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Attributional life cycle assessment of mounted 1.8kWp monocrystalline photovoltaic system with batteries and comparison with fossil energy production system

Kabakian, V.[ab**], McManus, M.C.[ab], Harajli, H.[c]

[a] Department of Mechanical Engineering, University of Bath, Bath BA2 7AY, United Kingdom
[b] Sustainable Energy Research Team (SERT), University of Bath, Bath BA2 7AY, United Kingdom
[c] United Nations Development Program – CEDRO Project, Beirut, Lebanon

Abstract

The use of renewable technologies will increase with the requirement to meet carbon reduction targets. However, this must be done in a sustainable manner. This paper compares the impact of the current Lebanese electricity system with production of electricity from PV. This is the first paper to look at how the addition of PV to this system, and explores the potential impact. As many electricity networks in the region suffer from similar issues and have similar climates this research will not only inform the Lebanese system, but can be used to influence and inform impacts of other systems. It evaluates the environmental impact, and therefore the actual sustainability, of a 1.8 kWp monocrystalline Photovoltaic (PV) system with and without Lead-Acid batteries (PbA) compared to the existing centralised electricity production mix and decentralised diesel neighbourhood gensets. The analysis is rigorous as it is conducted using the methodology of life cycle assessment (LCA), using the SimaPro software (Ecoinvent 2.2 database) and ReCiPe 2008 method for impact assessment. The environmental impacts of the PV technology are compared to that of the existing fossil fuel electricity generation mix. Results, using the functional unit of 1 kWh, indicate that the PV system, even when equipped with PbA batteries, has a lower environmental burden per delivered output compared to the Lebanese electricity mix, and even more so when decentralised diesel neighbourhood gensets are taken into account. The results of the analysis allows to calculate a series of parameters such as Global Warming Potential (GWP) (0.0402 kg CO_{2eq}/kWh and 0.0389 kg CO_{2eq}/kWh), Cumulative Energy Demand (CED) (4.41 MJ/kWh and 4.39 MJ/kWh), Gross Energy Requirement (GER) (1.23 and 1.22), Energy Pay-Back Time (EPBT) (16.9 years and 16.1 years), Carbon Dioxide Pay-Back Time (CO_{2eq}PBT) (3.52 years and 3.21 years), and Net Energy Ratio (NER) (1.48 and 1.55) for the PV system with and without PbA batteries.

Highlights

► ALCA study of a mounted 1.8 kW_p photovoltaic system with and without lead-acid batteries is performed. ► The main impact is related to the modules, inverter, and batteries. ► The comparison of LCA indicate that photovoltaic systems, even when equipped with storage systems, have less environmental burden on centralized electricity systems. ► The PV plant is energy sustainable because the EPBT = 16.1 years and reaches 16.9 years when storage systems are included. ►The results give an indication of the implications of rolling these systems out to a wider (global) community.

Keywords: Life Cycle Assessment; Photovoltaic; Environmental impact; Lead-Acid batteries; Energy production systems

* Corresponding author: vk223@bath.ac.uk; vahakn.kabakian@gmail.com; telephone +447810861819

1 Introduction

In recent years, the need to exploit alternative energy sources has become important, especially in order to reduce air pollution and mitigate climate change (Desideri et al., 2012a). The climate change threat should be a sufficient motive to tackle carbon-intensive lifestyles, based mainly on a high dependence on fossil fuels. Although the imperative to act on climate change has affected nearly every sector, the biggest emphasis is being placed on the electricity sector due to its important contribution to global emissions (nearly 26% of world greenhouse gas emissions) (IPCC, 2007). This is also driven by the need to meet the energy demand of a growing population. There are categories of pressure: the limited nature of the fossil energy sources, and their increasing prices (Sharma and Tiwari, 2013). The new options therefore need to be eco-friendly as well as abundant in nature. In fact, environmental degradation, technological advancement, public and political awareness are elements that create real perspectives in development of renewable energies. Among the different available renewable energy resources, solar energy is relatively more significant in a Mediterranean country such as Lebanon. Photovoltaic systems have turned into one of the most promising solutions for the urgent electrification problems of numerous remote consumers worldwide (Kazmerski, 2006 and Albrecht, 2007). In particular, photovoltaic (PV) technology allows the transfer of solar energy directly into electricity using the photovoltaic effect, without pollutant emissions during the operation phase (Goetzberger and Hoffmann, 2005). PV technology is growing globally at an average rate of almost 55% annually over the past five years, with global installations currently reaching almost 140 GW (REN21, 2014). This growth can be attributed to the combination of a steep decline in production costs and continued government support (Laleman et al., 2013) across several countries.

However, most of the components of the PV systems are manufactured using fossil fuel intensive materials and processes, which indicate that significant energy amounts are consumed during the various life stages of a PV system (Alsema and Nieuwlaar, 2000; Alsema et al., 2006; Kazmerski, 2006; Menoufi et al., 2013). In order to maintain the best environmental performance new technologies ought to be assessed on a life cycle basis (Pehnt, 2006) in order to avoid any error of assessment, especially from a climate change perspective. A photovoltaic system is more sustainable only if the energy produced during its operating life compensates the total energy costs that can be estimated through the life cycle assessment (LCA) methodology (Desideri et al., 2012a). In addition, from a wider environmental perspective, the systems must reduce emissions of pollutants as compared to the electricity from fossil sources it is substituting.

This paper assesses the environmental evaluation of a mounted stand-alone PV system with and without lead-acid batteries. This is compared with the impact of the current Lebanese electricity system (LES) with its two existing configurations: 1) the electricity mix consisting of the centralised power plants (i.e., the centralised electricity) and 2) the electricity mix consisting of the centralised power plants and the diesel gensets distributed within neighbourhoods (i.e., centralised electricity + diesel gensets). In addition, the following parameters are calculated: global warming potential (GWP), energy and CO_{2eq} payback time, cumulative energy demand (EBPT and $CO_{2eq.}$PBT), cumulative energy demand (CED), gross energy requirement (GER) and net energy ratio (NER). The different aspects of the Lebanese electricity system have been evaluated previously in terms of technical, financial and environmental capabilities. Chaaban and Ramadan (1998) presented options for energy conservation in high energy consuming economic sectors, while Chedid et al. (2000; 2001) identified the benefits of various energy efficiency measures to the national economy. Abi Said (2005), Comair (2009) and El-Fadel et al. (2010) provided an overview of the LES and investigated Lebanon's potential for renewable energy. Harajli et al. (2011) investigated the long-term implications and economic performance of onshore wind power integrated into the Lebanese electricity system, while El-Khoury et al. (2010) has conducted an assessment of wind power for electricity generation in Lebanon. El-Fadel et al. (2010) evaluated the sustainability of the Lebanese electricity system. El-Fadel et al. (2003), Ghaddar et al. (2005), Dagher and Ruble (2010) addressed the potential for greenhouse gas reduction in the power sector. Ruble and Nader (2011) looked at market incentives in solving the national energy crisis. With the exception of El-Fadel et al. (2010), the above literature lacks the application of the LCA approach, and although El-Fadel et al. (2010) has looked at various scenarios for the LES from applying LCA, none of these scenarios included renewable energy sources.

There are several knowledge gap that this study addresses:

1) From a broader LCA perspective, while there are various case studies and international life cycle inventory databases, the Arab region has virtually not engaged in any LCA studies (Ali et al., 2014). Therefore, the current study populates the literature from a region where LCA studies are absent.
2) There are also several efforts underway to address the critical need to organize and centralize a worldwide knowledge base of LCI data sources that will ease identification and acquisition of available data (Yung et al., 2013) – and this is particularly important since many developing countries supply resources to developed countries, thus the need for LCI databases to include products and services from such countries (Tharamurajah and Grant, 2002). Therefore when such efforts start in a more concerted manner, the current study would allow the further development of product-specific LCA in Lebanon, since it represents the LCA of the national electricity.
3) Within the framework of LCA of PV, a wide range of studies can be found in literature, using various LCA indicators, with the energy pay-back period as the principal interest with fewer numbers of studies conducted using various impact assessment methodologies as well as various indicators. Impact assessment methodologies such as the ReCiPe, Eco-Indicator 99 and Eco-Scarcity provide a wider environmental performance prospective (Menoufi et al., 2013). Therefore, a third gap that this research addresses is the examination of the performance of a PV system, which is site specific, within the existing Lebanese electricity system as a case study, through LCA using the ReCiPe impact assessment methodology. The approach uses a series of indicators and metrics such as energy pay-back period, global warming potential, cumulative energy demand, gross energy requirement, carbon dioxide payback time and the net energy ratio. It also provides a case study for other developing countries with similar weak electricity grid systems.
4) With the recent national electricity development (introduction of 12% RE in the electricity mix by 2020), the current study addresses the benefit of introducing a renewable energy technology (PV) on a kWh produced. As far as the authors are aware, no comprehensive LCA has been performed for a renewable energy technology coupled with the Lebanese electricity system. Therefore, this article contributes to the body of

knowledge on the environmental assessment of a country/region electricity mix which could be used in various databases.

2 Description of the LES

The Lebanese electricity sector is run by the Electricité du Liban, an autonomous state-owned (and therefore, a public monopoly) power utility that generates, transmits, and distributes electricity to all Lebanese territories. Most of the electricity is generated through 7 major thermal power plants operating on imported diesel and heavy fuel oil and 3.5-4.5% through hydro power plants. When circumstances permit, direct power is purchased from Syria (around 7.5%) (MoEW, 2010). Almost all of Lebanon's primary energy requirements are imported (Harajli et al., 2011), since the country does not have any indigenous energy sources (Hamdan et al., 2012) with the exception of a small share of hydropower. The HFO is bought from SONATRACH, the largest oil and gas company in Algeria and Africa, with a permissible sulphur content of the imported HFO of less than 1% (by weight). The Diesel Oil (i.e., gasoil) used in thermal power stations originate from two sources: SONATRACH and Kuwait Petroleum Company, with a permissible sulphur content not exceeding 0.5% (by weight). The purchase/import of both HFO and DO (gasoil) is performed by the government. In contrast, the diesel oil used in decentralised gensets are imported by the private sector companies from various sources (including European ones) with a maximum permissible sulphur level of 0.035% by weight (WB, 2008, MoE-UNDP-ECODIT, 2011).This importation drains national revenues and undermines energy security, currently judged very poor (Cantin et al., 2007; El-Fadel et al., 2010; Dagher and Ruble, 2010; Ruble and Nader, 2011; Harajli et al., 2011; MoE-UNDP-ECODIT, 2011; Fardoun et al., 2012; Hamdan et al., 2012). With the recent influx of Syrian refugee population, an increase in electricity demand in the order of 251 MW to 362 MW is projected by end of 2014, a situation which requires additional capital investment in generation capacity associated with transmission and distribution networks (World Bank, 2013), rendering plans for 24-hour electricity farfetched and thus continuation of the blackout conditions.

Although available capacity reached 2,670 MW (Hamdan et al., 2012), actual availability of electricity has varied from as low as 1,500 MW to a maximum of 2,000 MW due to several shortcomings. In the case of the thermal plants these include plant failures and rehabilitation work, fuel supply and interruption of imported electricity from both Syria and Egypt; in the case of hydropower, rainfall variations, and subsequently water levels (Harajli et al., 2011). In addition, the transmission and distribution network face two types of problems: technical losses in the range of 15% and non-technical losses (e.g., theft) amounting to 20% (MoEW, 2010). Due to these shortages, power cuts average at around 6 hours/day at the country level (GEF, 2011), with rationing hours unevenly distributed between cities (Dagher and Ruble, 2010). Since supply does not meet the demand, self-generation, in the form of diesel neighbourhood generators, is playing an increasing role in providing additional electricity, especially for the industrial and residential sectors. It was estimated that 33% of total consumed power in 2007 was provided by standby private diesel power generators distributed randomly throughout the country (World Bank, 2008). This share has reached 37% in 2012 (as calculated in Table 3). The negative influence of exposure to emissions from diesel power generators on human health has been shown previously (see for example Sehlstedt et al., 2007), and diesel engine exhaust has recently been classified as carcinogenic to humans (IARC, 2012).

3 Description of the PV system

The system under study is a 1.8 kWp monocrystalline photovoltaic system. The modules are made in the People's Republic of China. It is installed on the roof of a public school in the South of Lebanon, at a distance of 110 km from Beirut, the capital city of Lebanon. The installation is part of the UNDP-CEDRO project (www.cedro-undp.org), a project that aims to complement the national power sector reform strategy by installing energy efficiency and renewable energy applications in public facilities throughout the country. The system consists of 24 modules in total, with dimensions of 119.5cm x 54.1cm x 3cm per module. Table 1 provides the module's characteristics and its electrical specifications.

Table 1. Module's type and electrical and system specifications (at STC)

Model	STP075S-12/Bc
Type	Mono-crystalline
Total number of modules	24
Rated Maximum Power (P_{max})/module	75 Wp (total power 1.8 kWp)
Area/module	0.65 m^2 (total area: 15.5 m^2)
Output tolerance	±5 %
Current at P_{max} (I_{mp})	4.35 A
Voltage at P_{max} (V_{mp})	17.3 V
Short-circuit Current (I_{SC})	4.72 A
Open-circuit Voltage (V_{OC})	21.7 V
Nominal Operating Cell Temp. (T_{NOCT})	45°C ± 2°C
Weight	8 kg
Maximum System Voltage	1000 V
Maximum Series Fuse Rating	8 A
Efficiency	13.1%
Tilt	45°
Total weight	192 kg

The balance of system (BOS) consists of an aluminium mounting structure an inverter, water and UV-resistant, flexible multi-stranded cables, 8 lead-acid (PbA) batteries, and a stainless steel cabinet housing the inverter, batteries and electric parts. The technical details of the BOS are given in Table 2 below. The system boundary is defined as the pre-manufacturing, manufacturing, installation and use stages. Recycling and disposal stages are excluded.

Table 2. BOS components and specifications

Mounting structure (aluminum)	8.36 kg
Inverter	Studer X tender, Model X TM 4000-48 4000 W/48 V Sine wave 220 vac Battery temperature sensor 22.9 kg Made in Switzerland
Batteries	Vented Lead acid (PbA) deep discharge Hoppecke, 5 OPzS 250 6 V 250 Ah C10 Ufloat = 2.23 V/cell d20 C/68F = 1.24 kg/l Total weight= 21 kg (max weight) Made in Germany
Cabinet	Chromium steel 18/8 25.2 kg Includes 0.047m^2 of tin plated chromium steel sheet

4 Life Cycle Assessment

An environmental Life Cycle Assessment (LCA) was completed to illustrate the current environmental performance of the Lebanese electricity mix, with and without diesel gensets (self-generation), as well as electricity generation from a 1.8 kWp photovoltaic system installed in Lebanon.

LCAs can be used to compare and analyse the environmental impacts of products and services. This is done by identifying energy and materials used and waste released into the environment over the entire life cycle of the process or activity, including extraction of raw materials, manufacture, transport, distribution, use, reuse, recycling and final disposal (SETAC, 1990). The life-cycle stages of a product or process begins with the required inputs of raw materials and energy through the processes and consequences of manufacturing, use, reuse, maintenance, recycling, and disposal (including the transportation requirements in-between) to the final outputs in the form of air, water or solid pollutants (EPA, 2006). The technical framework for LCA consists of four components, each having a role in the assessment (Durlinger et al., 2012):

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation

The SimaPro Software (V7.3.3) was used to complete the LCA along with the Ecoinvent v.2.2 database. The PV modules and BOS were modelled using the life cycle databases in the software. Specific changes to the information were made to adjust for site specific conditions. For the PV system, the Ecoinvent 3kWp mono-crystalline LCA is used (Jungbluth et al, 2009), while adjusting for the Chinese grid from the database (replacing European grid with Chinese). For the BOS (Table 2), the inverter information was adjusted from (Jungbluth et al, 2009) to accommodate the wattage (2,500 W) of the installed inverter (4,000 W), while for the batteries, the information contained in McManus (2012) were added to the software. Cabinets and mounting structure are also included; surface area is calculated based on actual installation and using material information contained in the Ecoinvent database, proper modelling was conducted and incorporated in the final output. All transportation distances were calculated based on the origin of the respective components, and modelled accordingly using the Ecoinvent database. The Lebanese electricity fuel generation mix of the year 2012 (the most recent information available) were used as the input data as shown in Table 3 (information on generated power were obtained from the utility directly; the utility also estimated the demand to have amounted to 18,000 GWh in 2012).. Lebanon’s electricity is primarily generated from oil-fired power plants (91.88%) in addition to a small portion from hydropower (8.12%). The suppressed demand is met by the use of decentralized diesel generators at the neighbourhood level, constituting a 37% of the total electricity generation.

Table 3. Lebanese electricity system generation mix in 2012

Power source	2012 production (GWh)	Share from the functional unit (1 kWh electricity mix)	Share from the functional unit (1 kWh electricity mix with self-generation)
Thermal power plants			
Zouk (HFO[*])	1,897	0.919	0.58
Jieh (HFO)	1,218		
Hrayche (HFO)	200		
Deir Ammar[a] (DO[**])	2,977		
Zahrani[a] (DO)	2,984		
Baalbeck[a] (DO)	531		
Tyr[a] (DO)	599		
Hydropower plants			
Kadisha	72	0.081	0.05
Litani	680		
Nahr Ibrahim	92		
Bared	54		
Richmaya	20		
Sub-Total	11,324	1	
Self-generation			
Decentralised diesel generators	6,676		0.37
Total	18,000		1

[a] Running on back up fuel due to the unavailability of natural gas
[*] Heavy Fuel Oil
[**] Diesel Oil

The functional unit was selected to be 1 kWh of electricity generated and delivered to the Lebanese consumer, and the LCA was completed with and without the impacts of the diesel gensets. This was estimated in terms of the environmental burdens per kWh (as per the functional unit), and therefore if the diesel powered self-generation (i.e., centralized electricity + diesel gensets) is excluded the LCA was based entirely on the centralized Lebanese electricity network (i.e., centralized electricity). Conversely, when the diesel powered self-generation was included, the LCA was made up of 37% diesel powered self-generation and the remainder from the centralised power plants. The value-shares applied to the functional unit for both generation types are shown in Table 3. It was assumed that the average thermal efficiency of a diesel genset used for self-generation in Lebanon was 20%. In order to slightly offset the lower generation efficiency, it was assumed that there would be a small saving in transmission and possibly distribution losses for such generators, with transmission and distribution (T&D) losses 7.5%, since the electricity from diesel genset has a much shorter distance to travel, and will not pass through the high voltage transmission lines. As for the centralized electricity generation LCA, the impact of constructing T&D networks and the losses within the cables (considered as 15%) are included. There is substantial illegal leaching of electricity (estimated conservatively at 20%), however, this was not considered since from the environmental perspective, the electricity is generated/consumed and therefore needs to be accounted for. The impact of the low, medium and high voltage T&D networks were included in the assessment.

5 Impact Assessment

In a life cycle assessment, the emissions and resources consumed lined to a specific product are compiled and documented in a life cycle inventory. An impact assessment is then performed, generally considering three areas of protection: human health, natural environment, and issues related to natural resource use (EC-JRC-IES, 2011). Two main groups of choice for category indicators exists: midpoints and endpoints, where midpoints are considered to be a point in the cause-effect chain (environmental mechanism) of a particular impact category, prior to the endpoint, at which characterization factors can be calculated to reflect the relative importance of an emission or extraction in a life cycle inventory (e.g., global warming potentials as defined in terms of radiative forcing and atmospheric half-life differences) (Bare et al., 2000). Such methodologies include EcoIndicators 95. However, for LCA studies that require the analysis of trade-offs between and/or aggregation across impact categories, endpoint-based approaches are more suitable (Bare et al., 2000). Such methodologies include assessing human health and ecosystem impacts at the endpoint that may occur as a result of climate change, ozone depletion, as well as other categories addressed using midpoint category indicators. Examples of endpoint methodologies include ExternE and EcoIndicators 99. The ReCiPe methodology, developed by (Goedkoop et al., 2009) is an LCIA methodology that combines both midpoint and endpoint category indicators and harmonizes the different approaches taken to LCIA by the widely accepted CML guide (2002) and the EcoIndicator 99 to produce a single LCIA framework. This study uses the ReCiPe life cycle impact assessment method. ReCiPe implements the disability-adjusted life year (DALY) in the category of Human Health endpoint impact, which considers the year of life lost and the year of life disabled due to environmental interventions. Damage to Ecosystems is described by species lost in a predefined period (species/yr) as a result of emissions to terrestrial, freshwater, and marine systems. Damage to Resources is calculated as the economic loss ($) caused by the marginal increase in costs due to the extraction of a resource (Goedkoop et al., 2009). ReCiPe also employs a cultural theory with three archetypes being used to describe three groups of considerations and assumptions (Dong and Ng, 2014): Individualist (I) considers the short-term impact due to the most relevant chemicals. Egalitarian (E), on the other hand, is based on the precautionary principle that considers long-term perspective and involves more risks. Hierarchism (H) is balanced perspective based on the common policy principles. Finally, ReCiPe provides another set of weighting factors (A) by averaging the weighting factors of the three perspectives. In this study, the "World ReCiPe E/E" weighting set, referring to the normalisation values of the world with the weighting set belonging to the egalitarian perspective is adopted.

5.1 Photovoltaic System

Characterised results are shown in the Figure 1 below, while Figure 2 shows the single score impact assessment. Results indicate that from the 5 components of the installed photovoltaic system (inverter, photovoltaic module, cabinet, mounting structure and lead-acid (PbA) batteries), the impact of the photovoltaic module is the highest, followed by the inverter, the batteries, the cabinet, and the mounting structure respectively. Human toxicity was ranked as the major impacts resulting from the photovoltaic module, the inverter and the PbA batteries (0.835 Pt, 0.571 Pt and 0.111 Pt respectively). Climate Change Human Health ranked as the second most important impact resulting from the photovoltaic module (with 0.197 Pt).

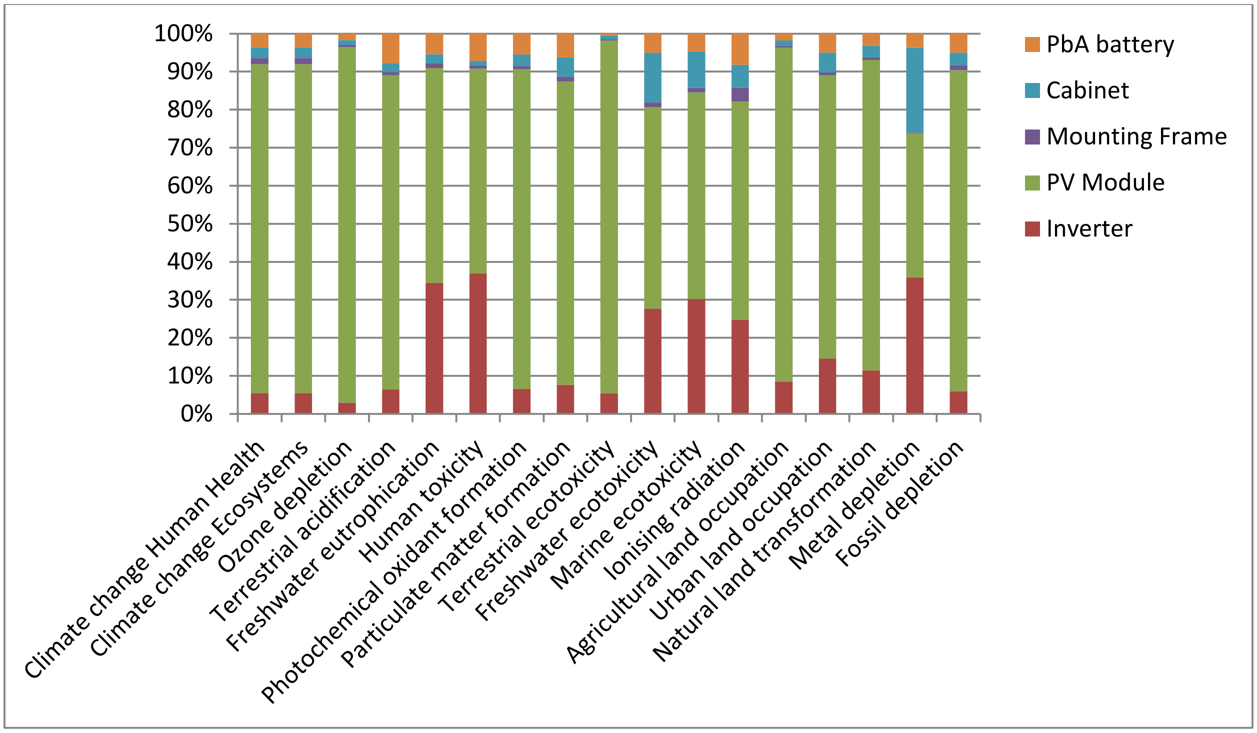

Figure 1. Characterised results of the photovoltaic system (Method: RecipeEdpoint(E) V1.07/WorldReCiPe E/E/Characterisation)

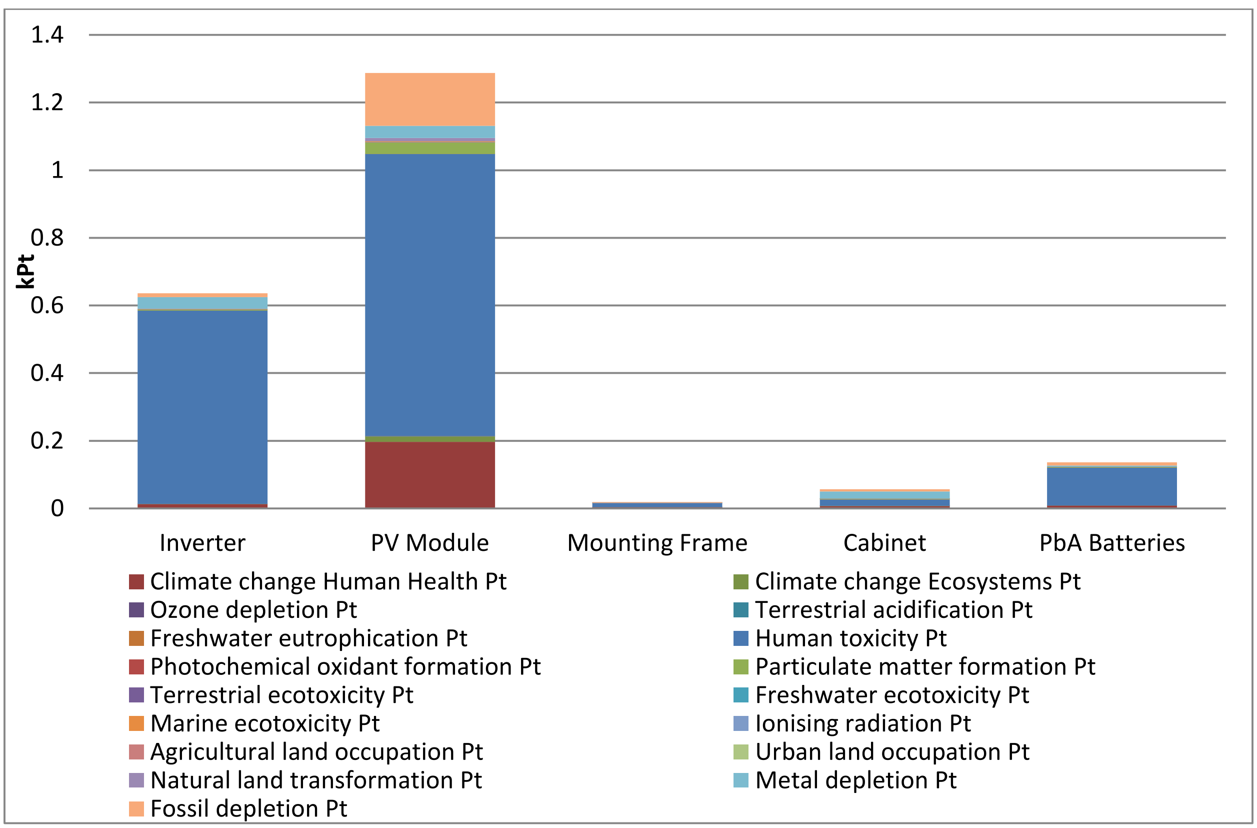

Figure 2. Single score impact assessment results (Method: Recipe Endpoint (E) v1.07/World ReCiPe E/E/Single Score)

5.2 Lebanese Electricity System and Photovoltaic system

When new technologies enter the market, their environmental superiority over competing options must be asserted based on a life cycle approach (Pehnt, 2006). Therefore, a comparison of the Lebanese centralised electricity sector, with and without decentralised diesel gensets, are compared to the photovoltaic system.

The results of the LCA of the LES with the PV system are displayed in Figure 3, with the characterised results for 17 different impact categories. The results indicate that the Lebanon electricity mix with diesel gensets has a higher impact in all categories with the exception of the terrestrial ecotoxicity, marine ecotoxicity and metal depletion, compared to the Lebanese electricity mix without diesel gensets. The first two results can partially be explained by the fact that large centralised plants have highly concentrated forms of generation, which require large amounts of cooling water with more concentrated emissions rather than when geographically dispersed. The marine ecotoxicity results are confirmed in a study regarding the northern coastal zone of Lebanon by Doumani (2007). In contrast, there is substantial reduction in photochemical oxidant formation and particulate matter formation, terrestrial acidification, climate change impacts (both human health and ecosystems categories) and ozone depletion, when considering only the centralised electricity production.

This might be explained by the fact that the centralised power stations are equipped with air pollution control technologies while the diesel gensets are not equipped with any type of air pollution control. The use of the photovoltaic as a source of electricity generation shows the best option to reduce environmental impacts. However, with the inclusion of the impact of the batteries been incorporated in the analysis, the PV system's LCA indicated an additional environmental burden since the storage equipment (i.e., batteries) are known to have relatively high environmental impacts (Majeau-Bettez et al., 2011; McManus, 2012; Rehman and Al-Hadhrami, 2010; Yu et al., 2012). Table 4 indicates the results in endpoint categories. The results indicate that for the Human Health impact category, the lowest impact is the PV system without batteries, with the impact increasing by 6.25%, 500% and 724% for the PV system with batteries, Lebanon Centralised Electricity and Lebanon Centralised Electricity + Diesel gensets respectively. Similarly for the remaining two impact categories, the impacts increase 3%, 1,253% and 1,892% for Ecosystems impact categories, and 4.4%, 4,360% and 2,667% for Resources impact category for the PV system with batteries, Lebanon Centralised Electricity and Lebanon Centralised Electricity + Diesel gensets respectively.

Table 4. Results per functional unit (1kWh) in endpoint impact categories

	Centralised Elect. + Diesel Gensets	Centralised Elect.	1.8 kWp PV	1.8 kWp PV +PbA batteries
Human Health (DALY)	9.23E-06	6.74E-06	1.12E-06	1.19E-06
Ecosystems (species.yr)	2.65E-08	1.80E-08	1.33E-09	1.37E-09
Resources ($)	6.74E-02	4.46E-02	2.49E-03	2.60E-03

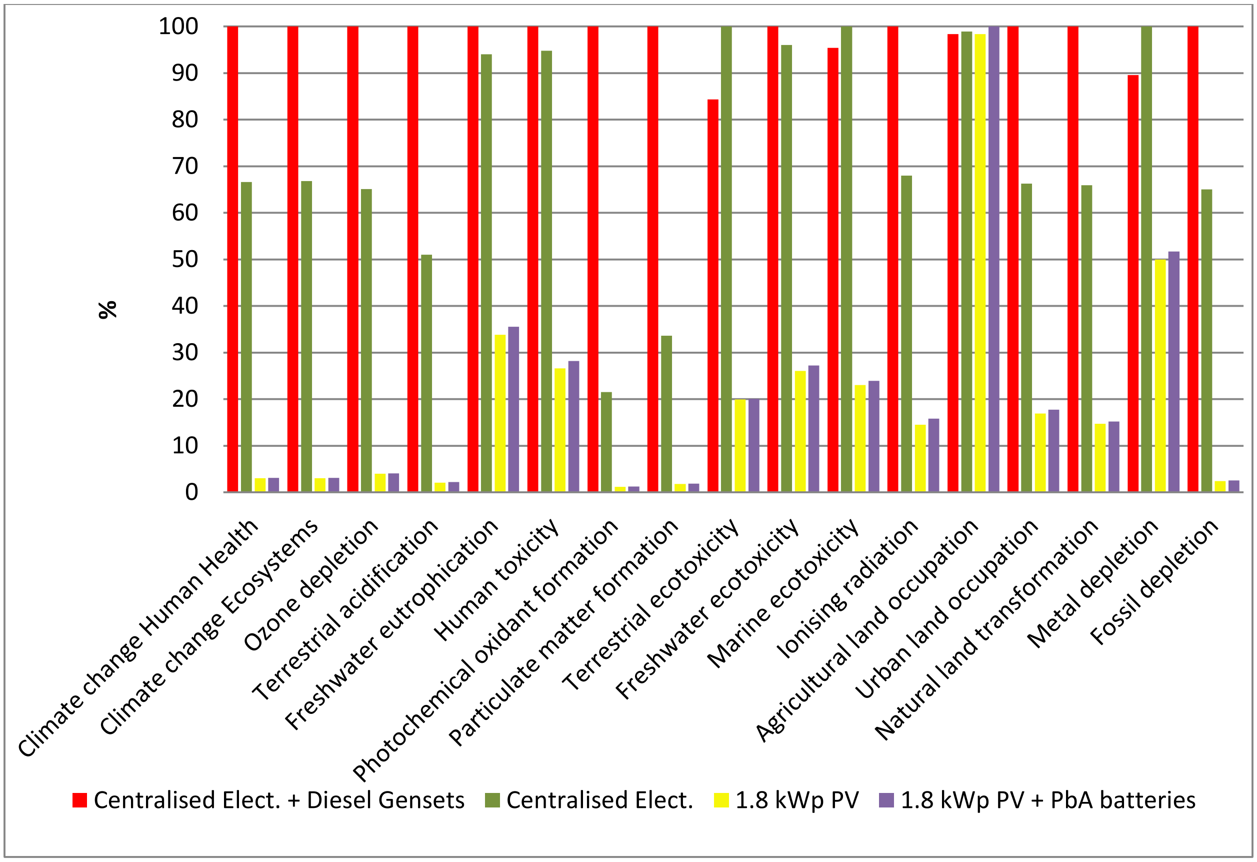

Figure 3. Characterised impacts of the Lebanese electricity with and without diesel gensets, and of a PV system (with and without battery), per 1 kWh of delivered electricity (Method: Recipe Endpoint (E) v1.07/WorldReCiPe E/E/Characterisation)

5.3 Global Warming Potential

The Global Warming Potential (GWP) assessment method, developed by the Intergovernmental Panel on Climate Change, is frequently used in energy research to investigate the impact of a product or a service on global warming (Bravi et al., 2007; Heller et al., 2004; Lechon et al., 2008; Mohr et al., 2009). Three GWP methods have been developed, each for a different time span (20, 100 and 500 year). In this study, the 100 year method was used.

When exploring the carbon footprint of the four electricity generation categories, using the IPCC 2007 GWP 100a v1.02 impact category, the footprint of 1 kWh electricity produced from centralised + diesel gensets is 1.23 kg CO_{2eq}/kWh, while the footprint of the centralised generation is 0.818 kg CO_{2eq}/kWh. The photovoltaic generation with and without batteries are 0.0402 kg CO_{2eq}/kWh and 0.0389 kg CO_{2eq}/kWh respectively as shown in Figure 4. The ecoinvent v2.2 UCTE indicates a carbon footprint of electricity generation from fossil fuel (oil) 0.885 kg CO_{2eq}/kWh, as compared to 0.818 kg CO_{2eq}/kWh from centralised generation; this value increases to 0.89 kg CO_{2eq}/kWh when hydropower is excluded from the Lebanese centralised generation, getting closer to the UCTE fossil fuel value.

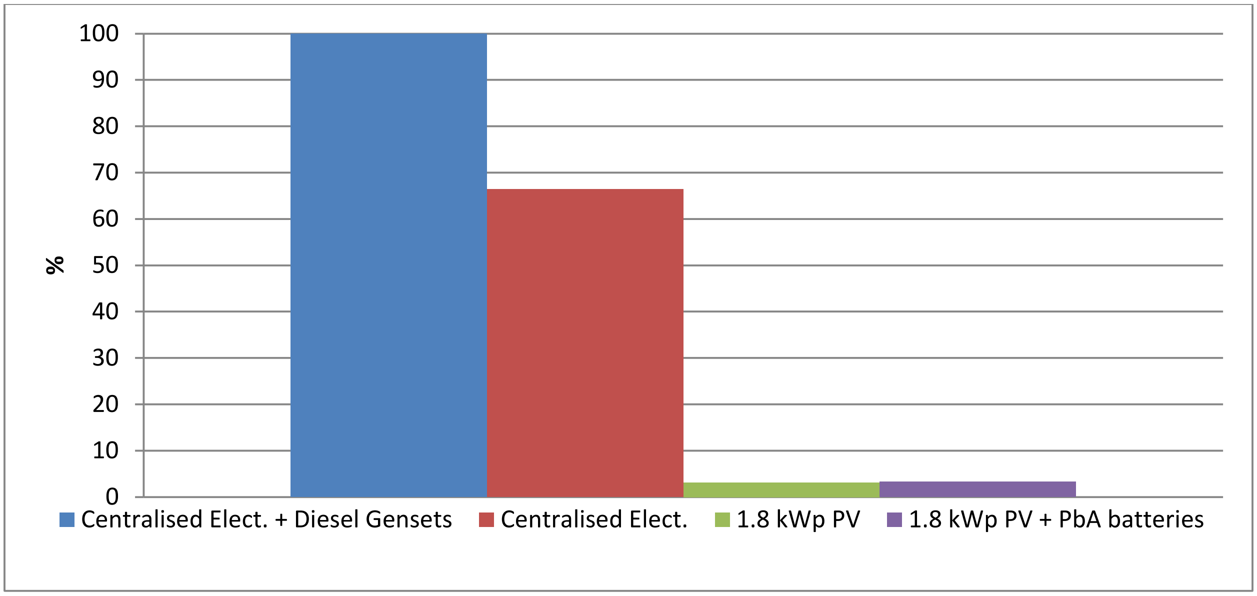

Figure 4. The attribute of CO_2 reduction of centralized Lebanese electricity generation and the PV cases (IPCC 2007 100aV1.02/Characterisation)

5.4 Cumulative Energy Demand and Gross Energy Requirement

The cumulative energy demand, used in renewable energy technology research (Alsema, 1998, Alsema, 2000; Alsema and Nieuwlaar, 2000; Alsema and de Wild-Scholten, 2005; Huijbregts et al., 2006; Jungbluth et al., 2007) quantifies all the energy consumed during the life cycle of a product.

Total cumulative energy demand for the Lebanese electricity mix with and without diesel gensets per functional unit (1 kWh) is 18.13 MJ and 11.91 MJ respectively, while for the electricity generated by the PV system is 4.41 MJ and 4.39 MJ with and without batteries

respectively (

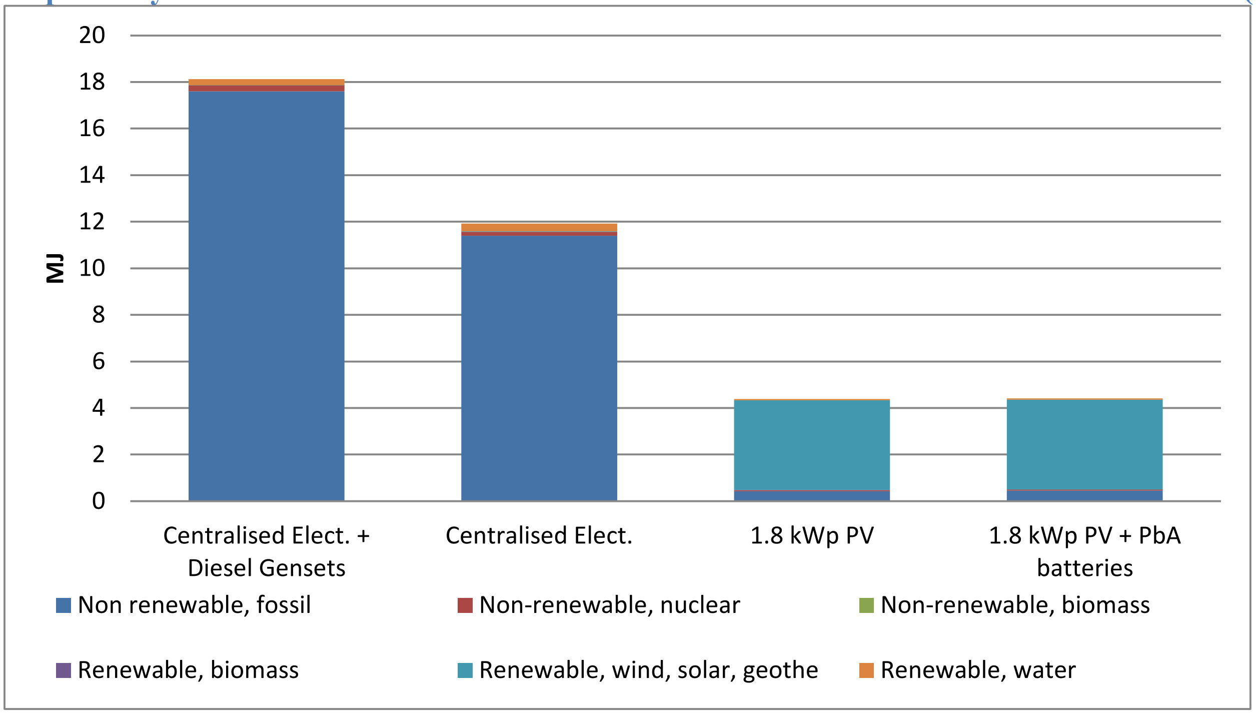

Figure 5). Consequently the gross energy requirement (GER), which is the life cycle primary energy inputs required to deliver a good or service to the point of interest (in the case of this study: 1 kWh) are summarised in Table 5.

Table 5. Gross energy requirements of electricity technologies per 1 kWh

Electricity generation technology	**GER ($MJ_{primary}/MJ_{delivered}$)**
Centralised Electricity + Diesel Gensets	5.04
Centralised Electricity	3.30
1.8 kW_p PV	1.22
1.8 kW_p PV + PbA batteries	1.23

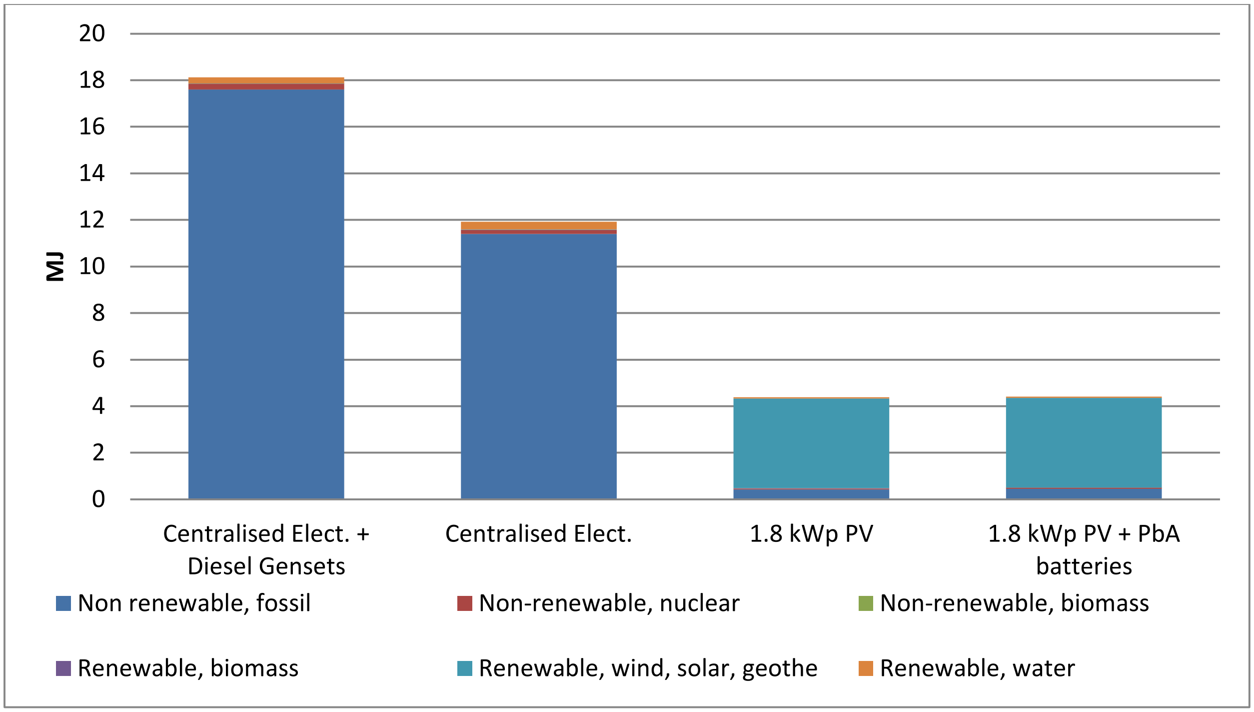

Figure 5. Cumulative Energy Demand of the four systems per 1 kWh (Method: Cumulative Energy Demand V1.08/Cumulative energy demand/Single score)

5.5 Energy and CO_{2eq} pay-back time

The energy payback time (EPBT) is the time during which the PV system will produce the same energy used for its construction and is a frequently used parameter because of its input-output format and its ease to interpret (Laleman et al., 2013).

The total amount of used energy in the PV system and the estimation of energy production by the PV system over its life time are needed. The former is equal to 20,583 kWh (CED calculated to be equal 74,100 MJ), while the energy produced on an annual basis is 1,272.15 kWh (Arranz et al., submitted). Therefore, the EPBT is equal to 16.1 years. This is a value that falls higher than the range of data reported in literature (e.g., Battisti and Corrado, 2005; Vasilis et al., 2008; Tiwari et al., 2009; Desideri et al., 2012a; Proietti al., 2013), which report EPBT value ranges between 1 and 6 years, depending on the average site insolation and the installation type. However, if batteries are taken into account, the CED is equal to 21,611 kWh (77,800 MJ), increasing the EPBT to 16.9 years. Both the CED and the EPBT are consistent with values found in recent literature reporting results for PV systems equipped with batteries (see for example, García-Valverde et al., 2009; and Sharma and Tiwari, 2013).The system under study, with an estimated life-time of 25 years, will therefore generate almost 1.54 times the energy embodied (when considered without batteries) and almost 1.47 times the energy embodied during its life-time.

The total CO_{2eq} kg of the PV system is 5,510 kg and 5,322 kg with and without batteries respectively (based on the IPCC GWP 100a impact method). The CO_{2eq}PBT calculates the time required for the PV system to save the exact amount of CO_{2eq} emitted during its entire life cycle. The CO_{2eq}PBT is primarily dependant on the amount of kWh produced by the system, and the grid CO_{2eq} /kWh emission factor. The latter was calculated as 1.23 kg CO_{2eq}/kWh and 0.818 kg

CO_{2eq}/kWh for the Lebanese electricity mix with and without diesel gensets respectively. This means that the annual CO_{2eq} reduction is 1,567.75 kg/yr (1272.15 kWh x 1.23 kg CO_{2eq}/kWh), resulting in a 3.52 years CO_{2eq}PBT and 3.21 years CO_{2eq}PBT with and without batteries respectively. Using a similar approach, and considering the Lebanese electricity mix without diesel gensets, the CO_{2eq}PBT are 5.3 years and 5.11 years for the PV system with and without batteries. In both cases, the PV system will displace the embodied carbon dioxide during its life-time.

However, the outputs from the PV systems will be displacing electricity generated by the existing Lebanese supply system. Therefore, consequential LCA, which aims to describe how environmentally relevant flows will change in response to possible decisions (Curran et al., 2005), i.e., use of PV systems, is relevant. Another useful metric therefore is the total amount of CO_2 reduction that can be achieved from the use of the PV system. This will also allow for the proper evaluation of the environmental merits of the PV system over the current supply systems (García-Valverde et al., 2009). Considering that the estimated energy production of the photovoltaic system in 25 years is 31,803.75 kWh (ignoring annual degradation of PV output), and assuming that it replaces the same energy produced by the Lebanese supply system (assuming that it remains unchanged), the avoided emissions from the PV-PbA system are 37.84 and 24.74 tonnes of CO_2 when considering the current electricity mix with and without diesel gensets respectively. In the case of the PV system without batteries, the avoided emissions are 37.88 and 24.78 tonnes of CO_2 when considering the current electricity mix with and without diesel gensets respectively.

Table 6 provides a comparative assessment to where the studied PV systems stand in terms of the metrics used above, indicating that both systems (with and without batteries) do fall within the reported ranges.

Table 6. LCA results of mono-Si PV systems (adapted from Peng et al., 2013)

Location	Irradiation (kWh/m²/yr)	Module Efficiency (%)	Life time (yr)	Perf. ratio	EPBT (yrs)	GHG emissions (g CO_{2eq}/kWh)	Reference
UK	1,253	12.0	20	0.80	12.1	N/A	Wilson and Young, 1996
Japan	1,427	12.2	20	0.81	8.9	61	Kato et al., 1998
South-European	1,700	13.7	30	0.75	2.6	41	Alsema and de Wild-Scholten, 2005
South-European	1,700	14.0	30	0.75	2.1	35	Alsema et al., 2006
Switzerland	1,117	14.0	30	0.75	3.3	N/A	Jungbluth et al., 2007
South-European	1,700	14.0	30	0.75	1.75	30	de Wild-Scholten, 2009
China	1,702	N/A	N/A	0.78	2.5	50	Ito et al., 2010
South-European	1,700	14.0	N/A	0.75	1.8	30	Fthenakis et al., 2009

India*		N/A	30	0.55	18.9	N/A	Sharma and Tiwari, 2013
Lebanon	1,867[a]	13.1	25	0.58[a]	16.1	167	Present study
Lebanon - Simulation	1,867	13.1	25	0.76	8.6	89	Present study
Lebanon*	1,867[a]	13.1	25	0.58[a]	16.9	173	Present study
Lebanon-Simulation*	1,867	13.1	25	0.76	9.0	92	Present study

* These systems are equipped with batteries
[a] (Arranz et al., submitted)

5.6 Net Energy Ratio

The net energy ratio (NER) can be interpreted as the amount of energy that a technology can produce relative to the total amount of energy that was consumed, over the total life cycle, and is therefore an indication of its life-cycle energy efficiency (Desideri et al., 2012b; Laleman et al., 2013). The NER of both PV systems under study are 1.48 and 1.55 for the PV system with and without batteries (calculated by dividing the lifetime – 25 years – of the technology over the energy pay-back time). By definition, a technology with an NER higher than 1 is renewable.

6 Discussion and Conclusion

A life-cycle assessment of 1.8 kWp Photovoltaic system (both with and without PbA batteries) was conducted and its environmental attributes compared to the existing Lebanese electricity mix (both with and without diesel gensets). Of the various components of the PV, the module's impact was the highest, followed by the inverter, the batteries, the cabinet and the mounting structure respectively. This is consistent with a range of different similar studies, which report the module's impact being the highest. For example, Desideri et al. (2013), reports, using the Eco-Indicator99 impact assessment methodology, that the module production has the most significant part in most of the impact categories. Similar results are also reported in Zhong, et al. (2011). The PV module's relatively high total score is associated with the high environmental impact of the PV cell manufacturing process (Lamnatou and Chemisana, 2014). Of the various impact categories of the ReCiPe impact assessment method, human toxicity was ranked as the highest, followed by climate change human health impact. A similar result, using the ReCiPe methodology, was reported in Mohr et al. (2013) indicating that the highest 2 impact categories are damage to human health due to climate change and human toxicity. The PV system, even when equipped with storage systems, has shown that this addition would reduce the environmental burden per delivered output compared to the Lebanese electricity mix. The reduction is even more apparent when decentralised diesel gensets are taken into account.

The remaining metrics, of the PV system without batteries are comparable with values obtained elsewhere. Regarding the obtained GWP (0.0389 kg CO_{2eq}/kWh) value of the PV system, they fall within the values reported by de Wild-Scholten (2013) for various types of photovoltaic systems in the range of 0.02 to 0.081 kg CO_{2eq}/kWh. As shown in Table 6, the EPBT value (16.1-16.9 years) falls within the higher end of values reported in similar studies (see e.g., Alsema and de Wild-Scholten, 2005; Alsem et al., 2006; de Wild-Scholten, 2009; Ito et al., 2010). Though the irradiation is higher in Lebanon, the performance ratio of the PV system was lower than the rest (0.58) due to technical reasons described in Arranz et al. (submitted). In fact, the impact of the presence of blackouts, which forbids the export of solar power, is particularly acute in the schooling sector – the reason being that the summer months, that are endowed with the most solar irradiance (and therefore most expected PV generation) also coincide with limited educational activity, where often only the administration is resent and working for half the day. This in return, results in the power being curtailed in the absence of the grid. Thus, from a domestic-PV system perspective, this study fails to convey the full potential of the PV systems. Therefore, and to cater the results (EPBT and GHG emissions) to load profiles of e.g., households, recalculating the EPBT and GHG emissions using the theoretical performance ratio (0.76) yields EPBT and GHG emissions of 8.6 – 9 years and 89 – 92 gCO_{2eq}/kWh respectively (see simulated Lebanon-SE in Table 6). The typical average household residential electrical consumption in Lebanon is reported to be around 7,000 kWh/yr (Houri and Ibrahim-Korfali, 2005); therefore, the system, under its theoretical performance (2,386 kWh/yr) would have covered 34% of a household need in Lebanon – this means a 4 kW_p PV installation is required in order to satisfy the electricity need of a typical Lebanese household. The simulated results fit better into the several reported ranges in the literature. Gerbinet et al. (2014) reports a range of similar metrics (summarizing over 15 different studies) with various different types of photovoltaic systems and functional units. The reported results, ranges from 1.45 years to 7.4 years for EPBT and 30 to 800 gCO_{2eq}/kWh. Peng et al., (2013) reports a range of 2.1-12.1 years for EBPT. Sherwani et al. (2010) reviewed a number of PV LCA studies and has reported EPBT to be in the range of 3.2 – 15.5 years and GHG emissions in the range of 44-280 gCO_{2eq}/kWh for mono-crystalline PVs. The considerable differences are mainly caused by different factors, such as irradiation levels, module efficiencies, types of installations, manufacturing technologies and source of silicon feedstock, estimation methods (Peng, et al., 2013).

Comparing the environmental impacts of the electricity produced by the PV compared to the existing centralized mix as well as centralized mix with diesel gensets, the results indicate substantive environmental merits of the PV. The results using the ReCiPe impact assessment method's categories indicate reduced impacts for Human Health, Ecosystems and Resources categories in the order of 87%, 95% and 96% respectively when compared to the centralized electricity mix with diesel gensets, and 82%, 92%, 94% respectively when compared to the centralized electricity mix without diesel gensets. In this respect, the results of this study can be used for comparative analysis in various countries in the region – Jordan, Syria and the Palestinian Territories have similar profiles in terms of per-capita electricity consumption for similar levels of economic development, while in terms of national electricity mix, Lebanon (0.72 kg CO_2/kWh) exhibits similarities with Iraq, Saudi Arabia, Kuwait and Libya, with heavy reliance on oil-based fuels for their electricity generation, with energy intensity values of 0.64 kg CO_2/kWh, 0.76 kg CO_2/kWh, 0.87 kg CO_2/kWh and 0.87 kg CO_2/kWh respectively (El Khoury, 2012).

The results show that the PV systems can help produce a low carbon and reliable electricity supply for Lebanon. Moreover, with the inclusion of batteries, although the impacts are slightly increased, they still remain far below the current alternatives and produce a mechanism for delivering a low carbon and reliable system. These results can be applied not only to the Lebanese situation, but to any other similar areas.

The PV system under study was among the first installed microgenerators designed to cater, technically, to the Lebanese electricity grid. Trials targeted towards larger commercial and industrial PV applications are ongoing. In these trials, battery storage, which are prohibitively expensive, are replaced by a design to synchronize the PV systems to the existing diesel gensets when power from the utility is off, and to the national grid when power is on. Future PV LCA work should consider these systems in terms of their environmental merits.

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7 References

1. Abi Said, C. 2005. Electric energy and energy policy in Lebanon. Report. GNESD Project.
2. Albrecht, L. 2007. The future role of photovoltaics: a learning curve versus portfolio perspective. Energy Policy, 35, 2296-2304.
3. Ali, A., Negm, A., Bady, M. and Ibrahim, M. 2014. Moving towards an Egyptian national life cycle inventory database. International Journal of Life Cycle Assessment, 19 (8), 1551-1558.
4. Alsema, E.A. 1998. Energy requirements of thin-film solar cell modules – a review. Renewable and Sustainable Energy Reviews, 2 (4), 387-415.
5. Alsema, E.A. 2000. Energy pay-back time and CO_2 emissions of PV systems. Progress in Photovoltaics: Research and Applications, 8 (1), 17-25.
6. Alsema, E.A., and Nieuwlaar, E. 2000. Energy viability of photovoltaic systems. Energy Policy, 28, 999-1010.
7. Alsema, E.A., and Wild-Scholten, M.J. 2005. The real environmental impacts of crystalline silicon P modules: an analysis based on up-to-date manufacture data. Proceedings of the 20th European Photovoltaic Solar Energy Conference, Barcelona, 6-10 June, 2005.
8. Alsema, E.A., Wild-Scholten M.J., Fthenakis, V.M. 2006. Environmental impacts of PV electricity generation – a critical comparison of energy supply options. In: 21st European photovoltaic solar energy conference, September 2006, Dresden, Germany.
9. Arranz, P., Harajli, H., Kabakian, V., Nassab, C., Obeid, J., and Vallve, X. submitted. Techno-financial appraisal of roof-top photovoltaic (PV) systems in Lebanon. Submitted to Solar Energy on April 16th, 2015.
10. Battisti, R. and Corrado, A. 2005. Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. Energy, 30 (7), 952-967.
11. Bare, J.C., Hofstetter, P., Pennington, D.W., and Udo de Haes, H.A. 2000. Midpoints versus Endpoints: The Sacrifices and Benefits. International Journal of Life Cycle Assessment, 5 (6), 319-326.
12. Bravi, M., Coppola, F., Ciampalini, F., Pulselli, FM. 2007. Comparing renewable energies: estimating area requirement for biodiesel and photovoltaic solar energy. Energy and Sustainability, 105, 187-196.

13. Cantin, R., Mourtada, A., Guarracino, G., Adra, N., Nasser, N., and Maamari, F. 2007. Scenarios of application of energy certification procedure for residential buildings in Lebanon. Energy Policy, 35, 3167-3178.
14. Chaaban, F.B., and Ramadan, S. 1998. Baseline energy and electricity consumptions in Lebanon and opportunities for conservation. Energy Policy, 26, 487-493.
15. Chedid, R., Chaaban, F.B., Salameh, S. 2000. Policy analysis of greenhouse gas emissions: the case of the Lebanese electricity sector. Energy Conversion and Management, 42, 373-392.
16. Chedid, R., Ghaddar, N., Chaaban, F.B., Chehab, S., Mattar, T., 2001. Assessment of energy efficiency measures: the case of the Lebanese energy sector. International Journal of Energy Research, 25, 355-374.
17. Comair, F. 2009. Renewable energy profile for Lebanon. In Renewable energy in the Middle East and North Africa Region [Mason, M., Mor, A. (eds.)]. Springer Science and Business Media.
18. Curran, M.A., Mann, M., Norris, G. 2005. The international workshop on electricity data for life cycle inventories. Journal of Cleaner Production, 13 (8), 853-862.
19. Dagher, L. and I. Ruble. 2010. Challenges for CO_2 mitigation in the Lebanese electric-power sector. Energy Policy, 38, 912-918.
20. Desideri, U., Proietti, S., Zepparelli, F., Sdringola, P., and Bini, S. 2012a. Life Cycle Assessment of ground-mounted 1778 kWp photovoltaic plant and comparison with traditional energy production systems. Applied Energy, 97, 930-943.
21. Desideri, U., Proietti, S., Sdringola, P., Cinti, G., Curbis, F. 2012b. MCFC-based CO_2 Capture System for Small Scale CHP Plants. The International Journal of hydrogen Energy, 37, 19295-19303.
22. Desideri, U., Zepparelli, F., Morettini, V., Garroni, E. 2013. Comparative analysis of concentrating solar power and photovoltaic technologies: technical and environmental evaluations. Applied Energy, 102, 765-784.
23. de Wild-Scholten, M.J., 2009. Energy payback times of PV modules and systems. Workshop Photovoltaik-Modultechnik, Köln, 26-27 November, 2009.
24. de Wild-Scholten, M.J. 2013. Energy payback time and carbon footprint of commercial photovoltaic systems. Solar Energy Materials and Solar Cells, 119, 296-305.
25. Dong, Y.D., and Ng, S.T. 2014. Comparing the midpoint and endpoint approaches based on ReCiPe – a study of commercial buildings in Hong Kong. International Journal of Life Cycle Assessment, 19, 1409-1423.
26. Doumani, F.M. 2007. Integrated Management of East Mediterranean Coastlines: Northern Lebanon, short and medium term priority action program III. University of Balamand, Lebanon.
27. Durlinger,B., Reinders, A., Toxopeus, M. 2012. A comparative life cycle analysis of low power PV lighting products for rural areas in South East Asia. Renewable Energy, 41, 96-104.
28. El-Fadel, M., Chedid, R., Zeinati, M., Hmaidan, W. 2003. Mitigation energy-related GHG emissions through renewable energy. Renewable Energy, 28, 1257-1276.

29. El-Fadel, R.H., Hammond, G.P., Harajli, H.A., Jones, C.I., Kabakian, V.K., Winnett, A.B. 2010. The Lebanese electricity system in the context of sustainable development. Energy Policy, 38, 751-761.
30. El Khoury, G. 2012. Carbon footprint of electricity in the Middle East. Carbon Initiative. http://www.carboun.com/energy/carbon-footprint-of-electricity-in-the-middle-east/
31. El-Khoury, M., Nakad, Z., and Shatila, S. 2010. The assessment of wind power for electricity generation in Lebanon. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 32 (13), 1236-1247.
32. EPA 2006. Life Cycle Assessment: Principles and Practice. EPA, Cincinnati, (68CO2-067).
33. European Commission-Joint Research Centre – Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook – Recommendations for Life Cycle Impact Assessment in the European context. First edition November 2011. EUR 24571 EN. Luxemburg. Publications Office of the European Union; 2011.
34. Fardoun, F., Ibrahim, O., Younes, R., Louahlia-Gualous, H. 2012. Electricity of Lebanon: Problems and recommendations. Energy Procedia, 19, 310-320
35. Fthenakis, V., Kim, H.C., Held, M., Raugei, M., Krones, J. 2009. Update of PV energy payback times and life-cycle greenhouse gas emissions. In 24^{th} European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany.
36. García-Valverde, R., Miguel, C., Martínez-Béjar, R., and Urbina. A. 2009. Life Cycle Assessment Study of a 4.2 kW_p stand-alone photovoltaic system. Solar Energy, 83, 1434-1445.
37. GEF. 2011. Small decentralized renewable energy power generation: Lebanon. Project Identification Form (PIF). Retrieved from http://www.thegef.org/gef/sites/thegef.org/files/gef_prj_docs/GEFProjectDocuments/Climate%20Change/Lebanon%20-%20(4749)%20-%20Small%20Decentralized%20Renewable%20Energy%20Power%20Generat/PIF%20revised%209%20January%202012.pdf
38. Gerbinet, S., Belboom, S., Leonard, A. 2014. Life cycle analysis (LCA) of photovoltaic panels: A review. Renewable and Sustainable Energy Reviews, 38, 747-753.
39. Ghaddar, N., Mezher, T., Chedid, R., El-Fadel, M., Moukalled, F. 2005. Final report on Renewable Energies Technologies Contribution and Barriers to Poverty Alleviation in Jordan, Lebanon and Syria. "Renewable Energy Technology" Working Group, Global Network on Energy for Sustainable Development.
40. Goedkoop, M., Heijungs, R., Huijbegts, M., Schryver, A.D., Struijs, J., and Zelm, R.V. 2009. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, First edition (version 1.08). Report I: Characterisation. May 2013.
41. Goetzberger, A., and Hoffmann, V.U. 2005. Photovoltaic Solar Energy Generation. Springer-Verlag: Berlin Heidelberg.
42. Hamdan, H., Ghajar, R.F., and Chedid, R.B. 2012. A simulation model for reliability-based appraisal of an energy policy: The case of Lebanon. Energy Policy, 45, 293-303.

43. Harajli, H., Abou Jaoudeh, E., Obeid, J., Kodieh, W., and Harajli, M. 2011. Integrating wind energy into the Lebanese electricity system: Preliminary analysis on capacity credit and economic performance. World Engineers' Convention, Geneva, 4-9 September, 2011.

44. Heller, M., Keoleian, G., Mann, M. Volk, T. 2004. Life cycle energy and environmental benefits of generating electricity from willow biomass. Renewable Energy, 29 (7), 1023-1042.

45. Houri, A., and Ibrahim-Korfali, S. 2005. Residential energy consumption patterns: the case of Lebanon. International Journal of Energy Research, 29, 755-766.

46. Huijbregts, M.A.J., Rombouts, L.J.A., Hellweg, S., Frischknecht, R., Hendriks, A.J., Van de Meent, D., Ragas, A.M.J., Reijnders, L., Struijs, J. 2006. Is cumulative fossil energy demand a useful indicator for the environmental performance of products? Environmental Science and Technology, 40 (3), 641-648.

47. IARC, Press Release No 213. 2012. IARC: Diesel Engine Exhaust Carcinogenic. http://www.iarc.fr/en/media-centre/pr/2012/pdfs/pr213_E.pdf

48. IPCC. 2007: Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Mayer 9eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 851 pp.

49. Ito, M., Komoto, K., Kurokawa, K. 2010. Life-cycle analyses of very-large scale PV systems using six types of PV modules. Current Applied Physics, 10 (2), S271-S273.

50. Jungbluth, N., Dones, R., Frischknecht, R., 2007. Life cycle assessment of photovoltaics: update of the ecoinvent database. 14th SETAC LCA case studies Symposium. Giteborg, 2007.

51. Jungbluth, N., Stucki, M. and Frischknecht, R. 2009. Photovoltaics. In Dones, R. (Ed.) et al., Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergliech von energiesystemen und den Einbezug von energiesystemen in Ökobilanzen für die Schweiz. Ecoinvent report No. 6-XII, Swiss Center for Life Cycle Inventories, Dübendorf, CH, 2009.

52. Kato, K., Murata, A., Sakuta, K. 1998. Energy pay-back time and life-cycle CO_2 emission of residential PV power system with silicon PV module. Progress in Photovoltaics Research and Applications, 6, 105-115.

53. Kazmerski, L. 2006. Solar photovoltaics R&D at the tipping point: a 2005 technology overview. Journal of Electron Spectroscopy and Related Phenomena, 150, 105-135.

54. Laleman, R., Albrecht, J., and Dewulf, J. 2013. Comparing various indicators for the LCA of residential photovoltaic systems. In Sing et al. (eds.) Life Cycle Assessment of Renewable Energy Sources, Green Energy and Technology. Springer-Verlag London.

55. Lamnatou, Chr., and Chemisana, D. 2014. Photocoltaic-green Roofs: A Life Cycle Assessment Approach with Emphasis on Warm Months of Mediterranean climate. Journal of Cleaner Production, 72, 57-75.

56. Lechon, Y., de la Rua, C., Saez, R. 2008. Life cycle environmental impacts of electricity production by solarthermal power plants in Spain. Journal of Solar Energy Engineering – ASME, 130 (2), 0210121- 0210127.

57. Majeau-Bettez, G., Hawkins, T. R., and Strømman, A. H. 2011. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. Environmental Science and Technology, 45 (10), 4548-4554.
58. McManus, M. C. 2012. Environmental consequences of the use of batteries in low carbon systems: the impact of battery production. Applied Energy, 93, 288-295.
59. Menoufi, K., Chemisana, D., and Rosell, J.L. 2013. Life Cycle Assessment of a Building Integrated Concentrated Photovoltaic Scheme. Applied Energy, 111, 505-514.
60. Ministry of Energy and Water (MoEW). 2010. Policy Paper for the Electricity Sector. Beirut, Lebanon.
61. Ministry of Environment – UNDP – ECODIT. 2011. State and trends of the Lebanese environment [El-Jisr, K. (ed)]. Beirut, Lebanon.
62. Mohr, N., Meijer, A.,Huijbregts, MAJ, Reijnders, L. 2009. Environmental impact of thin-film GaInP/GaAs and multicrystalline silicon solar modules produced with solar electricity. International Journal of Life Cycle Assessment, 14 (3), 225-235.
63. Mohr, N., Meijer, A.,Huijbregts, MAJ, Reijnders, L. 2013. Environmental life cycle assessment of roof-integrated flexible amorphous silicon/nanocrystalline silicon solar cell laminate. Progress in Photovoltaics: Research and Applications, 21 (4), 802-815.
64. Pehnt, M. 2006. Dynamic life cycle assessment (LCA) of renewable energy technologies. Renewable Energy, 31, 55-71.
65. Peng, J., Lu, L., Yang, H. 2013. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renewable and Sustainable Energy Reviews, 19, 255-274.
66. Proietti, S., Sdringola, P., Desideri, U., Zepparelli, F., Masciarelli, F., Castellani. F. 2013. Life Cycle Assessment of a Passive House in a Seismic Temperate Zone. Energy and Buildings, 64, 463-472.
67. Rehman, S., and Al-Hadhrami, L.M. 2010. Study of a solar PV-diesel-battery hybrid power system for a remotely located population near Rafha, Saudi Arabia. Energy, 35 (12), 4986-4995.
68. REN21. 2014. Renewables 2014 Global status report. Paris REN21 Secretariat.
69. Ruble, I., and P. Nader. Transforming shortcomings into opportunities: can market incentives solve Lebanon's energy crisis? Energy Policy, 39, 2467-2474.
70. SETAC. 1990. Technical framework for life-cycle assessments. SETAC and SETAC Foundation, Washington, DC.
71. Sehlstedt, M., Forsberg, B., Westerholm, R., Boman, C., Sandtrom, T. 2007. The role of particle size and chemical composition for health risks of exposure to traffic related aerosols – a review of the current literature. http://www20.vv.se/fud-resultat/Publikationer_000301_000400/Publikation_000310/EMFO%20litteraturstudie%20-Trafikrelaterade%20partiklar%20och%20h%C3%A4lsoeffekter%20-%20Final%20report%20071212.pdf
72. Sharma, R. and Tiwari, G.N. 2013. Life cycle assessment of stand-along photovoltaic (SAPV) system under on-field conditions of New Delhi, India. Energy Policy, 63, 272-282.

73. Sherwani, A.F., Usmani, J.A., Varun. 2010. Life cycle assessment of solar PV based electricity generation systems: a review. Renewable and Sustainable Energy Reviews, 14, 540-544.
74. Tharumarajah, A., and Grant, T. 2002. Australian national life cycle inventory database: moving forward. Proceedings of the 5th ALCAS Conference, Melbourne, Australia, pp 1-9.
75. Tiwari, A., Barnwal, P., Sandhu, G.S., Sodha, M.S. 2009. Energy metrics analysis of hybrid – photovoltaic (PV) modules. Applied Energy, 86 (12), 2615-2625.
76. Vasilis, M., Fthenakis, V., Kim, H.C., Alsema, E.A. 2008. Emissions from photovoltaic life cycle. Environmental Science and Technology, 42 (6), 2168-2174.
77. Wilson, R., and Young, A. 1996. The embodied energy payback period of photovoltaic installations applied to buildings in the UK. Building and Environment, 31 (4), 299-305.
78. World Bank. 2008. Republic of Lebanon – Electricity Sector Public Expenditure Review. Report No. 41421-LB. Washington DC: The World Bank.
79. World Bank. 2013. Lebanon – Economic and social impact assessment of the Syrian conflict. Washington DC; World Bank. http://documents.worldbank.org/curated/en/201economic-social-impact-assessment-syrian-conflict
80. Yu, Y., Wang, X., Wang, D., Huang, K., Wang, L., Bao, L. Wu, F. 2012. Environmental characteristics comparison of Li-ion batteries and Ni-MH batteries under the uncertainty of cycle performance. Journal of Hazardous Materials, 229-230, 455-460.
81. Yung, P., Lam. K.C., Yu, C. 2013. An audit of life cycle energy analyses of buildings. Habitat International, 39, 43-54.
82. Zhong, Z.W., Song, B., Loh, P.E. 2011. LCAs of a polycrystalline photovoltaic module and a wind turbine. Renewable Energy, 36 (8), 2227-2237.