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Environmental impacts of small-scale hybrid energy systems: Coupling solar photovoltaics and lithium-ion batteries

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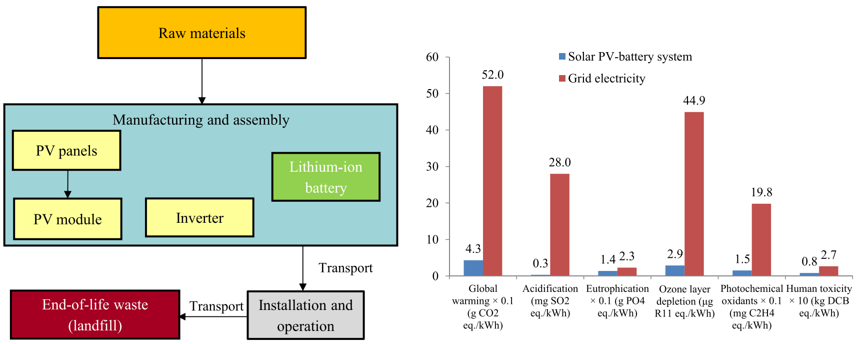
HIGHLIGHTS

- PV-battery system can meet up to 18.4% of the household's annual electricity needs.
- On a life cycle basis, it generates 4.7–8 times more energy than it consumes.
- The hybrid system has 1.6–82.6 times lower impacts than grid electricity.
- A very modest uptake at the national level (2%–8%) would save 558 kt CO_2 eq./yr.
- However, incentives will be needed for batteries to stimulate the uptake.

GRAPHICAL ABSTRACT



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ABSTRACT

One of the benefits of hybrid solar PV-battery systems is that they can reduce grid dependency and help balance electricity supply and demand. However, their environmental impacts and benefits remain underexplored. This study considers for the first time life cycle environmental impacts of domestic-scale PV-battery systems in Turkey, integrating multi-crystalline PV and lithium-ion battery. The impacts were estimated for both individual installations and at the national level, considering different regions across the country and taking into account their insolation and other climatic differences. Electricity generation and storage were modelled on an hourly basis taking into account consumer behaviour. The results show that the system can meet between 12.5% and 18.4% of the household's annual electricity needs. On a life cycle basis, it generates 4.7–8 times more energy than it consumes. Solar PV is the major contributor to most impacts (75%–81%). An exception is human toxicity which is mainly due to the battery (66%). The hybrid system has 1.6–82.6 times lower impacts than grid electricity. Assuming a very modest uptake at the national level (2%–8%), the use of hybrid systems would save 558,000 t CO_2-eq./yr compared to grid electricity. Thus, these results demonstrate clearly the environmental benefits of these hybrid systems. Together with the financial and energy security benefits for both the country and the consumer, this provides a strong impetus for their wider deployment. However, this will be difficult to achieve, as there are no incentives for battery storage. Therefore, it is recommended that relevant legislation be introduced to stimulate future uptake of hybrid PV-battery systems.

1. Introduction

Renewable energy sources are becoming more common, both for large and small scale applications. Some of the driving factors for this

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trend include concerns about security of energy supply, climate change and a desire to utilise local resources and improve national economies (Baranes et al., 2017). Given that the worldwide energy demand is projected to grow by almost 40% by 2040, it is expected that renewable energy will continue to bear significance in the global energy portfolio (Unites States Energy Information Administration, 2016). Buildings account for approximately 31% of global energy consumption (IEA, 2016) which is still largely derived from fossil fuels. Hence, switching to renewable energies in the building sector could bring significant benefits, including lower greenhouse gas emissions and increased security of energy supply (Leonard and Michaelides, 2018).

Among renewable energy technologies, solar photovoltaics (PV) have seen a considerable growth and uptake in many countries, supplying >1% of the demand in 2015 (Solar Power Europe, 2017). This has been driven largely by the feed-in-tariff incentives, providing payments to ‘prosumers’ for generating electricity and feeding it back to the grid. The main reason for promoting solar PV is that they can help mitigate climate change due to their low carbon emissions on a life cycle basis, as demonstrated by numerous life cycle assessment (LCA) studies (Gerbinet et al., 2014; Liu et al., 2015; Gong et al., 2015; Hou et al., 2016; Wong et al., 2016). They also have various other advantages. For example, PV panels convert sunlight directly to electricity silently and require little maintenance; they are also reliable, modular and rapidly deployable (Corkish and Prasad, 2006).

However, PV systems also have one main disadvantage: the intermittency. They cannot generate electricity in a continuous, reliable manner as solar radiation may not be present at all or it may not be at the desired level at all times during the day, depending on the location. Therefore, the following situations are often observed: PV systems fail to meet the instantaneous demand for most of the day, or they generate much more electricity than needed at certain times (Akbari et al., 2018). Hence, coupling a PV system with a battery is essential to decreasing the grid dependency and balancing supply and demand (Jossen et al., 2004). Coupling a PV system with a battery enables the user to store the excess amount of electricity generated during a low demand and then use this electricity when the generation fails to match the demand. Depending on the load profile and the location, it can be possible to achieve a net zero energy status, with buildings generating at least the same amount of electricity as they consume over a year (Ferrari and Beccali, 2017). However, some studies have shown that this may not always be the case and may depend on many factors (Balcombe et al., 2015). Nevertheless, the economic and environmental benefits of using a hybrid system that integrates solar PV with battery energy storage could be significant, particularly in countries with high contribution of fossil fuels in the electricity mix and a fast-growing population.

Turkey is one such country, where population is growing at an average rate of 1.4% per year (Turkish Institute of Statistics, 2016a, 2016b) and the annual electricity demand is expected to reach 802 TWh by 2035 (Republic of Turkey - Ministry of Energy, 2013). More than 90% of Turkey's primary energy demand is supplied by fossil fuels (International Energy Agency, 2013). Only 28.5% of the primary energy demand is met by domestic resources with the rest being imported (Turkyilmaz, 2015). Virtually all (99%) of the annual natural gas and 89% of oil consumption in Turkey is met via imports, costing the country US$60 billion (International Energy Agency, 2016). The only considerable local source of conventional energy is lignite; however, its quality is very low as it contains high sulphur and ash content (Atilgan and Azapagic, 2016). Hence, minimising the use of fossil fuels is of utmost importance for Turkey, from both economic and environmental points of view.

Turkey is ideally suited for utilising solar power as it lies in a sunny belt with an average of 2640 h of sunshine per year and solar radiation of 3.6 kWh/m^2 per day (Çakay, 2003). The total solar energy potential of the country is estimated at 380 TWh per annum (Kaygusuz and Sarı, 2003; Turkyilmaz, 2015). However, despite being one of the world leaders in the number of installations of solar water-heating systems (Altuntop and Erdemir, 2013; Üçtuğ and Azapagic, 2018), the utilisation of PV systems in Turkey has been progressing relatively slowly. As of 2016, electricity generated by solar PV accounted for only 0.2% of the annual electricity generation (International Energy Agency, 2016). Almost all of it comes from small-scale (<1 MW) ‘unlicensed’ systems which can sell the excess electricity back to the grid at variable feed-in-tariff rates. Large-scale ‘licensed’ generation (>1 MW) has started only very recently and the country's target is to have 5 GW of total installed solar power capacity by 2030 (Enerji Gunlugu, 2014). As one of the participating countries at the Paris COP21 Conference in 2015, an increase in the uptake of solar PV systems could help Turkey to meet its climate change target of reducing greenhouse gas (GHG) emissions by 21% by 2030 (UNFCCC, 2017).

However, the potential GHG and other environmental benefits of utilising solar PV systems in Turkey are unknown, particularly when coupled with battery storage. Therefore, this paper estimates for the first time the environmental impacts of hybrid systems combining solar PV and battery storage installed in domestic buildings in different regions in Turkey. The impacts are considered both at the level of individual installations and across the whole country, taking into account regional insolation levels and the hourly household energy demand. The impacts are estimated on a life cycle basis, using LCA as a tool. While there are several previous LCA studies of solar PV, batteries and their combination elsewhere in the world, as far as we are aware, this is the first study to consider a hybrid system integrating solar PV and battery storage in Turkey.

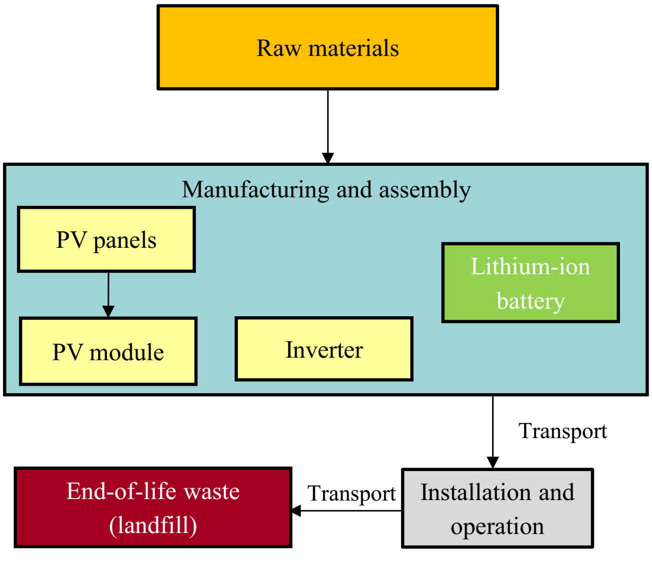


Fig. 1. System boundaries and the life cycle stages considered in the study.

Table 1
Specification of the PV-battery system.

PV panel		Li-ion battery	
Parameter	Value	Parameter	Value
AC system size	1 kWp	Nominal voltage	51.2 V
Module type	Standard multi-crystalline	Maximum discharge current	50 A
Array type	Fixed (rooftop)	Weight	27 kg
System losses	15%	Dimensions	W215 × H160 × D522 (mm)
Tilt	33.7°		
Azimuth	180°		

Table 2
Inventory data for the PV-battery system (Fu et al., 2015; International Energy Agency, 2011; Atilgan and Azapagic, 2016; Ecoinvent, 2017).

Material	Ecoinvent data set	Process	Unit	Amount
Manufacture of PV panels (China)				
PV cell factory	Photovoltaic cell factory	Production of 150,000 t wafer over 25 years	kWp^{-1}	1.33×10^{-10}
Argon	Argon, liquid, at plant	Ingot casting	kg	10.50
Compressed air	Compressed air, average installation, 6 bar gauge, at station	Ingot casting	kg	169.80
Electricity	Electricity, medium voltage, at grid, China	Ingot casting	MJ	157.54
Hydrofluoric acid	Hydrogen fluoride, at plant	Ingot casting	kg	0.13
Silicon	Silicon, solar grade, modified Siemens process, at plant	Ingot casting	kg	27.60
Sodium hydroxide	Sodium hydroxide, concentrated	Ingot casting	kg	0.047
Steam	Steam	Ingot casting	kg	7.60
Water	Process water, from ground	Ingot casting	kg	492.47
Silicon carbide	Silicon carbide, at plant	Ingot casting & wafer slicing	kg	0.24
Compressed air	Compressed air, average installation, 6 bar gauge, at station	Wafer slicing	kg	263.00
Electricity	Electricity, medium voltage, at grid, China	Wafer slicing	MJ	24.01
Steel wire	steel, hot rolled coil	Wafer slicing	kg	17.11
Water	Process water, from ground	Wafer slicing	kg	528.63
Adhesive	Adhesive for metals, at plant	Wafer slicing (for temporary attachment of bricks to wire-sawing equipment)	kg	1.22
Glass	Flat glass, uncoated, at plant	Wafer slicing (for temporary attachment of bricks to wire-sawing equipment, assumed same as multi-wafers)	kg	2.47
Acetic acid (98%)	Acetic acid, 98% in H_2O, at plant	Wafer slicing (wafer cleaning)	kg	0.60
Deionized water	Water, deionized, at plant	Wafer slicing (wafer cleaning)	kg	65.00
Dipropylene glycol monomethyl ether	Dipropylene glycol monomethyl ether, at plant	Wafer slicing (wafer cleaning)	kg	0.30
Sodium hydroxide (50%)	Sodium hydroxide, 50% in H_2O, production mix, at plant	Wafer slicing (wafer cleaning)	kg	0.015
Aluminium	Aluminium, primary, at plant	Cell processing	kg	0.38
Ammonia	Ammonia	Cell processing	kg	0.088
Electricity	Electricity, medium voltage, at grid, China	Cell processing	MJ	686.69
Ethanol	Ethanol from ethylene, at plant	Cell processing	kg	0.23
Hydrochloric acid (30%)	Hydrochloric acid, 30% in H_2O, at plant	Cell processing	kg	3.17
Hydrofluoric acid	Hydrogen fluoride, at plant	Cell processing	kg	0.78
Natural gas	Natural gas, production mix, at service station	Cell processing	kg	0.59
Nitric acid	Nitric acid, 50% in H_2O, at plant	Cell processing	kg	2.00
Nitrogen	Nitrogen	Cell processing	kg	7.62
Phosphoric acid	Phosphoric acid, industrial grade, 85% in H_2O, at plant	Cell processing	kg	0.0093
Potassium hydroxide	Potassium hydroxide, at regional storage	Cell processing	kg	2,76
Silver	Silver, at regional storage	Cell processing	kg	0.068
Steam	Steam	Cell processing	kg	26.15
Water	Process water, from ground	Cell processing	kg	866.04
Assembly of the PV module (Turkey)				
PV module factory	Market for photovoltaic panel factory	Annual production capacity of 300 MW eq. PV modules and an operational life time of 25 years	kWp^{-1}	1.33×10^{-7}
Glass	Solar glass, low iron, at regional storage	Module assembly	kg	63.26
Aluminium	Aluminium sheet	Module assembly	kg	11.77
Polyethylene terephthalate (PET)	Polyethylene terephthalate, 100% recycled	Module assembly	kg	3.27
Polyvinyl fluoride film (PVF)	Polyvinyl fluoride film, at plant	Module assembly	kg	3.27
Ethanol	Ethanol from ethylene, at plant	Module assembly	kg	0.057
Ethylene vinyl acetate copolymer (EVA)	Ethylene vinyl acetate copolymer, at plant	Module assembly	kg	7.52
Isopropanol	Isopropanol, at plant	Module assembly	kg	0.018
Water	Process water, from ground	Module assembly	kg	118.4
Steam	Steam	Module assembly	kg	16.22
Electricity	Electricity, Turkish mix	Module assembly	MJ	84.46
Manufacturing of inverter (Turkey)				
Inverter	Inverter production, 2.5 kW	Converting DC to AC	–	0.4[a]
Manufacturing of lithium-ion battery (Germany)				
Lithium-ion battery	Battery, rechargeable, prismatic, at plant	Energy storage (2.1 kWh storage capacity per unit)	–	3[b]

[a] Scaled down linearly from 2.5 kW to the capacity of the inverter considered in the study (1 kW).

[b] Due to the shorter lifetime of the battery (10 years) compared to the solar PV (25 years), the battery has to be replaced twice (i.e., three batteries are required in total).

The next section provides an overview of previous relevant LCA studies, before detailing in Section 3 the methods used in the study. The results are presented and discussed in Section 4 and conclusions are drawn in Section 5.

2. Literature review

2.1. LCA of solar PV systems

The energy output of PV systems depends strongly on the location and so do their life cycle impacts per unit of electricity generated (Li et al., 2016; Li et al., 2017). To explore the effect of the location on the impacts, Lamnatou and colleagues conducted an LCA of concentrating PV systems for building-integrated applications (Lamnatou et al., 2015). They calculated the energy and GHG payback times for installations in the following cities in the UK, Ireland, Spain and France: Exeter, Dublin, Barcelona, Madrid and Paris. The payback periods were found to vary between 2.5 and 3.5 years and, as expected, the locations in southern latitudes had lower payback periods. Concentrating PV systems for building applications in Spain were also considered in another study (Menoufi et al., 2013) which found a significant reduction in the impacts compared to conventional mono-crystalline silicon PV installations.

The latter were compared with multi-crystalline systems for installations in Spain and the UK (Stamford and Azapagic, 2018), showing that the both types of systems had 60% lower impacts in Spain than the UK. Furthermore, multi-crystalline systems had on average around 10% higher impacts regardless of the installation region.

Another study (Bekkelund, 2013) considered the impacts of mono-crystalline solar PV for the Norwegian conditions, in comparison with two thin-film technologies: cadmium telluride (CdTe) and copper indium gallium selenide (CIGS). These were found to have significantly lower impacts than the mono-crystalline option. For instance, global warming potential of the latter was estimated at 208 kg CO_2-eq./m^2, while that of CdTe and CIGS was 75 and 86 kg CO_2-eq./m^2, respectively. Silicon extraction and purification were the main cause of the higher impacts for the mono-crystalline PV.

Fu and colleagues focused on multi-crystalline PV systems in China (Fu et al., 2015). The primary energy demand was estimated at 12.61 MJ/W and the energy payback period ranged between 2.2 and 6.1 years, depending on the location. Similar to the mono-crystalline study by Bekkelund (2013), silica extraction and purification were also the main contributors to the environmental impacts of the multi-crystalline system.

Some studies considered the manufacturing of solar PV in different countries to demonstrate the effect on the impacts. For example, Nian compared mono- and multi-crystalline systems produced in a number of countries (Nian, 2016): Australia, China, France, Germany, Japan, Norway, Singapore, South Korea, Taiwan and the United States. The impacts of manufacturing per kWh of electricity generated were found to be the highest in Australia, twice as high as in France. Mono-crystalline systems had approximately 80% higher global warming potential than the multi-crystalline. Furthermore, Stamford and Azapagic (2018) found that the shift of manufacturing from Europe to China in the period 2005–2015 has increased environmental impacts by an average of 9%–13%, negating the technological progress over the period.

2.2. LCA of batteries

A few LCA studies of different types of battery are available, for both stationary and mobile applications. Given the focus in this work, only stationary applications are discussed below.

A review of environmental impacts of lithium-ion batteries for stationary applications found that, on average, 1 kWh of storage capacity is associated with a cumulative energy demand of 328 kWh and emissions of 110 kg CO_2-eq. (Peters et al., 2017). It was also noted that most studies considered only global warming potential, omitting other environmental impacts.

In a comparative study of the global warming potential of lithium-ion and nickel metal hydride batteries (NiMH), Liang and co-workers showed that the former had a factor of ten lower impact than the latter (12.7 vs 124 kg CO_2-eq. (Liang et al., 2017)). On the other hand, another study (McManus, 2012) found that both types had much higher impacts than lead acid, nickel cadmium and sodium sulphur batteries, especially global warming potential and depletion of metals. However, the cumulative energy demand of lithium-ion batteries was relatively low (150 MJ per MJ of battery capacity) compared to nickel cadmium (≈200 MJ/MJ) and nickel metal hydride (≈300 MJ/MJ) batteries.

2.3. LCA of hybrid PV-battery systems

Most LCA studies of hybrid systems focused on multi-crystalline PV and lead-acid batteries and compared the results to the grid electricity. For example, a study based in Lebanon (Kabakian et al., 2015) found that such a hybrid system had lower environmental impacts than the electricity from the grid. The authors also reported that the impacts of the battery were negligible compared to those of the PV. For instance, the global warming potential of the hybrid system was 40.2 g of CO_2-eq./kWh and without the battery, 38.9 g. Similarly, there was a very small difference in the cumulative energy demand with and without the battery (4.41 vs 4.39 MJ/kWh, respectively). Overall, the addition of the battery did not increase the impacts more than 3%.

A similar trend was reported by Belmonte et al. (2016) who compared the global warming potential of two hybrid systems installed in Italy, both with multi-crystalline PV but one with lithium-ion battery and another with proton-exchange-membrane fuel cell. The system with the battery had a lower impact than the one with the fuel cell. Like Kabakian et al. (2015), this study also found that the majority of the impact (80%) from the PV-battery system was caused by solar PV.

In a study based in the UK, Balcombe et al. (2015) studied the impacts of a microgeneration system combining multi-crystalline solar PV, Stirling engine and lead-acid battery. Most environmental impacts were found to be lower by 35% to 100% than for the equivalent amount of electricity from the grid and heat from a gas boiler. However, the depletion of elements increased by a factor of 42 due to the use of antimony in batteries.

Hybrid systems with the lead-acid battery were also considered by Dufo-López et al. (2011). They compared the impacts of coupling this type of battery with mono-crystalline PV, wind turbine or diesel generator. Based in Spain, the study found that the PV-based system had the lowest impacts (Dufo-López et al., 2011).

As mentioned earlier, no LCA studies of hybrid PV-battery systems were found for Turkey. Therefore, this is the first study for this region.

Table 3
Transport data (import to Turkey).

Component	Origin - destination	Transport mode	Distance (km)
PV panel	PV manufacturing plant – Shangai Port	Transport, lorry (>16 t), fleet average	50
PV panel	Shangai Port – Kocaeli Port	Container ship	15,000
PV panel	Kocaeli Port – PV assembly plant (Gebze)	Transport, lorry (>16 t), fleet average	50
Lithium-ion battery	Li-ion battery manufacturing plant (Berlin) – Gebze	Transport, lorry (>16 t), fleet average	2200

Table 4
Transport data (within Turkey)[a].

	Origin	Destination and distance (km)						
PV lithium-ion battery system	Gebze	Marmara (Istanbul)	Aegean (Aydin)	Mediterranean (Mersin)	Central Anatolia (Kirikkale)	Eastern Anatolia (Erzurum)	Black Sea (Samsun)	Southeastern Anatolia (Mardin)
		65	525	886	469	1280	682	1420

[a] Lorry, >16 t.

The specific technologies considered are multi-crystalline PV and lithium-ion battery. This type of solar PV was selected as it occupies the majority (70%) of the global market share (Fraunhofer Institute for Solar Energy Systems, 2016). A lithium-ion battery was chosen because of its superior technical performance compared to the other types, with higher power and energy densities as well as durability (Rudolf and Papastergiou, 2013). As discussed above, only one LCA study of such a hybrid system was found in the literature, based in Italy (Belmonte et al., 2016); however, like most other studies of hybrid systems, it only considered global warming potential.

This work goes beyond the current state-of-the-art to consider a range of environmental impacts. A further novelty includes estimation of the impacts for a range of different geographical regions in Turkey, covering the full spectrum of solar irradiation across the whole country. Moreover, electricity generation and storage were modelled on an hourly basis taking into account consumer behaviour. The next section provides more details on this, together with the methods, assumptions and data used in the study.

3. Methods

The study follows the ISO 14040/44 guidelines (ISO, 2006a, 2006b) for LCA methodology, starting with the goal and scope definition in the next section and followed by inventory data in Section 3.2. The CML 2001 (Guinée et al., 2002) impact assessment method was used and the following impacts were considered: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone layer depletion potential (OLDP), photochemical oxidant creation potential (POCP), and human toxicity potential (HTP). In addition, the energy payback period was also estimated, as detailed further below. The system was modelled and the impacts calculated using the CCaLC software (CCaLC, 2016).

3.1. Goal and scope definition

The goals of the study were as follows:

i) to estimate the environmental impacts of the hybrid system integrating solar PV and a lithium-ion battery and identify the hotspots;
ii) to compare the impacts with the grid electricity and identify any environmental benefits from using the hybrid system; and
iii) to determine the environmental implications of deploying such a hybrid system across Turkey, taking into account household hourly energy demand and solar irradiation in different climatic regions.

The scope of the study was from cradle to grave (Fig. 1), encompassing extraction and processing of raw materials, the manufacture of the solar PV and the battery, their installation and use and end-of-life waste management. The system consists of 1 kWp solar PV with 1 kW inverter and 2.1 kWh lithium-ion battery. The reason for choosing this size of the system is largely the affordability as larger systems would be too expensive for most income groups in Turkey. Furthermore, this capacity of lithium-ion batteries, which have to be imported, is readily available on the international market (Murata, 2018). The total lifetime of the system was assumed at 25 years, corresponding to the lifespan of the solar PV unit (Kabakian et al., 2015). However, the lifetime of the battery was assumed to be 10 years (Hesse et al., 2017), requiring its two replacements over the lifespan of the whole system. It was also assumed that no maintenance of the system was required.

For the first two goals of the study, the functional unit was defined as 1 kWh of electricity supplied by the system. For the analysis at the national level (third goal), the functional unit was the total annual energy demand by households in detached houses in Turkey. The reason for choosing detached houses is the larger roof area available for PV panels. Furthermore, such households are in a higher-income group and more likely to be able to afford these systems. The detached houses provide accommodation for approximately 40% of the Turkish population (Üçtuğ and Azapagic, 2018), so the impacts at the national level refer to this proportion of the population.

3.2. Inventory data

The technical data for the system can be found in Table 1. Solar PV panels with the installed capacity of 1 kWp occupy an approximate area of 6 m^2 (Üçtuğ and Yükseltan, 2012). Increasing the system capacity would increase the energy generation but, as mentioned earlier, it would not be technically or economically feasible for many households due to the increased area requirement and higher system costs.

The inventory data for the different parts of the systems are detailed in Table 2. Currently, there is no production of PV panels in Turkey, only the module assembly. Therefore it was assumed that the panels are manufactured in China and then transported to Turkey for assembly into a PV system. Similarly, there is no production of lithium-ion batteries in Turkey either and it was assumed that they are imported from Germany. The transportation details can be found in Tables 3 and 4. Only the transport of the finished products was considered; transport of the raw materials was excluded due to a lack of data. The data on waste management are summarised in Table 5; all materials were assumed to be landfilled due to a lack of recycling facilities for these systems in Turkey. Country-specific inventory data were used as much as possible. The data for the PV manufacturing are for the production in China (Fu et al., 2015) whereas the PV module assembly data were

Table 5
Waste management data.

Component	Ecoinvent dataset	Amount (kg)
Raw materials		
Silicon	Disposal, slag from MG silicon production, 0% water, to inert material landfill	4.38
Wafer	Disposal, waste, silicon wafer production, 0% water, to underground deposit	2.10
PV panel	Wastewater treatment, PV cell production effluent, to wastewater treatment, class 3	1227
End-of-life management		
Glass	Disposal, glass, 0% water, to inert material landfill	63.26 kg
Glass	Treatment of waste glass, inert material landfill	63.26 kg
Aluminium	Disposal, aluminium, 0% water, to sanitary landfill	11.80 kg
Aluminium	Treatment of waste aluminium, sanitary landfill	11.80 kg
Lithium-ion battery	Disposal, Li-ion battery, mixed technology	3 units

obtained from the assembly industry in Turkey and from the literature. For the manufacturing of the lithium-ion battery and the inverter, data from Ecoinvent v2.2 were used (Ecoinvent, 2017).

To enable consideration of different power outputs of the PV system depending on the geographical location, the systems were assumed to be installed in seven cities, situated in seven different regions across Turkey. The selected cities are shown in Fig. 2. These cities were selected because they all lie more or less in the central part of their respective geographical regions. Therefore, it was assumed that the solar irradiation for each city is representative of the entire region where they are situated.

The data for hourly electricity generation by the PV systems in each city were estimated using the NREL tool (pvwatts.nrel.gov, 2017). In cases where no data were available for the selected location, data for the nearest location were used instead.

3.3. Estimation of electricity supply and consumption

To carry out the LCA, it was necessary to determine the energy flows into, within and out of the hybrid system, including generation by solar PV, storage and supply by the battery and imports from the grid. As detailed further below, these were estimated at hourly intervals. The main challenge, however, was to determine the hourly consumption patterns based on households' habits and behaviours. As these data are not readily available, they were collected as part of this study, making certain assumptions, as described next.

First, a typical household size of four people was assumed across all the geographical regions considered (Üçtuğ and Azapagic, 2018). As only detached houses were considered, they were all assumed to be identical. Secondly, an extensive list of electrical appliances typically used in Turkey was defined, together with their typical power ratings (see Table 6). It was assumed that all the appliances were identical across all the households. However, the use of some of the appliances and the related energy consumption were varied according to the regional climates, as relevant.

Thirdly, to obtain energy consumption data, an in-depth survey of a real Istanbul-based household with a PV installation was carried out. A questionnaire was developed for these purposes, which included questions on their eating, working, leisure and sleeping times; how often and at what time of the day they normally used particular appliances; how often they charged their mobile phones, whether they left certain devices on standby, etc. For further details on the questions, see section S1 the Supplementary Information (SI). The questionnaire results were combined with the power rating of the appliances to estimate hourly consumption of electricity over one year, taking into account seasonal requirements for the lighting, heating and air conditioning. It was assumed that the household would behave in the same way in terms of energy consumption throughout the year, with the exception of the aforementioned season-dependent activities. The estimated energy consumption was compared to the actual household's electricity bills for the previous year (before the household had the PV installed) to validate the estimation methodology and the results; this is discussed in the Results and discussion section. Next, we detail the methodology which was used to estimate electricity consumption by the households across the seven regions considered, assuming the same energy consumption pattern across the regions, with the exception of region-specific requirements related to climate. The other parameters that were estimated and are described below include electricity generation by the PV, storage and supply by the battery and the imports from the grid.

The hourly electricity consumption by the households was estimated using the following relationship:

$$EC_h = \sum_n^N \left(P_n \times \beta_{n,h}\right)/1000 \ \ (\text{kWh}) \qquad (1)$$

where:

EC_h: total electricity consumption by all appliances in hour h (kWh)

P_n: power rating of appliance n (kW)

$\beta_{n,h}$: binary value indicating if appliance n is on (=1) or off (=0) in hour h (−).

Fig. 2. Selected cities in the seven geographical regions of Turkey [The red stars indicate the location of the cities considered, situated in the following regions: Istanbul - Marmara (north-west); Aydin - Aegean (west); Kirikkale - Central Anatolia (centre); Mersin (a.k.a. İçel) - Mediterranean (south); Samsun - Black Sea (north); Erzurum - Eastern Anatolia (east); Mardin - Southeastern Anatolia (southeast)].

The values of $\beta_{n,h}$ were determined based on the type of the appliance and the results of the household survey which indicated when different appliances were used. For example, the TV set or the air conditioning unit had β equal to 1 for the time of day when they were being used and zero at other times. For the appliances that are always on, such as refrigerators, β was always equal to 1.

The electricity generated by the solar PV system is only stored in the battery if the generation is greater than the hourly demand. Thus, the energy stored is equal to the difference between the generation and demand:

$$ES_h = EG_h - EC_h \quad (\text{kWh}) \tag{2}$$

ES_h: electrical energy stored by the battery in hour h (kWh)

EG_h: electricity generation by the solar PV system in hour h (kWh).

The hourly amounts of electricity generated by the PV were estimated for each of the seven locations using the NREL tool (pvwatts.nrel.gov, 2017), based on the system parameters in Table 1.

The hourly amount of electricity EI_h imported from the grid was estimated as:

$$EI_h = EC_h - EG_h \quad (\text{kWh}) \tag{3}$$

The net amount of energy stored by the battery in the first hour of the year considered, ESN_1, is equal to the amount of energy stored during that hour, i.e.:

$$ESN_1 = ES_h \quad (\text{kWh}) \tag{4}$$

For all the remaining 8759 h of the year, the net stored energy ESN_h is estimated as:

$$ESN_h = ESN_1 + ES_h - EI_h \quad (\text{kWh}) \tag{5}$$

where EI_h is a balance between the consumption and generation as given in Eq. (3). If the estimated ESN_h is negative (i.e., the consumption exceeds the generation), it is assigned a value of zero.

The net electricity flow ENF_h in and out of the battery is defined as follows:

$$ENF_h = ESN_h - ES_{h-1} \quad (\text{kWh}) \tag{6}$$

A positive ENF_h value means that electricity is stored in the battery and a negative that it is discharged for use. Therefore, only negative values of ENF_h are considered for the estimation of electricity supply $ESUP_h$ from the battery:

$$ESUP_h = -ENF_h \quad \forall\, ESUP_h < 0 \quad (\text{kWh}) \tag{7a}$$

$$ESUP_h = 0 \quad \forall\, ESUP_h \geq 0 \quad (\text{kWh}) \tag{7b}$$

An example estimate using Eqs. (1)–(7a–b) can be found in Table S1 in the SI.

3.4. Country-wide implications of using the hybrid system

The estimates at the level of the individual households, discussed in the previous section, were then used to determine the implications of using the hybrid systems at the level of the whole country. As mentioned earlier, only detached houses were considered and they provide accommodation for around 40% of the population. Therefore, the number of detached houses with the solar PV-battery system was calculated in each city as follows:

$$DH_c = OR_c(P_c \, x \, 0.4)/4 \quad (-) \tag{8}$$

where:

DH_c: number of detached houses with the hybrid system in city c (−)

OR_c: ownership ratio of the hybrid system in city c (−)

P_c: population in city c (−)

0.4: population ratio with detached houses (−)

4: number of people per household (−).

Table 6
Information on the households and appliances.

Households	
Type of house	Detached
Number of occupants	4
Floor area	120 m^2
Number of rooms	6 (1 living room, 1 kitchen, 1 bathroom, 1 master bedroom, 2 smaller bedrooms)

Appliances

Type	Number	Average power rating (W)
Light bulbs	18	60
Television	2	100
Satellite receiver	2	60
Dishwasher	1	2200
Washing machine	1	1800
Refrigerator	1	75
Oven[a]	1	3300
Kitchen hood	1	350
Water heater (kettle)	1	1800
Electrical controls for gas-fired central heating	1	100
Air conditioning unit	3	1000
Iron	1	1000
Vacuum cleaner	1	2400
Blow dryer	1	1800
Internet modem	1	5.5
Computer	2	300

[a] Cookers are not considered as they are gas-fired rather than electrical.

The OR_c values in different regions were varied from 5%–20% as detailed in Table 7. Given that only detached houses are considered, which provide accommodation for 40% of the population, this is equivalent to the overall uptake of 2%–8% at the national level. Two main factors were assumed to determine the ownership ratio: the latitude and the average income of the region's population. The former is important as it determines the energy output and hence the economic viability of the system. For that reason, the assumptions on the potential ownership are quite conservative as it would not be realistic to expect a higher uptake at least in the near future, particularly as there are no financial incentives for batteries.

The DH_c values estimated for each city were then summed up to obtain the total number of hybrid systems in Turkey. Overall, 81 cities were considered across the seven geographical regions. The data on the population in the cities and nation-wide consumption of electricity were obtained from the literature (Turkish Institute of Statistics, 2016a, 2016b; Turkish Chamber of Electrical and Electronics Engineers, 2015). These data were then combined with the electricity generation and supply by the hybrid system, estimated using Eqs. (2)–(7a), (7b), to determine how much of the country's electricity demand could be met by the hybrid systems. These results were then used to estimate the associated

Table 7
Assumed ownership ratios for the hybrid system in different geographical regions.

Region	Ownership ratio (%)	Comment
Marmara	10	High average income (AI), northern latitude
Aegean	15	High AI, middle and southern latitude
Mediterranean	20	High AI, southern latitude
Central Anatolia	10	Medium AI, medium latitude
Black Sea	5	Medium AI, northern latitude
Southeastern Anatolia	5	Very low AI, southern latitude
Eastern Anatolia	5	Low AI, middle and northern latitude

Table 8
Estimated vs actual consumption of household electricity (Istanbul).

Month	Estimated consumption (kWh)	Actual consumption (kWh)	Relative error (%)
January	595.7	577.7	3.0
February	526.9	536.8	−1.9
March	513.4	563.8	−9.8
April	501.7	558.0	−11.2
May	404.0	442.8	−9.6
June	475.6	517.6	−8.8
July	490.4	534.4	−9.0
August	858.7	655.9	23.6
September	672.9	653.3	2.9
October	595.1	604.9	−1.7
November	772.7	682.4	11.7
December	912.3	812.2	11.0
Total	7319.4	7139.7	8.7[a]

[a] Average error based on the absolute values of errors for each month. The cumulative error over one year is 2.5%, based on the total estimated and actual yearly consumption.

environmental impacts of supplying electricity the hybrid systems in comparison with electricity from the grid.

4. Results and discussion

4.1. Estimates of electricity supply and consumption

The estimates of monthly electricity consumption by the surveyed household based in Istanbul is shown in Table 8. These values represent the total hourly estimates for each month, obtained using Eq. (1). To validate the assumptions and the estimations, they were compared with the actual electricity bills for the previous year. As can be seen in Table 8, the average monthly error is 8.7% while the error relative to the total yearly consumption is only 2.5%. Hence, the estimates agree well with the actual consumption values. The only anomaly appears to be for the month of August where the estimated consumption is much higher than the actual, with the error of 23.6%. This may be due to the assumption in the estimates that in August, the hottest month in Turkey, air conditioning is used 50% more than the average of the other summer months, which may not have been the case for the particular year when the analysis was carried out. To allow for the spread of behaviours and climates considered in the study, the original assumption on the usage of air conditioning in August was retained.

The same approach was then used to estimate electricity consumption by households in the other cities/regions and these results are shown in Table 9. For brevity, only the total yearly consumption is shown but the values were estimated on an hourly basis for each region, taking into account the respective climates and seasonal requirements. These results are available from the authors on request.

The estimated electricity generation and supply by the hybrid system, obtained using Eqs. (2)–(7a), (7b), are also shown in Table 9. As can be seen, the system can meet from 12.5% to 18.4% of the household's annual electricity needs. Cities in southern regions, such as Aydin, Mersin and Mardin, have both higher electricity generation (due to more abundant solar radiation) and higher annual consumption (due to more excessive use of air conditioners during summer) than the northern cities. The city where the system supplies the highest amount of electricity is Mardin (southeastern Anatolia) and the lowest is Samsun (Black Sea region). The reason for this is that they have the highest and lowest solar irradiation, respectively.

4.2. Energy payback

As indicated in Fig. 3, the hybrid system provides between 4.7 and eight times more energy than it consumes over its lifetime. Even in the case of Eastern Anatolia (Erzurum), where solar radiation is not as abundant as in the southern regions, it provides approximately six times more energy than it consumes. Although a financial feasibility analysis was outside the scope of this work, it can be inferred from these results that installing the hybrid systems would be economically viable across the climatic regions of Turkey.

4.3. Life cycle environmental impacts

4.3.1. Individual installations

The life cycle environmental impacts of the individual hybrid systems in the seven regions considered are given in Fig. 4, also showing the contribution of different life cycle stages. The same pattern can be observed in the figure across the impact categories: the systems installed in the southern regions have the lowest and those in the north the highest impacts, with the difference of around 40% between the minimum and maximum values. This is due to the significant variation in the energy output between the regions, as shown in Fig. 3.

For most of the impact categories, the main contributor is the manufacture of solar PV panels, causing 75% of AP, ODP and POCP and 81% of GWP. The EP is split equally between the PV and the battery. On the other hand, the majority of HTP (66%) is due to the battery. For details on the impacts of solar PV and the battery, see Tables S2–S4 and Fig. S1 in the SI.

The raw materials and manufacturing of the system components are the main contributors to GWP, AP and POCP. The remaining three impacts are mainly caused by the raw materials. The contribution of transport and the use stage is insignificant.

The impacts from the raw materials are largely due to the materials used for the PV cell. For GWP, silicon, polyvinyl fluoride film and solar glass account for 45% of the total impact. A similar trend is found for AP. The raw materials account for >80% of eutrophication, mainly related to aluminium production and silicon purification processes. The main contributors to ozone layer depletion are wafer production used for solar PV and polytetrafluoroethylene used for the battery. Approximately two-thirds of POCP is caused by the raw materials, related to the electricity consumption for silicon production. The contribution of the raw materials is highest for HTP (95%) and is attributed to the disposal of silicon and wafer waste generated in the manufacturing process.

In the manufacturing stage, the major contributors are the production of PV cells (50%) and the production of the lithium-ion battery (35%), followed by the production of the inverter (15%).

Table 9
Region-wise annual electricity supply by the solar PV-battery system.

City (region)	Total annual consumption (kWh)	Generation by PV (kWh)	Supply by battery (kWh)	Supply by PV + battery (kWh)	Total share of PV + battery (%)
Istanbul (Marmara)	7319.4	971.6	200.4	1172.0	16.0%
Aydin (Aegean)	10,486.9	1209.6	224.4	1434.0	13.7%
Kirikkale (Central Anatolia)	6747.6	997.7	242.3	1240	18.4%
Samsun (Black Sea)	7319.4	798.6	114.6	913.2	12.5%
Mersin (Mediterranean)	10,486.9	1286	286.8	1572.8	15.0%
Mardin (Southeastern Anatolia)	10,894.9	1367.8	262.7	1630.5	15.0%
Erzurum (Eastern Anatolia)	6783.6	1051.4	137.2	1188.6	17.5%

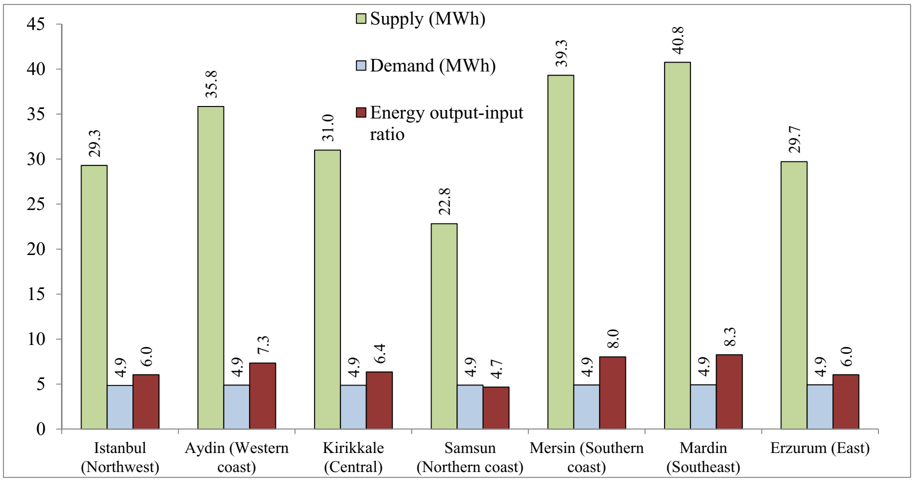
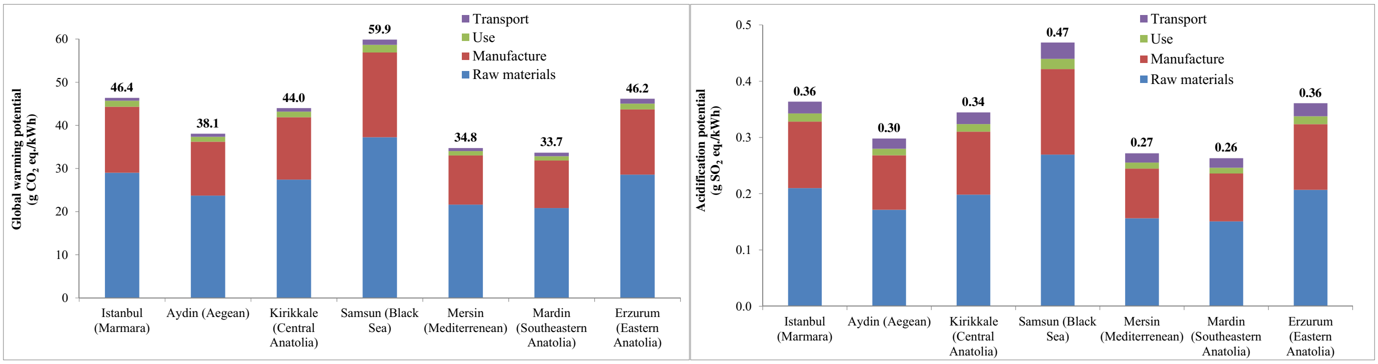
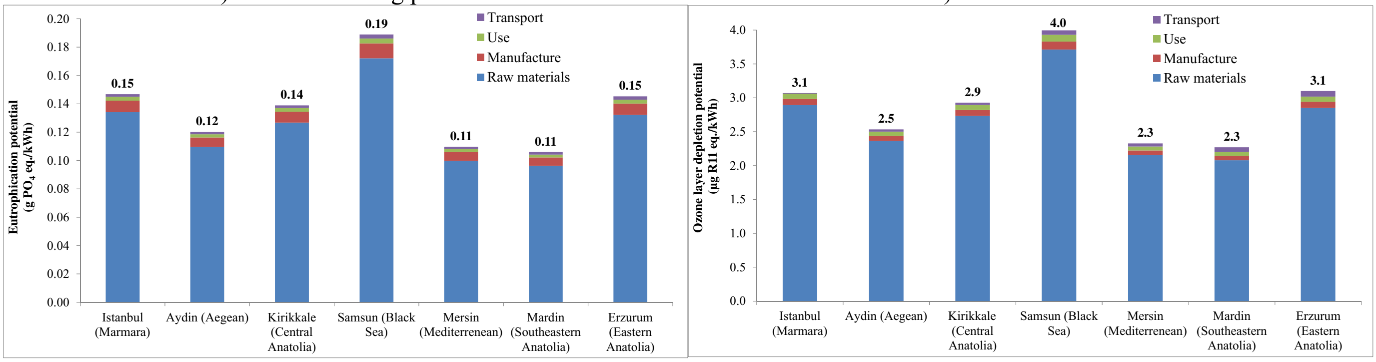


Fig. 3. Energy payback for the solar PV-battery system.



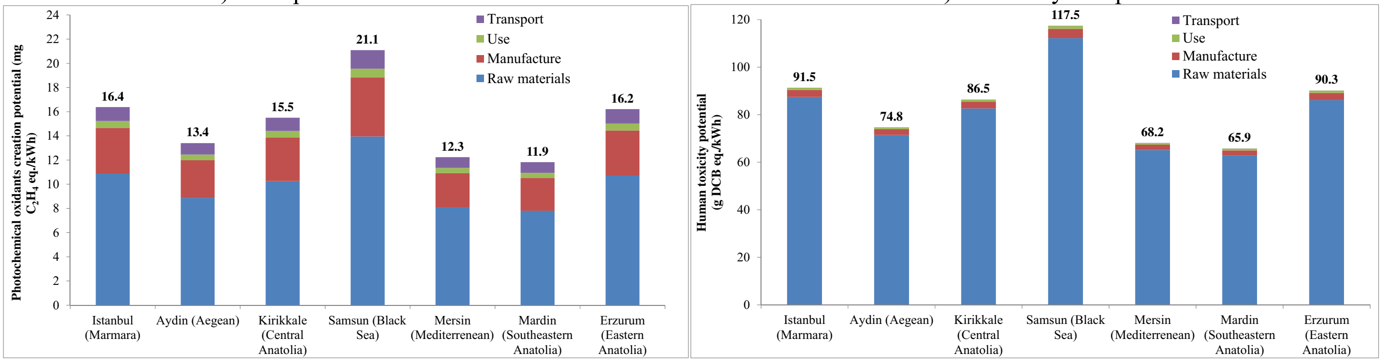
a) Global warming potential

b) Acidification



c) Eutrophication

d) Ozone layer depletion



e) Photochemical oxidants

f) Human toxicity

Fig. 4. Environmental impacts of the solar PV-battery system for different geographical regions, also showing the contribution of different life cycle stages (DCB: dicholorobenzene).

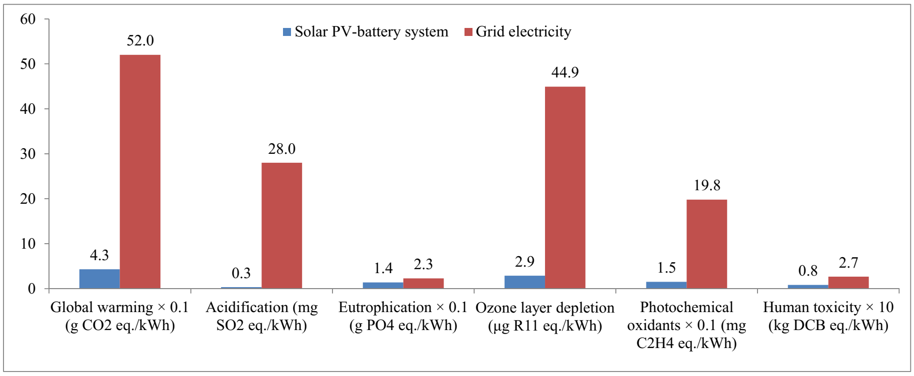


Fig. 5. Environmental impacts of electricity supplied by the solar PV-battery system (average across the regions) in comparison with Turkish grid electricity. (Data for grid electricity sourced from Atilgan and Azapagic (2016). DCB: dichlorobenzene).

4.3.2. Comparison with grid electricity

The impacts of the hybrid system averaged across the regions are compared with the environmental impacts of Turkish grid electricity in Fig. 5. The hybrid system has 1.6–82.6 times lower impacts, with the former corresponding to eutrophication and the latter to acidification. The high difference in acidification is due to the large share of fossil fuels in the Turkish electricity mix, high sulphur content in domestic coal and a lack of desulphurisation units in power plants. Therefore, deploying the PV-battery system across the country to displace the grid electricity would lead to significant environmental benefits. This is explored further in the next section.

4.3.3. Country-wide installations

Based on the values in Tables 7 and 9, the annual energy supply by the hybrid systems is estimated at 1.073 TWh. This is equivalent to 0.4% of the annual electricity consumption in Turkey of 275 TWh (Enerjiatlasi.com, 2018). The corresponding environmental impacts are shown in Fig. 6 in comparison with the impacts of the equivalent amount of grid electricity. As can be seen, significant reductions in the impacts can be achieved, ranging from two to 88 times for eutrophication and the acidification, respectively. The annual reduction in GHG emissions would amount to 558,000 t CO_2-eq. Taking into account the total national GHG emissions of 459.1 Mt. CO_2-eq. (Turkish Institute of Statistics, 2015), this represents a saving of 0.12%. Although the GHG savings appear insignificant, the reduction in the other impacts would justify wider deployment of the hybrid systems, together with other benefits, such as lower energy bills for consumers, gains for the national economy due to the reduced costs of imported fuels and improved energy security.

5. Conclusions

This study presented the life cycle environmental impacts of electricity from a domestic hybrid system integrating solar PV and lithium-ion battery. The impacts were estimated for both individual installations and at the national level, considering seven regions across Turkey and taking into account their insolation levels and other climatic differences. The result show that the system can meet from 12.5% to 18.4% of the household's annual electricity needs. On a life cycle basis, it generates 4.7–8 times more energy than it consumes. The main environmental hotspots were found to be the raw materials and the manufacturing of system components, largely related to solar PV, except for human toxicity, which is mainly due to the battery. Among the materials, silicon is the biggest contributor to the impacts, followed by polyvinyl fluoride film and solar glass. In the manufacturing stage, the major contributors are the production of the PV cells, battery and the inverter. The transportation and use stages combined account for <10% across the impact categories.

In comparison with grid electricity, the PV-battery system has significantly lower impacts (1.6–82.6 times). Extrapolating the results to the entire country showed that the annual electricity consumption from the grid can be reduced by 0.4%, saving 558,000 t CO_2-eq./yr, or 0.12% of the national emissions. While this is not significant and will not help Turkey to meet its COP21 targets, the reduction in the other impacts justifies wider deployment of the hybrid systems, together with the financial and energy security benefits for both the country and the consumer.

However, reaching even the conservative uptake levels considered here will be difficult. While the feed-in-tariffs have been effective in stimulating the uptake of solar PV, there are no incentives for

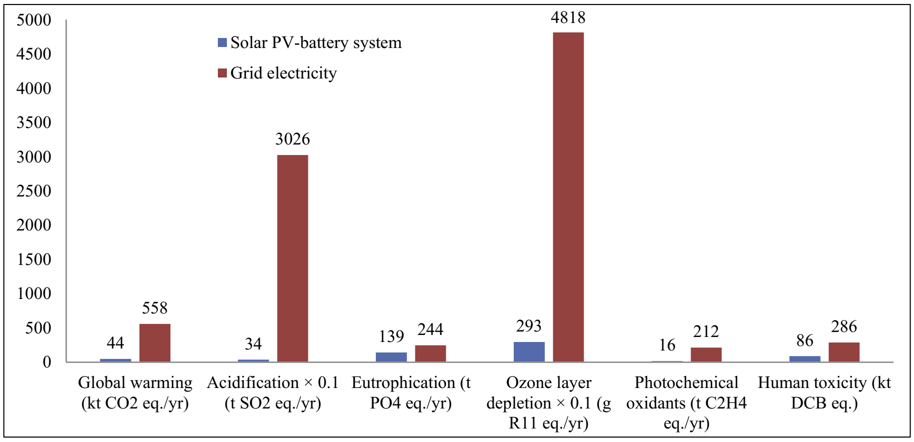


Fig. 6. Annual environmental impacts of the hybrid systems at the national level (country average) compared to the grid electricity. (Data for grid electricity sourced from Atilgan and Azapagic (2016). DCB: dichlorobenzene).

consumers to purchase batteries. Perversely, households that have a hybrid system cannot claim the feed-in-tariff for the excess electricity generated as the relevant laws excludes battery storage from the definition of 'renewable energy'. As the results of this work show clearly, integrated PV-battery installations have significant environmental and socio-economic advantages over the grid electricity, thus providing a strong impetus for policy makers to amend legislation and stimulate the uptake of hybrid systems.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.06.290.

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