to accelerate with government subsidies sourcing from GHG emission-reduction commitments, energy security and independency targets of the country [2, 6].

Industry-wise, PV production is limited in Turkey and panel-assembly facilities are more prevalent. Installed panels are mainly of European and Chinese production. However, industrial production is expected to rise with increasing solar power demand [7].

1.1 Literature review

Despite the tremendous increase in the utilization of PVs in electricity generation, the existing literature for Turkey does not provide sufficiently detailed information about the potential environmental impacts of solar PVs and their contribution to the electricity mix.

In analysing the environmental impacts of energy technologies, life-cycle assessment (LCA) methodology is extensively utilized. LCA analyzes the environmental impacts of a product, process or service by evaluating all resource use (inputs) and outputs to the environment (air, water, soil) throughout the life cycle. By quantifying several environmental impacts, LCA aims either to compare the same product produced with different technologies or to define areas of improvement within a process by determining dominant process steps [8, 9].

LCA of the Turkish electricity mix is extensively studied. Atılğan and Azapagic evaluated the 2010 electricity-mix life-cycle impacts as well as social and economic aspects, concluding that

hydropower is the most sustainable energy option for Turkey. The 2010 electricity mix did not have any solar component [10]. Gunkaya *et al.* compare the life-cycle impacts of the 2012 electricity mix and the expected mix of 2023. In their analysis, solar power had only a 0.23% ratio in the 2023 Turkish electricity mix. However, the solar ratio in the electricity mix had already reached 3.05% by 2019 [4, 11]. Gunkaya *et al.* evaluated standard 3-kWp slanted roof-mounted panels without specifying their types [11]. Yılan *et al.* ranked several energy options in the 2014 electricity mix with respect to their sustainability score, reaching the same conclusion as Atılğan and Azapagic [10, 12]. Furthermore, it can be concluded that solar and wind power are known to have reasonable sustainability scores [12]. However, it is worth mentioning that the 2014 electricity mix had only a 0.01% solar component [4] and they did not specify the type of PV evaluated [12]. Hence, the studies mentioned do not represent utility-scale, on-grid solar systems properly.

In terms of solar PV LCA studies in Turkey, a home-scale, rooftop-mounted polycrystalline silicon (pc-Si) PV LCA is performed by Üçtuğ and Azapagic by not covering utility-scale PVs. They utilize Chinese production data representing production technology before 2014 and do not account for the thinning and improved resource intensity of silicon-based PVs [13]. Furthermore, the utilization of solar PVs in irrigation systems in remote areas and its economic superiority with respect to diesel pumping have been revealed by Senol [14]. LCA of a water-treatment plant situated in Turkey shows that utilizing solar or wind energy in powering the plant reduces environmental impacts considerably with respect to using coal or grid mix [15]. Similar results are obtained when LCA of water heating is performed by using solar energy rather than natural gas [16]. Optimal location determination for solar PVs through geographical information systems (GIS) [17, 18], improving environmental impacts of human residences using solar energy for heating rather than fossil resources [19, 20] and policy issues to enhance solar PV adoption in Turkey [21] are other areas of research available. However, the evaluation of solar PVs as utility-scale, on-grid energy options and a detailed LCA of monocrystalline silicon (mc-Si) PVs are not available.

Furthermore, the review of Miloussi *et al.* working on thin-film, Si-based solar PVs and solar thermal collectors reveals the environmental advantage of solar energy with respect to fossil fuels and the financial feasibility of solar PVs in locations with high insolation values. This work presents the carbon emission of the PV system as being in the range of 26–60 g CO₂ eq/kWh [22]. Asdrubali *et al.* reviewed the LCA of electricity production from renewable energy sources and analysed 11 review papers and 34 case studies about PV power plants. Harmonized values show the GWP range as 9.40–167 g CO₂ eq/kWh [23]. Üçtuğ and Azapagic report a GWP range of 33.7–59.9 CO₂ eq/kWh for rooftop-mounted pc-Si solar PVs operating in Turkey [13]. Several life-cycle impacts related to solar power are evaluated in these three works [13, 22, 23].

Technology-wise, the solar PV market is dominated by silicon-based panels. Pc-Si PVs are currently the most widely used and preferred PV types because of their lower energy requirement in production than mc-Si PVs [24, 25]. Recent development is the thinning of cell thickness that results in a resource-intensity reduction in the production of Si-based solar PVs. This in turn reduces the impacts of the PV-production stage [26].

1.2 Aim and significance

Of the current (both utility-scale and home-scale) solar panels in Turkey, 95.4% are pc-Si (62.4%) and mc-Si (33.0%) PVs. The ratio of home-scale PVs is <0.5% [26]. Despite recent developments in

different types of solar PVs with increasing efficiency, a change in PV type preferences is not expected in the near future [24, 25]. Hence, this work has two aims. The first aim is to evaluate the life-cycle impacts of pc-Si and mc-Si PVs as utility-scale, on-grid energy options and determine their impact distribution within Turkey. It is important to note that mc-Si PV impacts have not been evaluated in detail for Turkey. The second aim is to determine the role of pc-Si and mc-Si solar PV combinations to improve the environmental performance of the Turkish electricity mix (cases in which the solar power ratio in the mix increases from 3.05% to 5%, 10%, 15% and 20% are analysed). Filling these two information gaps is crucial and forms the main contribution and novelty of this work.

All in all, the presented work performs cradle-to-grave LCA of utility-scale, on-grid pc-Si and mc-Si PV systems under local conditions in Turkey starting from PV production to plant decommissioning. We analysed the environmental impacts at 14 different locations in Turkey (two cities from each of seven geographical regions with the lowest and highest insolation values) and Turkey's average to determine the distribution of impacts within the country. The sensitivity of environmental impacts to the changing pc-Si and mc-Si ratio (60% pc-Si:40% mc-Si and 70% pc-Si:30% mc-Si cases) in the solar combination was also analysed. Then, for the base year of 2019, we analysed the effect of increasing the solar electricity ratio in improving the environmental performance of the Turkish electricity mix.

The rest of this article is arranged as follows. Section 2 explains the LCA methodology, the application of LCA to the evaluated PV systems, the Turkish electricity-mix calculations and the related assumptions that are utilized in the work. Section 3 presents solar PV analysis results and the electricity-mix impact improvement results with increasing solar contributions. The article ends with conclusions and recommendations in Section 4.

2 Methodology

This section consists of three parts. The first part is the application of LCA to solar systems that we evaluate. The second part consists of the conversion of solar PV impacts on a kWh basis and sensitivity to changing the pc-Si and mc-Si ratio in the solar combination. The last part is the calculation of changes in the environmental impacts of the Turkish electricity mix with increasing

contributions of solar power (increases from 3.05% to 5%, 10%, 15% and 20%).

2.1 Application of LCA to pc-Si and mc-Si PV systems

LCA is a well-established environmental-impact evaluation method that has been developed since the 1990s. It analyzes the environmental impacts of a product, process or service by evaluating all resource use (inputs) and outputs to the environment (air, water, soil) throughout the life cycle. The LCA framework comprises goal and scope definition, inventory analysis, impact assessment and interpretation steps [8, 9]. A detailed explanation of LCA steps is presented in Section 1 of the online [Supplementary Data](#).

As stated in the 'Introduction' section, 95.4% of the current solar panels (both utility-scale and home-scale) in Turkey are pc-Si (62.4%) and mc-Si (33.0%) PVs [26]. A change in solar PV type and composition is not expected in the near future. Furthermore, the ratio of solar energy in the Turkish electricity mix continuously increases [6]. So, we selected to perform a detailed environmental-impact assessment of pc-Si and mc-Si panels as on-grid, utility-scale energy options. This is crucial both to understand the contribution of solar power to the electricity mix and to fill the knowledge gap about solar PVs as centralized energy options in Turkey.

The production of Si-based solar PVs starts with metallurgical-grade silicon (MG-Si) production from quartz; solar-grade silicon (SoG-Si) is produced by further purification of MG-Si. Crystallization takes place either for pc-Si or mc-Si production. Wafer slicing, solar-cell production and panel assembly are the other steps of the solar PV-production stage [26, 27]. Transportation of the assembled panels, open-ground mounting, inverters and transformers for grid connection, battery banks for energy storage and plant decommissioning after the end of life of the PVs are the other life-cycle steps considered in this analysis. Because of the intermittent nature of solar power, storage systems are crucial for the times at which solar energy is not available for securing energy system reliability. This is also common practice in Turkey for open-ground mounted PV systems even if they are grid-connected [12, 13, 21]. Hence, the impacts of Li-ion batteries are included in the analysis.

2.1.1 Goal and scope definition

The first goal of this work is to determine the cradle-to-grave environmental impacts of pc-Si and mc-Si solar panels and their

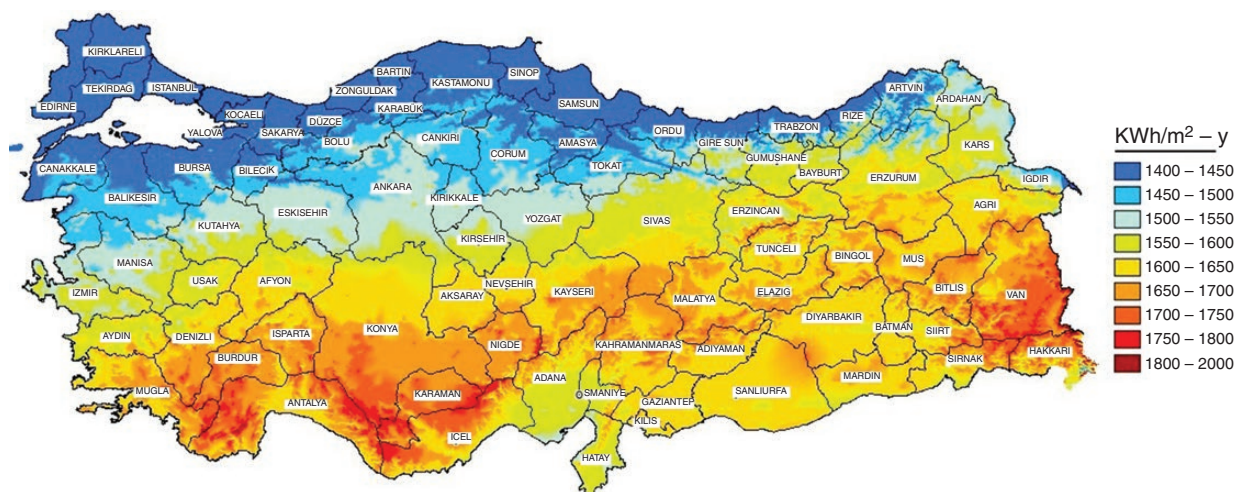


Fig. 1: Solar Energy Atlas (SEA) of Turkey [5].

impact distribution range within Turkey. The analysis boundary includes PV panel production, transportation of panels, transformers and inverters for grid connection, battery banks for energy storage, open-ground mounting and plant decommissioning. The life-cycle analysis boundary considered is given in Fig. 2.

Since 95.4% of the current solar panels in Turkey are pc-Si (62.4%) and mc-Si (33.0%) PVs and combined ratios of CdTe, Copper Indium disulfide (CIS) and micro-Si are below 5% on the whole [26], the contribution of CdTe, CIS and micro-Si panels is neglected. Taking weights of mc-Si and pc-Si panels on the whole, we can say that 34.6% of PVs are mc-Si and 65.4% are pc-Si. In order to standardize the comparison of impacts and determine their distribution within the country, 1-kWh electricity generation is chosen as the functional unit for each panel type. Hence, the impacts calculated for 1 m² of each solar PV (processed inventory data are for 1 m² panel production of each type) are converted into a kWh basis. This conversion will be explained in Section 2.2 of the article.

The characteristics of the evaluated panels are presented in reference [26] on page 21. The mc-Si panel has 195-W rated power and 19.5% panel efficiency per m² of the panel. The same values for the pc-Si panel are 180 W and 18.0%, respectively, and both panels have 25 years of lifespan [26].

2.1.2 Inventory analysis

The PV-production industry in Turkey is limited and it is panel-assembly dominated. Installed panels are mainly of European and Chinese production [7, 13]. Due to the lack of Turkish production data and similarities in electricity grid structure and process efficiencies, the average European production inventory data presented in the solar life-cycle inventory report of the International Energy Agency are utilized for the production phase of the mc-Si and pc-Si PV panels [26]. In Europe, the leading solar PV producer is Germany [7, 24]. In this case, panel production is assumed to be in Germany. Framed mc-Si and pc-Si solar PVs are later transported to the Gebze, Turkey or Mersin, Turkey ports from the Husum, Germany port. The transportation of PV panels to the place of installation within Turkey is performed by lorries. The marine-transportation distances from Germany to Turkey are calculated using the Aquaplot website and the lorry-transportation distances are calculated using Google Maps [28, 29]. Open-ground mounting, inverter and transformer data are taken from the 2015 report of the International Energy Agency [27]. The battery-bank life-cycle impacts are calculated based on the works by Ellingsen *et al.*, Peters *et al.* and Accardo *et al.* [30–32]. Plant dismantling after the end of life of the PVs are modelled according to

considerations in the LCA guide prepared by the International Energy Agency [33].

Step-by-step explanation of how the inventory data are processed is given in Section 2.2 of the online [Supplementary Data](#). Table S1 in the online [Supplementary Data](#) presents the main input quantities required for production of 1 m² of mc-Si and pc-Si panels (that include metallurgical-grade silicon and solar-grade silicon production, crystallization, wafer slicing, solar-cell production and panel-assembly steps). Table S2 and S3 in the online [Supplementary Data](#) present the marine-transportation quantities and the coefficients utilized in the calculations of the Li-ion battery-bank impacts, respectively. Details of the inventory data for open-ground mounting, inverters and transformers as well as plant decommissioning can also be found in the following subsections of Section 2.2 of the online [Supplementary Data](#).

2.1.3 Life-cycle impact assessment

In this study, online software openLCA version 1.10.3 is used for calculations by employing the ELCD (European Platform on Life Cycle Assessment) and NEEDS (New Energy Externalities Developments for Sustainability) databases, conjunctively. The Centre of Environmental Science of Leiden University (CML) non-baseline impact assessment (IA) method among many other methods available in OpenLCA is chosen because of the impact categories that are suitable for the system analysed and the study goals [34–36].

This study covers the evaluation of the following environmental-impact categories:

- Global-warming potential (GWP): GWP is an indicator of the climate-changing impact of a process during the life-cycle stages considered. GHGs have the property of keeping the heat from the Sun that actually is needed to be reflected outside the Earth (IR radiation). To express all these gases under the same unit, they are converted into the equivalents of CO₂ using conversion factors during a time horizon of 100 years. If we consider the GWP of CO₂ as being equal to 1, the conversion factors for CH₄, NO₂ and chlorofluorocarbons (CFCs) are 23, 296 and 4600, respectively [34, 37, 38].
- Eutrophication potential (EP): Phosphorus, ammonia and nitrogen, which accelerate the growth of aquatic organisms, are the main sources of eutrophication that impact both terrestrial and aquatic ecosystems. The impact eutrophication is expressed in g PO₄³⁻ equivalents [34, 37, 38].

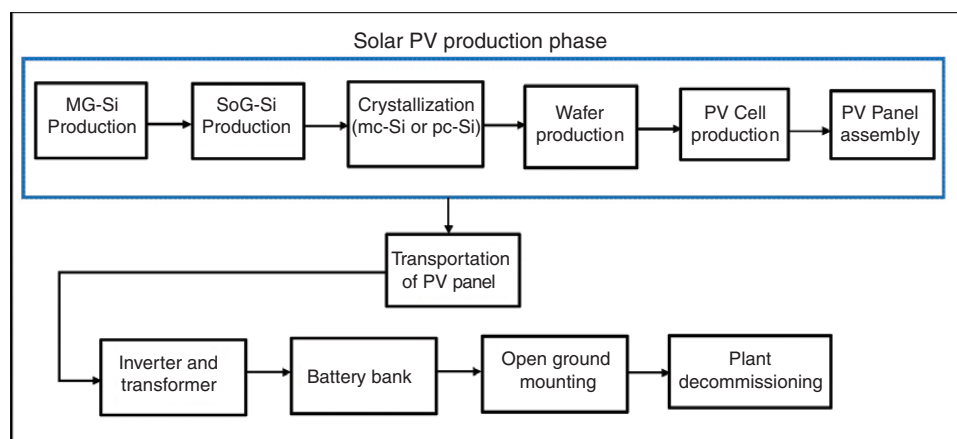


Fig. 2: Life-cycle analysis boundary considered for pc-Si and mc-Si solar PV panels.

- Acidification potential (AP): SO₂, NO_x and NH₃ are the chemicals contributing to the acidification potential of a process or a product. Free protons created as a result of the emission of these chemicals change the pH of the environment that they are released to and harm those ecosystems. The AP impact is expressed in g SO₂ equivalents [34, 37, 38].
- Human-toxicity potential (HTP): This impact is a measure of the harmful effects of several toxic chemicals to human health. It is expressed in g 1–4 DB equivalents.
- Ozone-layer depletion potential (OLDP): CFCs, halons and hydrochlorofluorocarbons (HCFCs) are the main gases that reach the stratosphere and damage the ozone layer that prevent carcinogenic UV radiation entering to the atmosphere. Ozone-layer depletion is expressed in g equivalents of CFC-11 [34, 37, 38].
- Photochemical ozone-creation potential (POCP): POCP values are used to estimate the potential of airborne substances for forming atmospheric oxidants. The presence of CO, SO₂, NO and volatile organic compounds creates this impact. It is measured in g ethylene (C₂H₄) equivalents [34, 37, 38].
- Freshwater ecotoxicity potential (FWEP): Toxic effects of substances released into freshwater bodies is determined with this impact and represented in g 1–4 DB equivalents [34, 37, 38].
- Terrestrial ecotoxicity potential (TEP): This impact is a measure of the effects of toxic substances on terrestrial ecosystems. It is measured in g 1–4 DB equivalents [34, 37, 38].

These impacts are selected in relation to their effects on climate; air, water and soil ecosystems; and human health. Data are evaluated as a representative for pc-Si and mc-Si solar PV operation under specific conditions in Turkey.

OpenLCA calculates and provides the impact results directly for each of the life-cycle steps evaluated. For this, all measurements in the same impact category are converted into the same unit equivalents (e.g. g CO₂ equivalents for GWP) through using conversion factors. Then, calculated impacts in each life-cycle step are summed under the main impact category for calculation of the overall result [8, 9], as shown in **Equation 1**:

$$\text{Absolute Life Cycle Impact} = \sum_{i=1}^6 \sum_{j=1}^j \text{Emission Type } (j) \cdot \text{Conversion Factor } (j) \quad (1)$$

In this equation, $i = 1, \dots, 6$ represent the solar PV production, transportation of PV panels, inverters and transformers, battery banks, open-ground mounting and plant-decommissioning life-cycle steps. j represents the different emission types creating the impact and their corresponding conversion factors in question; e.g. CO₂, CH₄ and NO₂ are the different emission types in the GWP calculation. So, in GWP, j goes from 1 to 3. The calculation of GWP in each life-cycle step and their summation as in Equation 1 will reveal the overall GWP impact result. For all of the eight life-cycle impacts, this procedure is applied individually. Further information on presented life-cycle impacts and their calculation can be found in Huang *et al.*, Curran, Pennington *et al.* and Huijbregts *et al.* [37, 39–41].

2.1.4 Interpretation

The findings obtained in life-cycle IA are evaluated in the interpretation step of the LCA. Based on this evaluation, the related conclusions and recommendations are derived aligning with the

targets of the goal and scope definition. The conclusions and recommendations derived in this work are presented in the 'Results and discussion' as well as the 'Conclusion' sections of the article.

2.2 Conversion of life-cycle impacts on a kWh basis and sensitivity analysis

To convert the cumulative environmental impacts calculated for unit area of solar panels to per-kWh electricity generation (the functional unit), the solar-insolation values of the selected locations and the quantity of electricity generated by each panel in those locations should be calculated first.

The SEA of Turkey prepared by GDEA provides city-by-city and average global radiation and sunny-hour data for Turkey [5]. **Table S5** of the online **Supplementary Data** presents annual solar-insolation, sunny-hour and area information for 81 cities of Turkey based on the SEA [5, 42]. Turkey has seven geographical regions, which are Marmara, Aegean, Mediterranean, Black Sea, Central Anatolia, Eastern Anatolia and South-eastern Anatolia. Two cities from each of these seven regions with the lowest and highest insolation values have been selected to see the life-cycle impact distribution within the country. The average impact values for Turkey have also been calculated to see how impacts in a certain location differ from Turkey's average. **Table 1** presents selected cities as an evaluation result of 81 cities with the lowest and highest insolation values from seven geographical regions [5, 42].

The solar panels evaluated have 19.5% and 18.0% module efficiency for mc-Si and pc-Si PVs, respectively [26]. Silicon-based solar panels have a 0.5–0.8% degradation rate per year. Determining an annual degradation rate of 0.50% for mc-Si panels and 0.65% for pc-Si panels, the electricity generation over a 25-year panel lifetime is calculated [43, 44]. **Table S7** of the online **Supplementary Data** shows the change in module efficiency values over 25 years of lifetime for each panel type based on the determined degradation rates. By multiplying the efficiency values in **Table S7** of the online **Supplementary Data** by the insolation values belonging to the selected cities given in **Table 1** together with the light-sensitive area of the panel (0.935 m²) and the inverter efficiency (3.60 MJ conversion per 3.85 MJ generated), the electricity production in kWh per m² of solar panel in different years for each city have been calculated using Equation 2 for both

Table 1: Cities selected from seven geographical regions of Turkey and their annual insolation values [5, 42].

City (j)	Insolation (kWh m ⁻² .year)	Region
Karaman	1660	Central
Ankara	1474	Central
Burdur	1632	Aegean
Canakkale	1384	Aegean
Antalya	1643	Mediterranean
Mugla	1617	Mediterranean
Giresun	1435	Black Sea
Bartın	1307	Black Sea
Van	1635	South-eastern
Sanliurfa	1586	South-eastern
Tekirdag	1338	Marmara
Edirne	1320	Marmara
Erzincan	1556	Eastern
Ardahan	1469	Eastern
Turkey	1524	Average

mc-Si and pc-Si PVs [26, 27]. The total electricity generation by each panel during its lifetime has been calculated by the addition of the generation in different years:

$$\text{Electricity Generation in the Life Cycle (kWh/m}^2\text{)} = \sum_{i=1}^{25} \text{Panel Efficiency (i). Solar insolation (j).light sensitive area. inverter efficiency} \quad (2)$$

In this equation, $I = 1, \dots, 25$ represents the years of operation and j represents the solar-insolation value belonging to the 14 different cities that are considered in the study.

The results of total electricity generated by the evaluated panels during their lifetime in 14 different cities can be found in Tables S8 and S9 in the online Supplementary Data.

Tables S10–S17 in the online Supplementary Data give cumulative life-cycle impact results determined for mc-Si and pc-Si panels in each step of the life cycle through the utilization of OpenLCA software 1.10.3. In order to calculate the per-kWh impacts resulting from electricity generation using this solar combination, 34.6% of the impacts of mc-Si panels and 65.4% of the impacts of pc-Si panels are divided by their life-cycle electricity generation and then summed up according to Equation 3:

$$\text{Life Cycle Impact per kWh} = \sum \frac{\text{Impact in Each Lifecycle Step of pc-Si}}{\text{Total Electricity Generation pc-Si}} \times 0.654 + \sum \frac{\text{Impact in Each Lifecycle Step of mc-Si}}{\text{Total Electricity Generation mc-Si}} \times 0.346 \quad (3)$$

To evaluate the effects of changing the pc-Si and mc-Si ratios on the environmental impacts of solar PV combinations, sensitivity analysis is performed; 60% pc-Si:40% mc-Si and 70% pc-Si:30% mc-Si cases are also analysed by changing the ratio values in Equation 3 for the pc-Si and mc-Si panels.

2.3 Changes in environmental impacts of the Turkish electricity mix with contribution of a solar power combination

Fig. 3 presents the Turkish electricity mix by different resources for the base year of 2019. In 2019, 56% of electricity was generated by fossil resources, mostly from imported hard coal and natural gas. In 2019, 3.05% of electricity production was from solar energy [45].

Atilgan and Azapagic studied Turkish electricity-generation life-cycle impacts based on the 2010 electricity mix in which there was no solar contribution [10]. Atilgan and Azapagic performed cradle-to-grave LCA of all energy technologies without considering the recycling and treatment of waste disposal. Our study is designed in parallel with the assumptions of Atilgan and

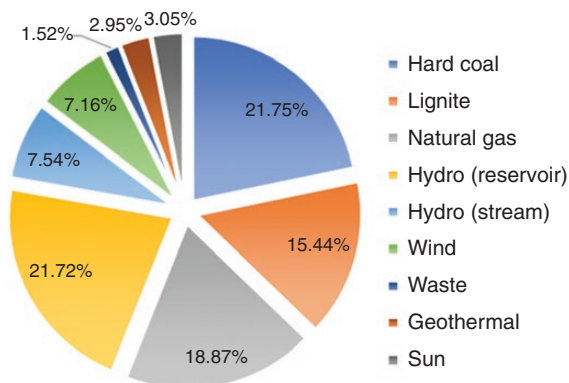


Fig. 3: Composition of electricity generation by different resources for the base year of 2019 [45].

Azapagic's work. Hence, the impacts of both studies are comparable.

Table S18 of the online Supplementary Data shows the life-cycle impacts of different energy resources per kWh in the Turkish electricity mix and of the solar power calculated in this work. By multiplying the percentage of each energy source by its per-kWh life-cycle impact value presented in Table S18 of the online Supplementary Data and summing the impacts of each of the energy resources, the total per-kWh impacts for the 2019 Turkish electricity mix can be calculated according to Equation 4:

$$\text{2019 Mix Life Cycle Impact per kWh} = \sum_{i=1}^9 \text{Percentage (i). Lifecycle impact coefficient (i)} \quad (4)$$

In this equation, i refers to the different energy resources (hard coal, lignite, etc. that can be seen in Fig. 3) and $percentage (i)$ refers to the percentage of different resources in the 2019 electricity mix. This calculation is performed for all of the eight impact categories individually.

Changes in the life-cycle impacts of the 2019 Turkish electricity mix when the ratio of solar power increases from 3.05% to 5%, 10%, 15% and 20% are evaluated as different cases by the application of Equation 5:

$$\text{Life Cycle Impact of Electricity Mix With Solar Contribution} = \text{2019 Impact Level(j). (1 - Solar Power Increase (i))} + \text{Solar Impact Level(j).Solar Power Increase(i)} \quad (5)$$

In this equation, i represents 5%, 10%, 15% and 20% solar cases in the electricity mix and $Solar Power Increase$ refers to increases from 3.05% to 5%, 10%, 15% and 20% that correspond to 0.0195, 0.0695, 0.1195 and 0.1695; j refers to different life-cycle impacts.

For example, the 2019 *Impact Level (GWP)* refers to the GWP impact level of the 2019 electricity mix by the contribution of different resources including 3.05% of solar energy. This is also true for the other seven impacts evaluated. The way in which increases from 3.05% of solar to 5%, 10%, 15% and 20% solar contribution will change the electricity-mix impacts are evaluated here through multiplying the 2019 impact level by $(1 - Solar Power Increase (i))$ in the equation and then adding up the individual solar power increases to avoid double-counting. For each of the eight different impacts, this calculation is performed individually. The 2019 electricity-mix impact levels utilized in the equation can be found in Table S19 of the online Supplementary Data.

3 Results and discussion

3.1 Solar PV life-cycle impacts and sensitivity analysis

Table 2 presents the life-cycle impact results determined for mc-Si and pc-Si panels analysed under local conditions in Turkey. Despite the pc-Si PV results being higher, the mc-Si and pc-Si PV environmental impacts are not considerably different from each other, especially for the GWP, AP and HTP impacts. The lowest environmental-impact values are determined for Karaman (the Turkish city with the highest solar insolation, at 1660 kWh/m². year; Table 1) and the highest impact values are detected for Bartın (the Turkish city with the lowest insolation, at 1307 kWh/m².year; Table 1). The mean values show environmental-impact levels for Turkey's average of 1524 kWh/m².year insolation.

Absolute magnitudes of environmental impacts for mc-Si and pc-Si panels are presented in Tables S10–S17 of the online Supplementary Data. In absolute terms, mc-Si panels have 4.47–9.16% higher environmental impacts than pc-Si panels. On average, mc-Si and pc-Si panels generate 6120 and 5550 kWh of

electricity per m² of panel area, respectively, over their lifetime (25 years) under Turkey's local conditions. This corresponds to 10.3% more electricity generation for mc-Si panels than for pc-Si panels. Despite this superiority, the higher energy (especially in crystallization in the PV-production step) and the material-input requirement for mc-Si panels make them have a higher impact in absolute terms. However, the higher efficiency (19.5% versus 18.0%) and slower degradation rate (0.5% versus 0.65% per year) of mc-Si panels make them have a lower impact on a kWh electricity basis.

Before calculating the environmental-impact distribution of the solar PV combination for Turkey, sensitivity analysis is performed to determine the effect of changing the pc-Si and mc-Si composition on the solar PV combination impacts. Three combinations are analysed. Combination 1 has a 60% pc-Si:40% mc-Si composition. Combination 2 represents the real case of 65.4% pc-Si:34.6% mc-Si. Combination 3 has a 70% pc-Si:30% mc-Si content. Table 3 shows the results of sensitivity analysis for the mean values of impacts calculated for Turkey's average of 1524 kWh/m².year insolation.

Analysis results show that even a 10% change in the pc-Si and mc-Si contribution to the solar combination does not have a significant effect on the life-cycle impact results. This is because of the close environmental-impact magnitudes of pc-Si and mc-Si panels on a kWh basis. Hence, we continued to utilize real-case (Combination 2) values for environmental-impact distribution calculations.

3.1.1 Solar PV combination impact distribution

Fig. 4 presents the GWP (a), AP (b), EP (c) and HTP (d) impacts of a 34.6% mc-Si:65.4% pc-Si solar PV combination for Turkey based on the life-cycle steps considered in the analysis boundary. In GWP, AP and HTP, the battery bank is the main component forming these impacts. This situation is due to the high level of energy required for the battery cells and chemicals required for electrode

production. PV production is the main contributor to EP that originates from the panel-assembly, crystallization for mc-Si panels, wafer slicing and SoG-Si production stages of the PV production.

Fig. 5 presents the OLDLP (a), FWEP (b), POCP (c) and TEP (d) impacts of a 34.6% mc-Si:65.4% pc-Si solar PV combination for Turkey based on the life-cycle steps considered in the analysis boundary. The battery bank is identified as the dominant component creating the FWEP, POCP and TEP impacts. The high energy requirement for battery-cell production and the chemicals needed for electrode production are the sources of the impacts, as in GWP, AP and HTP. PV production is the main contributor to the OLDLP in which panel assembly, crystallization and SoG-Si production are the main sources.

Furthermore, the panel-assembly stage of PV production creates ~50% of the AP, POCP and TEP impacts related to the PV-production step of the life cycle. The SoG-Si stage of PV production creates 63–70% (for mc-Si and pc-Si panels) of the GWP impact belonging to the PV production. In HTP, PV mounting creates 14.0% of the impact due to human toxic chemical release in construction. In FWEP, the inverter and transformer production and connections constitute 19.2% of the impact.

For all impacts, the lowest impact values are found for Karaman (the Turkish city with the highest insolation) and the highest impact values are determined for Bartın (the Turkish city with the lowest insolation). Karaman, Antalya, Burdur and regionally the Mediterranean and South-eastern regions appear to be most suitable areas for centralized solar installations in Turkey.

When compared with Üçtuğ et al.'s [13] results for home-scale (rooftop-mounted) pc-Si PVs in Turkey, we have determined a narrower distribution range within the country for the impacts analysed on a kWh basis. Despite the results being compatible in the order of magnitude, we have determined lower GWP (33.7–59.9 versus 27.1–34.4 g), HTP (65.9–117 versus 30.6–38.9 g) and AP (0.360–0.470 versus 0.305–0.388 g) for the utility-scale on-grid solar system combination that we analysed. The EP, OLDLP

Table 2: Solar PV life-cycle impact distribution for Turkey

Environmental impacts	mc-Si			pc-Si		
	Lower-bound	Upper-bound	Mean value	Lower-bound	Upper-bound	Mean value
GWP (g CO ₂ eq/kWh)	26.93	34.20	29.33	27.19	34.54	29.62
EP (g PO ₄ ³⁻ eq/kWh)	0.112	0.142	0.122	0.118	0.150	0.129
AP (g SO ₂ eq/kWh)	0.300	0.382	0.327	0.307	0.390	0.335
HTP (g 1–4 DB eq/ kWh)	29.90	38.00	32.60	31.00	39.40	33.80
OLDLP (mg CFC-11 eq/kWh)	0.00487	0.00618	0.00530	0.00500	0.00636	0.00545
POCP (g C ₂ H ₄ eq/kWh)	0.0216	0.0275	0.0236	0.0221	0.0281	0.0241
FWEP (g 1–4 DB eq/kWh)	1.440	1.830	1.570	1.490	1.900	1.630
TEP (g 1–4 DB eq/kWh)	0.137	0.173	0.149	0.142	0.180	0.155

Table 3: Sensitivity-analysis results of changing solar combinations

Impacts	Combination 1	Combination 2	Combination 3
GWP (g CO ₂ eq/kWh)	29.504	29.520	29.533
EP (g PO ₄ ³⁻ eq/kWh)	0.126	0.127	0.127
AP (g SO ₂ eq/kWh)	0.332	0.332	0.333
HTP (g 1–4 DB eq/ kWh)	33.320	33.385	33.440
OLDLP (mg CFC-11 eq/kWh)	0.005	0.005	0.005
POCP (g C ₂ H ₄ eq/kWh)	0.024	0.024	0.024
FWEP (g 1–4 DB eq/ kWh)	1.606	1.609	1.612
TEP (g 1–4 DB eq/ kWh)	0.153	0.153	0.153

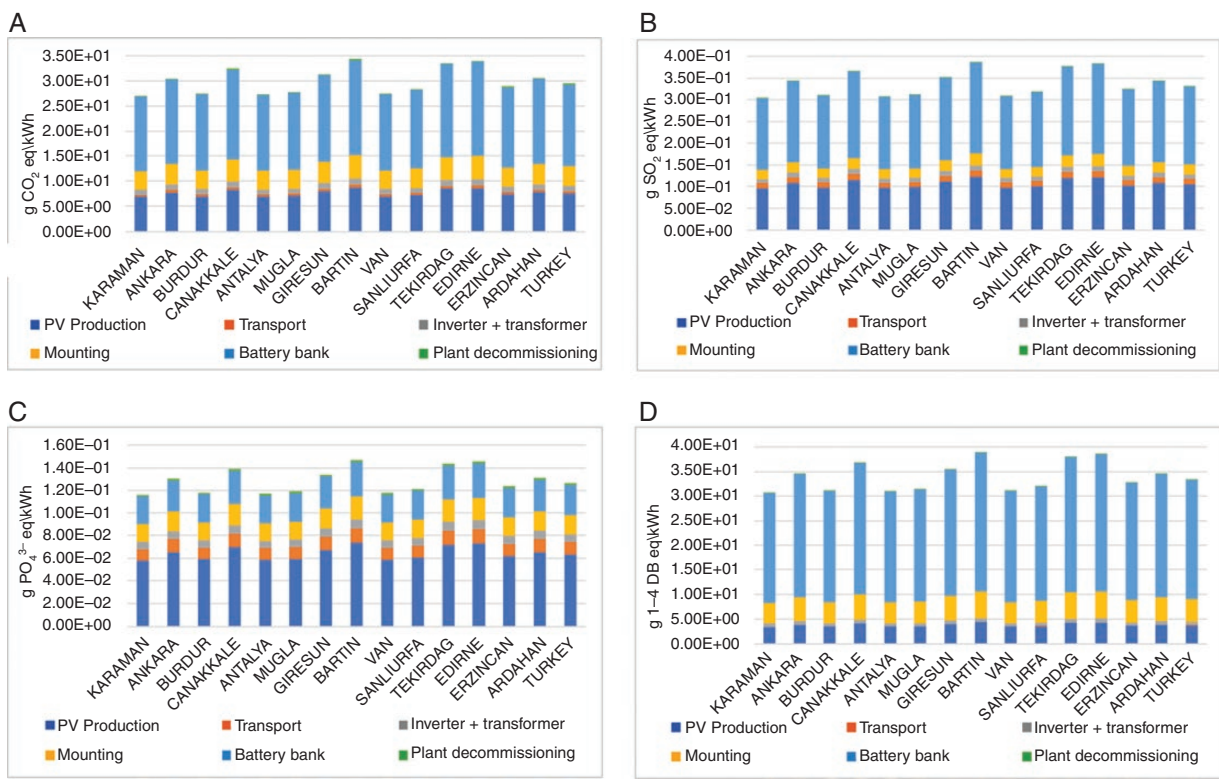


Fig. 4: Life-cycle impact distribution of mc-Si and pc-Si solar PV combinations in Turkey (a) GWP, (b) AP, (c) EP, (d) HTP.

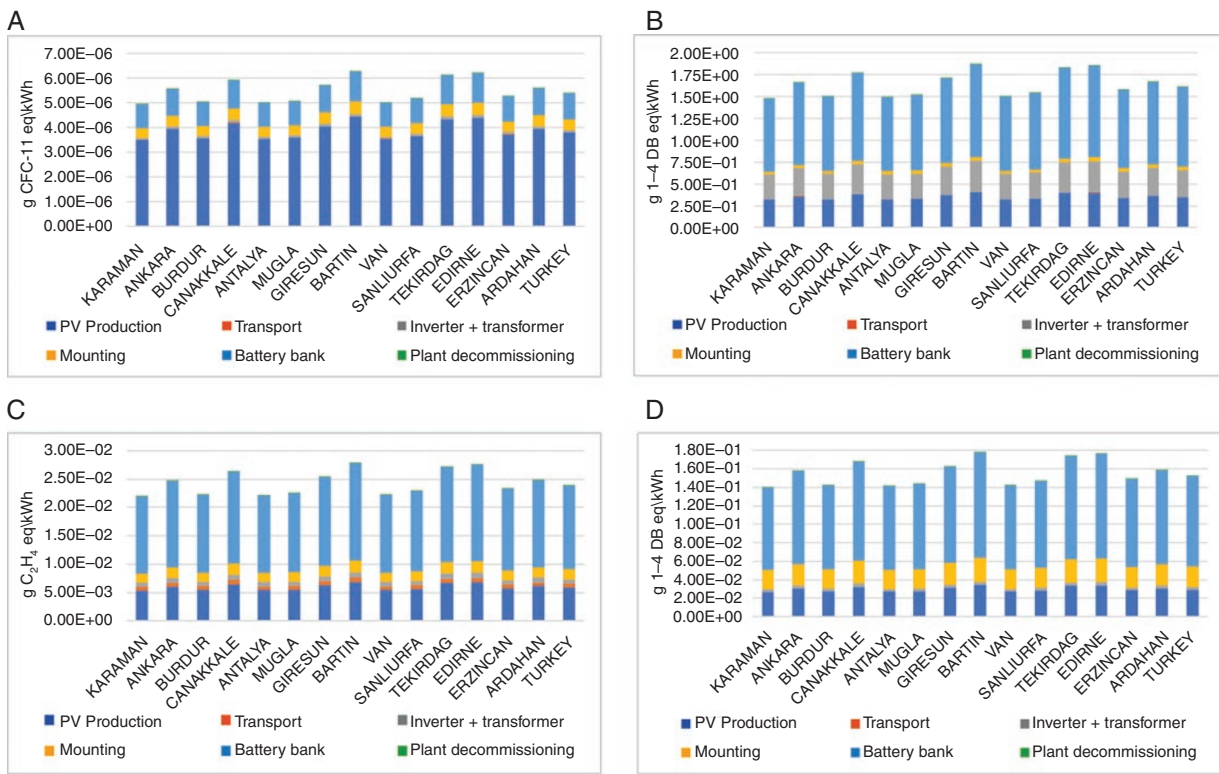


Fig. 5: Life-cycle impact distribution of mc-Si and pc-Si solar PV combinations in Turkey (a) OLDP, (b) FWEP, (c) POCP, (d) TEP.

and POCP impact values that Üçtuğ *et al.* present are 5–10% lower than the impact values of the utility-scale system. FWEP and TEP are not evaluated by Üçtuğ *et al.* Furthermore, all of the results of this work are found to be within the range of reported values in the literature [22, 23].

3.2 Turkish electricity-mix life-cycle impacts and changes with increasing the solar contribution

The life-cycle impact values of different resources on a kWh basis for Turkey can be found in Table S18 of the online Supplementary

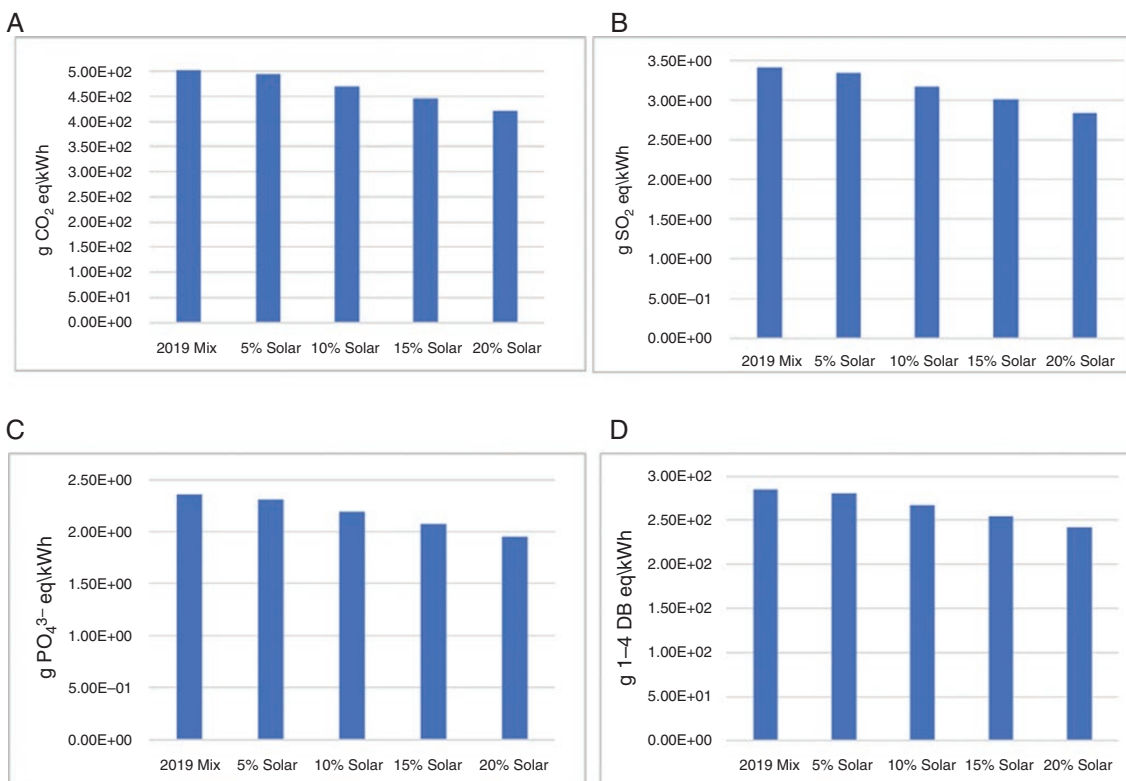


Fig. 6: Life-cycle impacts of the 2019 electricity mix and impacts of increasing solar power percentage cases in the mix for Turkey. (a)GWP, (b) AP, (c) EP, (d) HTP.

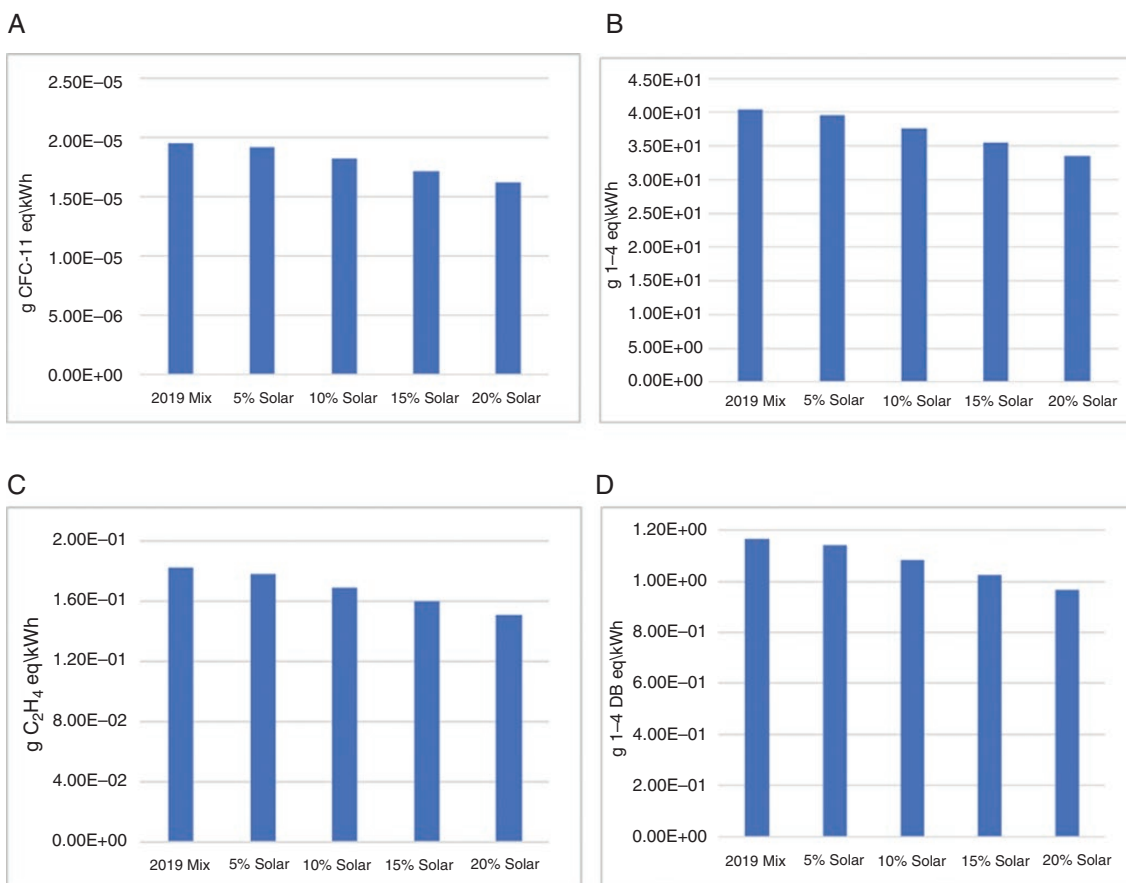


Fig. 7: Life-cycle impacts of the 2019 electricity mix and impacts of increasing solar power percentage cases in the mix for Turkey (a) OLDP, (b) FWEP, (c) POCP, (d) TEP.

Data. As can be seen in this table, coal (especially lignite) is the resource having the highest impact level in all of the impact categories except for OLDP. Natural gas is the resource having the highest OLDP level on a kWh electricity-generation basis. The ratio of solar power in the 2019 electricity mix is 3.05% (Fig. 3). Solar electricity has significantly lower environmental impacts than fossil resources except for OLDP, although it is still 5.85% of the OLDP level of natural gas (5.39×10^{-6} versus 9.21×10^{-5} g CFC-11/kWh). The AP impact of geothermal electricity is the highest among all renewable resources and is also higher than that of hard coal and natural gas. Wind and hydropower have lower HTP and GWP impact levels than the solar combination evaluated.

Figs 6 and 7 show the life-cycle IA results for the base-year 2019 electricity mix and the impacts of increasing the solar power percentage cases (5%, 10%, 15% and 20%) in the mix. All of the eight impacts evaluated in this work reduce increasingly with increasing the solar percentage in the electricity mix compared to the base year of 2019. Proportionally, the highest reduction occurs in the OLDP and POCP impacts, whereas the lowest reduction occurs in the HTP impact. The general tendency is that each percentage increase in solar electricity (generated by an mc-Si and pc-Si combination) in the mix reduces impacts by ~1.0%. For instance, the GWP level of 503 g CO₂ eq/kWh for the 2019 electricity mix can be reduced to 446 g CO₂ eq/kWh if the solar electricity ratio in the mix becomes 15%. Again, the 2019 HTP value of 285 g 1–4 DB eq/kWh can be reduced to 255 g 1–4 DB eq/kWh with a 15% solar contribution in the mix. Corresponding percentage reductions in all impacts with changing solar percentages can be found in Table S20 of the online Supplementary Data.

Finally, the electricity demand in Turkey is expected to be 5.52×10^5 GWh in 2030 with a 6.0% annual-increase rate. A 15% solar power ratio in the electricity mix by 2030 (a conservative assumption considering the solar power increase rates in Turkey) can achieve a GWP reduction of 31.3 million tons that will correspond to 12.7% of the commitment made by Turkey (246 million tons of CO₂ mitigation).

4 Conclusions

By performing cradle-to-grave LCA of mc-Si and pc-Si solar PVs as on-grid utility-scale energy options and determining the role of a pc-Si and mc-Si PVs solar combination in improving the environmental performance of the Turkish electricity mix, this study fills two crucial information gaps that also form the main contribution and novelty of this work.

Analysis of solar PVs reveal that mc-Si panels have 4.47–9.16% higher environmental impacts than pc-Si panels in absolute terms due to the higher energy (especially in crystallization in the PV-production step) and material-input requirement for mc-Si panels. However, the higher efficiency (19.5% versus 18.0%) and slower degradation rate of mc-Si panels (0.5% versus 0.65% per year) make them have a lower impact on a kWh electricity basis. In the analysis, the battery bank is found to be the main component contributing to GWP, AP, HTP, POCP, FWEP and TEP impacts due to the high level of energy required for battery-cell production and the chemicals required for electrode production. This reveals the importance of energy-storage technology and capacity selection for the environmental performance of solar PVs.

Furthermore, sensitivity analysis that is performed to determine the effects of changing the pc-Si and mc-Si content on solar PV combination impacts shows that even a 10% change in the pc-Si and mc-Si contribution to the solar combination does not have a significant effect on the life-cycle impact results. This is because of the

close environmental-impact magnitudes of pc-Si and mc-Si panels on a kWh basis. This result also proves the robustness of the analysis. For the solar combination, GWP and HTP impacts are found to be significantly lower for our on-grid centralized solar system than rooftop-mounted home-scale systems (33.7–59.9 g versus 27.1–34.4 g CO₂ eq/kWh 65.9–117 g versus 30.6–38.9 g 1–4 DB eq/kWh) operating in Turkey due to the higher capacity and efficiency of the centralized system. This result reveals the advantage of utilizing solar power as a centralized energy option. Karaman, Antalya, Burdur and regionally the Mediterranean and South-eastern regions appear to be most suitable areas for centralized solar installations for all of the eight impacts that we analysed.

The main finding for the Turkish electricity-mix analysis is that all of the eight impacts evaluated reduce increasingly by increasing the solar percentage in the electricity mix compared to the base year of 2019. The highest reduction occurs in the OLDP and POCP impacts, whereas the lowest reduction occurs in the HTP impact. The general tendency is that each percentage increase of solar electricity in the mix reduces each impact by ~1.0%. With a conservative assumption, if the solar power ratio in the mix increases to 15% by 2030, a GWP reduction of 31.3 million tons can be achieved that will correspond to 12.7% of the GHG-mitigation commitment made by Turkey (246 million tons of CO₂ mitigation). These results embody the potential and importance of solar power in improving the environmental performance of the electricity sector in Turkey.

Future work should include LCA of energy-storage systems such as chemical (H₂), thermal and other battery systems. Also, their integration with solar systems for high-capacity installations should be studied in detail to improve solar PV environmental performance. Additionally, higher-efficiency solar PVs that are being developed are candidates to further increase the potential of solar power in improving the environmental performance of the Turkish electricity mix.

Being dominated by imported coal and natural gas, sustainability of the Turkish electricity sector can significantly be improved with reductions in fossil-resource use and increases in the use of solar and other renewable energy resources.

Supplementary data

Supplementary data is available at *Clean Energy* online.

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Conflict of interest statement

None declared.

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