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Commercial-scale hybrid solar photovoltaic - diesel systems in select Arab countries with weak grids: An integrated appraisal

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Highlights

- *Integrated appraisal of solar PV systems in Palestine, Lebanon and Iraq is executed*
- *Life-cycle impact assessment methods are used for monetization*
- *Energy, environmental and economic results positive for all three countries*
- *Financial appraisal results are positive for Lebanon and Palestine, yet not Iraq*
- *Policy recommendation target tariff reforms, net metering, and soft loans*

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Abstract

Solar photovoltaic (PV) - diesel hybrid systems are effective solutions for sustainable energy transition in countries where utility grids are intermittent. An 'integrated appraisal' of a solar (PV) diesel is carried out to assess its overall energetic, environmental, financial and economic performance. The study carries out the analysis of hybridized solar photovoltaic energy using first-hand data and information collected from the Palestinian, Lebanese and Iraqi commercial and/or industrial sectors, adopting several scenarios of tariff and diesel fuel prices, capital costs assumptions, solar PV curtailment, and values for environmental damage adopted from life-cycle impact assessment methods that allow for monetization and are globally valid. Results show that hybrid PV-diesel systems have largely beneficial energy, environmental and economic performances in all three countries, whereas their financial performance are also positive for Palestine and Lebanon, however less promising in Iraq, mainly due Iraq's heavily subsidized electricity tariff. The study concludes with policy recommendations focused on promoting solar

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PV in the commercial and/or industrial sectors, namely; the gradual phasing-out of fossil fuel subsidies, the effective execution of net-metering, the provision of subsidized sustainable energy loans, and carefully designed energy management systems.

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Keywords*: Hybrid solar PV-diesel, cost-benefit analysis, Life-cycle assessment, Arab countries*

1. Introduction

Since the early 1990s, access to electricity has steadily improved globally, rising from over 71.3% of global population with 'access to electricity' to over 87.3% in 2016 (World Bank data, 2018). However, 'access to electricity' does not necessarily equate to reliable and affordable electricity provision. In Lebanon, Iraq, and Palestine, 'access to electricity' is indicated to be 100% in 2016 (World Bank data, 2018), however Lebanon and Iraq suffer from structured blackouts that average at least 6 hours per day in Lebanon (MEW, 2010; El-Fadel *et al*., 2010; Dagher & Ruble, 2010; Dagher & Harajli, 2015; Kabakian *et al*., 2015), and 10 hours per day in Iraq (Mills, 2018). In Palestine, the situation is complicated by the fact that Palestine is divided into two isolated geographic regions; the West Bank and Gaza, and dependency on imports of electricity stand at 89%, while fuel import dependency at 100% (Juaidi *et al*., 2016). In the West Bank, power availability is indicated to be approximately 97.2% (MAS, 2014), while in Gaza electricity is only available for 8 hours per day on average, and declines further in the summer period (World Bank, 2017a). All three countries rely, to varying extent, on distributed diesel generators to recompense this loss. In Baghdad alone, for example, there are 150,000 neighborhood diesel generators (Chaichan & Kazem, 2018).

For the commercial (and industrial) sector, an opportunity is present in the form of hybrid solar photovoltaic (PV) - diesel (hence forth termed 'hybrid solar-diesel') systems to reduce the reliance and costs associated with electricity supply from the combined respective national utilities and distributed diesel generators. However, appraising the hybrid solar-diesel system's costs and benefits and the extent of their contribution to sustainable development in the selected countries requires evaluation of these systems' performances in real-life situations through an 'integrated perspective'. The 'integrated appraisal' methodology has been advocated by Allen *et al*., (2008a), Hammond & Winnett (2006); Allen *et al.*, (2010), and Fadel *et al*., (2010), combining energy analysis, environmental life-cycle assessment, and financial and economic appraisal. This research builds on these earlier studies by more clearly distinguishing between the use and the results of financial appraisal and economic cost-benefit analysis (CBA), by utilizing a newer method for integrating life-cycle impact assessment outcomes into the CBA, and by implementing the 'integrated appraisal' approach on hybrid solar-diesel systems in three select Middle East countries; Iraq, Lebanon, and Palestine.

Several studies related to technical, financial and/or environmental performance of hybrid renewable energy (RE) and diesel systems have been assessed in the literature. Many studies (for example, Rehman & Al Hadrami, 2010; Diab *et al*., 2016; Yilmaz & Dincer, 2017; Halabi *et al*. 2017; Yahiaoui *et al.*, 2016; and Aziz *et al*., 2019) utilize optimization techniques through the software HOMER to find the least-cost (defined by 'net present costs') configurations of specifically combined RE technologies (e.g. wind and/or solar PV, diesel gensets, with or without battery storage). Such simulations apply financial appraisal optimization (based on net present costs and levelised costs of energy) on specific hybrid technology combinations, as well provide environmental benefits based on in-built HOMER values of displaced diesel and/or electricity, targeting specifically carbon monoxide, carbon dioxide, sulfur dioxide, nitrogen oxides, particulate matter, and unburned hydrocarbons. Other studies employ different modeling and simulation techniques. Atieh *et al.* (2018) optimizes for the lowest cost and lowest CO_2 emissions of a solar-storage-diesel for a Tunisian case study. Charfi *et al*. (2016) models the financial performance, among other objectives, of diesel systems, solar with storage, and solar-diesel-storage for cases in Tunisia, Saudi Arabia, and Jordan. Mahmoud and Ibrik (2006) and Omar and Mahmoud (2018) calculate the net present value (NPV), Internal Rate of Return (IRR), the levelised cost of energy (LCOE), and the payback period for a hybrid 24.6 kW solar PV system and for the residential sector, respectively. Omar & Mahmoud (2018) additionally provide the quantity of avoided carbon emissions. It was not part of the scope of these studies to differentiate between financial appraisal and economic cost-benefit analysis, and to monetize environmental benefits through the use of life-cycle assessment. To this regard, the present paper attempts to add value through the appraisal of all three elements in the overall evaluation of the hybrid solar-diesel systems.

The remainder of this paper is organized as follows: Sub-sections 1.1-1.3 summarize the current status of the electricity sectors, distributed energy, and solar PV technology in the three select countries, respectively. Section 2 provides the methodology and data used. Section 3 provides the results and discussion on the results. Section 4 presents the overall conclusion and policy recommendations.

1.1 Status of the select countries' electricity sectors

The Lebanese, Iraqi, and Palestinian power systems have striking similarities in terms of performance. All countries do not have the sufficient power capacity to meet the electricity demand and are thus subjected to rampant blackouts. Lebanon has approximately 2,066 MW of power installed, whereas average demand is 2,900 MW and can reach up to 3,400 MW in summer (GoL, 2018). In Iraq, power capacity supply in 2017 was approximately 11,300 MW, whereas electricity demand was 17,000 MW (Jafar, 2018). In Palestine, the electricity sector is heavily dependent on imports, as more than 97% of the West Bank's electricity needs are imported while 50% of the available electricity for Gaza is imported (European Parliament, 2016). With respect to transmission and distribution, the countries also suffer from sub-standard quality and performance. In Lebanon, technical losses associated with the transmission and distribution of power amount to 13%, whereas non-technical losses (i.e. uncollected bills and illegal connections) add a further 18% loss of power from a financial payback perspective (Lebanon CoM, 2018). In Iraq, losses in the transmission and distribution network is indicated to be approximately 32% (Yasen, 2016). This is accompanied by high theft of electricity on the demand side resulting from high levels of unmetered consumers, and absence of effective billing systems including high levels of uncollected or under-collected billed electricity (Al-Rikabi, 2017). In Palestine, the grid suffers excessive losses, reaching 22% in the distribution network (Arab Union of Electricity, 2016).

Lebanon projects an annual electricity demand increase of 5% (GoL, 2018), Iraq 7% (Jafar, 2018), and Palestine 3.5% (World Bank, 2017b). The energy situation of these countries is one of the key impediments of growth in the commercial and industrial sectors. In Lebanon, a recent World Bank survey (World Bank, 2013) shows that 84.6% of firms own a diesel generator to accommodate for electricity outages. This causes heavy financial burdens on companies to operate in Lebanon. It has been estimated by (Bouri & El Assad, 2016) that the economic cost of power cuts is approximately US$ 4.65 billion yearly or around 10% of GDP. In Iraq the situation is similar with 83.7% of firms owning a diesel generator (World Bank, 2011). The economic cost of power cuts in Iraq stands at approximately US$ 40 billion a year (ESCWA, 2017), equivalent to 23% of GDP. In Gaza, reliable supply of electricity is one of the top constraints for doing business with firms reporting an estimated 22% of losses in sales due to power outages (World Bank, 2014).

1.2 Existing distributed renewable electricity policy

Lebanon, Iraq and Palestine have established renewable energy targets. Lebanon has committed to reach 15% unconditional or 20% conditional renewable energy (RE) target by 2030 under its INDC commitments (RoL, 2015). The Government of Iraq committed a 1% RE target by 2020 (excluding hydro), and Palestine has indicated a target of 10% renewable electricity supply by 2020 (RCREEE & UNDP, 2016).

Various generation-based and/or investment-based policies for supporting the uptake of renewable energy at the distributed level are in place in Lebanon and Palestine, however are, as of 2018, lacking in Iraq. In Palestine, feed-in tariffs were established under the 'Palestinian Solar Initiative' approved by the Palestinian cabinet in 2012 (Omar and Mahmoud, 2018), yet only for the first 5 MW of solar project in the residential sector (CES-MED, 2015). Net metering has superseded the feed-in tariff initiative in Palestine, and some applications will be subjected to soft loans and/or investment-based subsidies through various schemes such as the Noor Palestine Solar Program (RCREEE & UNDP, 2016; Palestine Investment Fund, 2018). Furthermore, all custom duties are removed for renewable energy systems in Palestine (PIPA, undated). In Lebanon, a combination of support schemes are available. Net metering is enabled via a board decision from the national utility, EDL, while soft loans are present via several schemes such as National Energy Efficiency and Renewable Energy Action Plan (NEEREA) (MEW & LCEC, 2016), LEEREFF[2], EBRD GEFF[3], and import customs are removed on certain renewable energy items (UNDP DREG, 2018). Furthermore, several investment-focused partial and full grant schemes have been initiated since 2009 by the UNDP, supporting more than 5 MW of distributed solar projects.

In Iraq, the Ministry of Energy has established a Regulatory Authority and a Center for Renewable Energy and Environment (CREE) in 2012 (UNDP, 2014). CREE is tasked with the promotion of renewable energy, including supporting initiatives such as feed-in tariffs, net-metering, and tax exemptions (UNDP, 2014), however to date no such mechanisms have been established by CREE (RCREEE & UNDP, 2016). Available support for distributed renewable energy can be found under the Investment Law No. 13 of 2006, which provides, among other things, customs exemptions for imported renewable energy equipment and tax exemptions for 10 years of a 'projects' lifetime' and through Law No. 3 dated 1998, whereby any project in free zones in Iraq will be subject to full tax exemptions over their entire lifetime (Mayer Brown *et al.*, 2015).

1.3 Status of Solar PV applications

Solar PV power has been growing globally at an unprecedented rate over the past ten years, averaging an equivalent annual growth rate of approximately 55% from 2007 to 2017 (REN21,

[2] See https://leereff.com/
[3] See https://ebrdgeff.com/lebanon/

2018). In 2017, solar PV accounted for relatively most of the installed renewable energy capacity, taking a 55% share, and are now delivering 1.9% of the global total power supply (REN21, 2018). In Lebanon, solar PV power effectively began to pick up pace in 2010, following several demonstration and small-scale projects undertaken by the UNDP-CEDRO project[4]. From 2010 to the end of 2017, solar PV power capacity rose from approximately 0.35 MWp to over 35 MWp, averaging an annual equivalent growth rate of 100% (UNDP DREG, 2018). Similar trends can be observed for Iraq and Palestine. In Iraq, solar PV started to pick up in 2013, and by the end of 2017 there are approximate 37 MW installed (IRENA, 2018). In Palestine, solar PV installation began in 2012, and by the end of 2017 there are 35 MW installed (IRENA, 2018). These installations have to cater for unreliable power grids, subject to blackouts and brownouts. The overall performance and benefits of such systems are thus restrained by technical challenges of integration.

2 Methodology and data

The overall performance of the solar PV-diesel system is assessed through an integrated appraisal. An integrated approach is adopted as specified in Hammond and Winnett (2006), and applied in Allen *et al*. (2008a) for micro-generators in the UK, Hammond *et al*. (2012) for building-integrated photovoltaic (BIPV) systems in the UK, and El-Fadel *et al*., (2010), for the Lebanese electricity system. These studies employed energy analysis, environmental life-cycle assessment (LCA), financial appraisal and economic cost-benefit analysis to partially measure sustainability, as outlined in Figure 1. Additionally, indicators for social development could be used, such as employment potential and social acceptance, however they have not been

[4] UNDP-CEDRO: www.cedro-undp.org

integrated in this present paper, given that alternative non-monetary techniques, such as multi-criteria analysis, would need to be used whereas the focus of this paper is on cost-benefit analysis. Capturing the various environmental, social, and economic attributes of energy technologies is a way to encapsulate the options' sustainability performance. In the present study, the 'Stepwise2006' life-cycle impact assessment (LCIA) method used (discussed in Section 2.2) allows for the integration of the full life-cycle assessment (LCA) outcomes into the economic cost-benefit analysis.

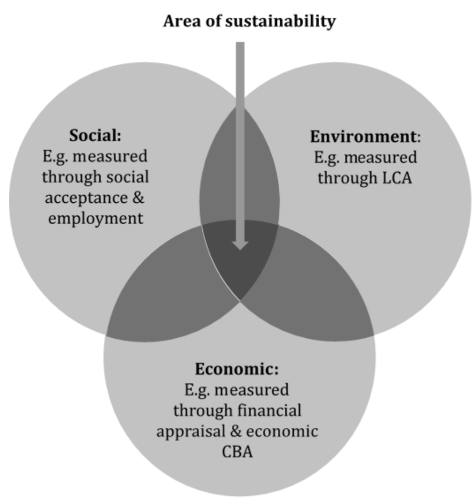


Figure 1. Sustainable development Venn diagram and related evaluation tools and indicators (adapted from Allen *et al*., 2008a)

The added value of this paper is the use of the integrated appraisal for the first time to evaluate hybrid solar-diesel systems in the three select Arab countries using recent (2018) data and information. The analysis models the actual interfaces of the solar PV system's performance with its energy, environmental, financial, and economic outcomes. The study does not include the social implications of the solar PV systems, however several studies have ascertained the relative advantage of solar PV systems' social benefits through the use of alternative methodologies, namely multi-criteria analysis, using social indicators such as job creation, conflict generation or reduction (in terms of characteristics of energy systems that trigger conflicts), and security of supply (for example, Kis *et al.*, 2018; NEEDS, 2008 & 2009).

2.1 Energy analysis

Energy analysis is used to determine the 'energy payback time' of the solar PV system, integrated into an existing diesel genset. An initial energy outlay, known as 'embodied energy' is required to produce it (Hammond *et al*. 2012). The embodied energy can be compared with the energy (strictly power output or electricity) 'generated' to determine a payback period.

Two different payback periods are utilized in this study; the first is a 'simple payback period' (sEPBT) (Eq. 1), where the embodied energy of production is directly compared with the quantity of electricity generated by the solar PV system (Allen *et al.,* 2010; Hammond *et al.*, 2012). In the case of the solar PV-diesel installations, this would include the deduction of any solar PV power output lost due to solar PV curtailment.

$$sEPBT = \frac{E_{input}\,(MJ)}{E_{output}\,(MJ/yr)} \qquad \text{Eq.1}$$

E_{input} is the primary energy input of the complete manufacturing, transportation, installation, operation and maintenance, and disposal of the entire solar PV system, including the modules, inverters, support structures, cabling and so forth. E_{output} is the annual primary energy generated from the PV unit.

The second payback period is called a 'displaced energy payback period' (dEPBT) (Hammond *et al.*, 2012). This considers that electricity generated by the solar PV system displaces both fuel use and capacity (on a case by case basis) of diesel gensets, and electricity from the national utility, and is calculated as Eq. (2).

$$dEPBT = \frac{sEPBT}{Overall\ efficiency\ of\ the\ electricity\ mix} \quad \text{Eq.2}$$

(Adapted from Peng et al., 2013; Wu et al., 2017, & Bhandari et al., 2015)

The 'overall efficiency of the electricity mix' is defined as the quantity of the primary energy (including all upstream activities) required to support all activities necessary to deliver one unit of electricity to the consumer (Hammond *et al.*, 2012). For this the gross energy requirement' (GER) (Allen *et al.*, 2008b), which is the ratio of the embodied energy ($MJ_{embodied}$) (using CED V1.10) over the generated energy ($MJ_{generated}$), is calculated.

2.2 Life-cycle assessment

Life cycle assessment (LCA) is used to compare and analyze the environmental impacts of products and services through the identification of 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 (Kabakian *et al.*, 2015) based on the ISO 14040 and ISO 14044 (ISO, 2006). An environmental LCA is conducted to illustrate the environmental performance of the diesel gensets (one system used for all three countries), the full multi-crystalline-silicon photovoltaic (PV multi-Si) panels (using country-specific yields), and the national grids of Lebanon, Iraq and Palestine. The SimaPro Software (V8.5.2.0) is used to complete the LCA along with the Ecoinvent V.3.4 database (Wernet *et al*., 2016; Steubing *et al.*, 2016). The functional unit chosen is 1 kWh. The national grids for Lebanon and Iraq are used directly from the Ecoinvent database, while the Palestinian grid is constructed using information from Ismail *et al.*, (2012), the World Bank (2016) and from PENRA (2017). The life cycle impact assessment method 'Stepwise2006' (V1.05.3) (Weidema, 2009) is selected in this analysis given its 'globally valid' application and to facilitate the monetization of the impacts (Pizzol *et al*., 2015).

The Stepwise2006 method (Weidema, 2009) monetizes a wide range of environmental impacts, enhancing the applicability and practicability of cost-benefit analyses (Nguyen *et al*., 2016). It calculates characterized results at midpoint level (e.g., global warming, acidification, eutrophication, human toxicity, eco-toxicity, non-renewable energy, etc.) by combining the characterization models from two life-cycle assessment methods, the Impact Assessment of Chemical Toxics (IMPACT2002+) and the Environmental Development of Industrial Products (EDIP2003) methods. The Impact2002 method (Jolliet *et al*., 2003) defines 15 mid-point categories including carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic eco-toxicity, terrestrial eco-toxicity, terrestrial acidification/nitrification, land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy and mineral extraction, all of which are connected to the inventory results. These mid-point categories are then structured into 4 damage categories: human health (including carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, and respiratory organics mid-points), ecosystem quality (including aquatic eco-toxicity, terrestrial eco-toxicity, terrestrial acidification/nitrification, and land occupation mid-points), climate change (including global warming mid-point), and the resources depletion (including non-renewable energy and mineral extraction mid-points). The EDIP2003 (Hauschild & Potting, 2005), which is a mid-point based assessment method, includes the following categories: acidification, climate change, eco-toxicity (in continental water, in marine water, and in soil), eutrophication (aquatic eutrophication, terrestrial eutrophication), human toxicity (via air, via soil, via water), ozone layer depletion, and photochemical oxidation (photochemical ozone formation – human health, photochemical ozone formation – vegetation). The Stepwise2006 method further combines the mid-points of Impact 2002+ (V2.1) and EDIP 2003 with small modifications into three damage categories (Human Health, Ecosystem Quality and Resource Productivity), and it allows normalization of data by monetization expressed in Euro, thus calculating potential socioeconomic cost of environmental externalities (Saxe *et al.*, 2018).

Due to recent concerns on climate change and global warming, the carbon footprint is one of the most common currently employed environmental indicators used to evaluate the environmental impacts associated with a process or a product (Grilo *et al.*, 2018). The impact assessment method selected herein is the IPCC 2013 GWP100a (V1.03), which is based on the Global Warming Potential (GWP) conversion factors published by the Intergovernmental Panel on Climate Change (IPCC, 2013). GWP can be defined as "[…] the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas" (Houghton *et al*., 1990), being a measure of the relative radiative effect of a given substance compared to another (in this case CO_2), and integrated over a chosen time horizon. The environmental impact is expressed in kg CO_2-equivalent (kg CO_2-eq, or carbon footprint) over a time horizon of 100 years (IPCC, 2013), which is long enough to assess the cumulative effects of GHG. The Cumulative Energy Demand (CED), volume V1.10, impact assessment method (Frischknecht *et al.*, 2003) is used to evaluate the CED, which is expressed in MJ. The CED is the sum of all energy sources, including the natural non-renewable and renewable resources extracted directly from the Earth.

2.3 Financial appraisal and economic assessment

Financial appraisal (FA) and economic assessment (EA) are two types of methods that can be employed to assess the private (FA) and society-wide (EA) costs and benefits of deploying solar PV-diesel applications. The methods are well established in the literature (for example, see Campbell and Brown, 2003, and Boardman *et al*., 2006) and have been used extensively to evaluate sustainable energy technologies. The evaluations either adopt financial appraisal techniques (for example, Schmid & Hoffmann, 2004; Mahmoud and Ibrik, 2006; Rehman & Al Hadrami, 2010; Diab *et al*., 2016; Charfi *et al*., 2016; Yilmaz & Dincer, 2017; Halabi *et al*. 2017;

Yahiaoui *et al.*, 2016; Atieh *et al.*, 2018; Omar & Mahmoud, 2018; Aziz *et al.*, 2019) which rely on cost optimizations using HOMER or other software or methods to calculate net present costs, levelised cost of energy or other similar indicators, or economic evaluations, which include environmental externalities (for example, see the CASES project[5], and Kis *et al.*, 2018), or a combination of financial and economic appraisal (Hammond *et al.*, 2012; Allen *et al.*, 2008a; Allen *et al.*, 2008b; Allen *et al.*, 2010). The results are expressed in the net present value (NPV) for both the FA and the EA, independently, while additional indicators of the internal rate of return (IRR), the dynamic payback period (DPP), and the levelised cost of energy (LCOE - to allow for comparability between technologies) are employed for the FA only. We use equations 3 and 4 to calculate the NPV and the LCOE, respectively.

$$NPV = -C_0 + \sum_{t=1}^{t} \frac{R_t}{(1+i)^t}$$

Equation 3. NPV

$$LCOE = C_0 + \left(\frac{\sum_{t=1}^{t} \frac{A_t}{(1+r)^t}}{\sum_{t=1}^{t} \frac{E_t}{(1+r)^t}} \right)$$

Equation 4. LCOE

Where:

C_0: Initial capital expenditure on the solar PV system

R_t: Net revenue in year t, (equal to electricity tariff rates + displaced marginal cost of back-up generation – operation and maintenance (O&M) of solar PV system).

$A_{t:}$ O&M cost in year t

$E_{t:}$ Energy production in year t

i: discount rate (see section 2.4)

t: Year of operation

[5] CASES Project: http://www.feem-project.net/cases/

The IRR is calculated through an iterative process by solving for 'i' to equate the NPV result to zero and the DPP is calculated by solving for 'n' when other parameters yield a NPV of zero. The project lifetime selected is 25 years, accounting for the design lifetime of the solar PV systems.

Monte-Carlo simulations are used to calculate the NPV, DPP, and the IRR of the different hybrid PV-diesel-utility systems in the selected countries. Given that there is a range of values for capital costs, operation and maintenance costs, curtailment percentages, and energy price increase scenarios, Monte-Carlo simulations can better capture the range of the uncertainties, test the impact of variability and identify the most important parameters affecting profitability (Chanwoong & Juneseuk, 2014; Byrne *et al*., 2017).

The problem with economic evaluation is the monetization of environmental and social impacts. As aforementioned, evaluating social impacts would merit alternative methods, such as multi-criteria analysis. For environmental impacts, they can be site-specific and therefore require extensive local assessments or global, such as from greenhouse gas emissions, and therefore global values can be adopted from the literature. Our research attempts to outline the implications of the hybrid solar-diesel system taking into account either the complete 'local' context (through the Stepwise 2006 LCIA), or through focusing only on the globally valid environmental impacts (through the use of the social cost of carbon estimates). However, even global pollutants such as the social cost of carbon (SCC) are confronted with many uncertainties and varying assumptions and the calculated values range from negative (i.e., positive overall global impacts) to costs of over $1,800 per tonne of emitted carbon (Tol, 2011). This study thus assumes two values adopted from Nordhaus (2017) for the SCC, a baseline value of $40 per tonne of carbon dioxide (2018 value), and $141 per tonne of carbon dioxide (2018 value), which assumes temperature increase is constrained, on average, to 2.5^{o}C.

The conversion of life-cycle impact assessment outcomes into monetary values that can be used in the cost-benefit analysis is an important step to deliberate to achieve a more thorough economic analysis that integrates environmental externalities. This consideration is tackled in the literature in the form of using monetary valuation in the weighting phase of LCA (Finnveden *et al.*, 2006; Ahlroth *et al.*, 2011; Huppes *et al.*, 2012; Ahlroth, 2014; Pizzol *et al.*, 2015; Nguyen *et al.*, 2016; Huysegoms *et al.*, 2018). Various life-cycle impact assessment (LCIA) methods have been established to this end, most notably Ecotax 2002 and Ecovalue08 (mostly restricted to inhabitants of Sweden), LIME (restricted to Japanese inhabitants), EPS2000 (restricted to OECD countries' inhabitants), Eco-costs99 (restricted to European inhabitants) (Ahlroth, 2014; Finnveden *et al.*, 2006; Huysegoms, 2018) and Stepwise2006 (European focused yet values are applicable on a global scale) (Weidema, 2009; Weidema, 2014; Pizzol *et al.*, 2015). LCA impacts have a high level of 'abstraction', meaning that they do not refer to specific situations but are generalizable because they account for 'potential' rather than 'actual impacts', and emissions 'from different processes and activities, as well as their impacts, are aggregated over space and time' (Pizzol *et al.*, 2015). Extending this fact to economic valuation means that the impacts identified through the LCA and monetized through the LCIA Stepwise2006 method are likewise to be considered as 'potential' economic impacts.

The values of Stepwise2006 are based on 2003 values and in Euros. The analysis applies the effective exchange rate of the time (from Euros to US dollars) and inflate these values to the baseline date of 2018. The same is applied to the estimates of the social cost of carbon adopted from Nordhaus (2017) to estimate the impact of climate change only. The use of Stepwise2006 aims for a more complete evaluation of the environmental externalities involved, albeit with relatively higher uncertainty, whereas the use of the IPCC 2013 GWP100a LCIA method and the accompanying assumptions on the value of the SCC aims for less relative uncertainty in the EA values obtained at the expense of relatively more completeness.

2.4 Data

The data required to undertake the 'integrated appraisal' task in the three select countries was acquired from various published sources, communications with energy specialists and/or centers in the respective countries, actual information collected from recent solar-PV diesel tendering rounds and actual logged data of solar PV performance in several implemented sites. The values selected reflect the best current available knowledge on the system and economic calculation parameters.

Input data on turn-key capital costs are shown in Table 1, retrieved from actual information from implementations of solar-diesel systems in each of the three respective countries. Turn-key capital costs for the solar system are differentiated in the financial appraisal and the economic cost-benefit analysis. The former includes any taxes and/or subsidies, while the latter excludes these. These costs have been obtained from projects implemented in each of the three select countries. The operation and maintenance costs of solar system are assumed to be approximately 1.5 – 2.5% of capital costs per year.[6]

Country	Capital expenditure (EPC) ($/kW) - Inputs to economic assessment[7]			VAT (%)	Custom Duties (%)[8]	Capital expenditure (EPC) ($/kW) - Inputs to financial appraisal		
	Low	Medium	High	Current	Current	Low	Medium	High
Lebanon	780	1,090	1,400	11%	0%	866	1,210	1,554
Palestine	1,000	1,250	1,500	16%	0%	1,160	1,450	1,740
Iraq	1,000	1,400	1,800	0%	0%	1,000	1,400	1,800

Table 1. Solar PV capital cost values (2018 data)

The electricity displaced by the use of the solar PV system is both electricity from the respective national grids and the reduction in the use of diesel gensets electricity. Table 2 identifies these utility tariffs (subsidized and unsubsidized) and the marginal diesel genset costs being displaced, in each of the three countries, respectively.

Country	Electricity tariff rates ($c/kWh)[9]		Marginal diesel genset electricity tariffs ($c/kWh)[10]
	Current tariff	Unsubsidized tariff	
Lebanon	8.51	16.5	20

[6]Based on data collected from the EIA, IEA, Lazard and NREL: "https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf", "https://www.bv.com/docs/reports-studies/nrel-cost-report.pdf", "https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf", "https://www.lazard.com/media/450773/lazards-levelized-cost-of-energy-version-120-vfinal.pdf".

[7] Lebanon: Data from UNDP CEDRO Project "http://www.cedro-undp.org/"; Palestine: National Beverage Company (Alaa Esawi -Technical Department Coordinator), and Najah University Hospital (Imad Ibrik); Iraq: UNDP Iraq - Environment, Energy and Climate Change (Tarik Islam - Program Manager and Mohammed Faez Al-Attar - Solar Engineer).

[8] Lebanon: Lebanese Customs "http://www.customs.gov.lb"; Palestine: Palestinian Investment Promotion Agency "http://pipa.ps/"; Iraq: Iraqi budget law report for 2017.

[9] Lebanon: Summary of power sector report (Lebanon CoM, 2018); Palestine: IEC "https://www.iec.co.il"; Iraq: Values adopted from two academic articles: (Istepanian, 2014) and (Al-Rikabi, 2017).

[10] Lebanon and Iraq based on the local cost of diesel adopted from "https://www.globalpetrolprices.com", Palestine based on minimum diesel fuel cost (Nassar & Alsadi, 2019).

Palestine	15	-	29
Iraq	1.85	9.42	19.7

Table 2. Current electricity tariffs and marginal diesel genset costs

The analysis hikes the real price of electricity and genset power through the adoption of a range of increase in fuel prices; where the fuel price varies from a low end point of 0%, mid end-point of 1.28% increase, and high end-point of 1.77% increase in fuel prices over the 25-years lifetime of the solar PV system.[11] With respect to energy production from the solar system, Table 3 outlines values in the three countries. Palestine and Lebanon share similar values in terms of average global horizontal irradiance (GHI) and thus specific energy yield. Iraq has slightly more power given its relatively higher average solar resource. In all three countries, we have assumed a 50% utility power availability, whereas the remaining 50% the solar PV synchronizes with the diesel gensets. Xavier *et al.* (2016) published a guideline report on hybrid solar-diesel systems, differentiating between four categories, namely, hybrid solar-diesel systems that have a PV energy annual fraction that is (1) less than 20% (2) between 20% and 50% (3) between 50% and 80% (4) greater than 80%. The four categories differ in the amount of solar PV curtailment needed and in the level of sophistication of the energy management system required. Solar curtailment is required, as a rule of thumb, when diesel generators begin operating below 30% of their nominal capacity. In this study, we assume the system under investigation performs at the lowest curtailment rate (<20%) which corresponds with the observed data monitoring results of implemented PV systems in Lebanon. Consequently, we vary the curtailment rates in the

[11] Adopted from the oil price forecasting approach of the IEA found in the WEO 2017 report “https://www.iea.org/weo2017” based on a straight-line appreciation approach. Low estimate represents Sustainable Development scenario, medium estimate represents New Policies scenario and high estimate represent Current Policies scenario.

calculations from 0% for the low end-point, 10% for the mid end-point and 20% for the high end-point.

Country	Average GHI (kWh/m2/day)[12]	Average specific yield for commercial scale PV system (kWh/kWp)[13]	Solar PV displacement assumption (diesel power vs. utility power)	Curtailment percentage (with diesel self-gen only)		
				Low	Medium	High
Lebanon	5.3	1,670	50:50	0%	10%	20%
Palestine	5.4	1,670	50:50			
Iraq	5.7	1,712	50:50			

Table 3. Solar power output and curtailment values

The final assumptions relate to the cost of capital required for the financial appraisal and the social rate of discount, required for the economic cost-benefit analysis. The assumptions are shown in Table 4.

Country	FA discount rate (WACC) (%)			Adopted WACC (%)[14]	EA discount rate (SDR) (%)[15]
	Debt cost[16]	Equity cost[17]	WACC (70-30)		

[12]Lebanon average GHI: UNDP CEDRO Project "Photovoltaic Plants in Lebanon" report "http://www.databank.com.lb/docs/Photovoltaic%20plants%20in%20Lebanon-Cedro%202013.pdf"; Palestine average GHI: (Saeed *et al*., 2016); Iraq average GHI: adopted from (Juaidi *et al.*, 2016).

[13] Specific yield for all countries based on the average GHI was imported from "https://globalsolaratlas.info".

[14] This study adopts a 10% WACC to take a longer view, noting the IRR is also included that can be used to compare the financial outcome of the solar PV systems with the current existing 'unstable' investment climate (which may thereby change) as reflective in the high WACC value of Table 4 (especially for Iraq).

[15] A review on the social discount rate (SDR) concluded that 'more than 90 percent of experts are comfortable with a SDR somewhere in the interval of 1 percent to 3 percent' (Drupp *et al*., 2018). We adopt the higher range of the SDR values.

[16] The average value for up to the last 15 years of available lending interest rate data from the World Bank was calculated "https://data.worldbank.org/indicator/FR.INR.LEND?locations=IQ-PS-LB".

[17] Based from UNDP's De-Risking Renewable Energy Investments Report (UNDP, 2017).

Lebanon	9	16	11	10	3
Palestine	7	16	10	10	3
Iraq	15	16	15	10	3

Table 4. Discount rate assumptions

(weighted average cost of capital and the social discount rate)

3 Results and Discussion

3.1 Energy analysis

The overall embodied energy of the solar PV system is 110,499 MJ (calculated using the Simapro software and the CED V1.10). Using the specific yields (see Table 3) for each country, the annual energy outputs are 18,036 MJ (for Lebanon and Palestine) and 18,439.6 MJ for Iraq.

Therefore, the sEPBT for the three cases above are 6.13 years for Lebanon and Palestine, and 5.98 years for Iraq. This means that it would take 6.13 years of operating the solar PV plants in Lebanon and Palestine in order to repay, in energy terms, the amount of energy it took to produce and install these systems. For Iraq, results are slightly better in energy terms, given the higher relatively average global horizontal irradiance (as shown in Table 3). sEPBT results are influenced by the solar irradiance present and the lifetime of the solar system assumed, among other parameters, such that the results on sEPBT for solar PV yields many different results depending on country and context (Ludin *et al.*, 2018).

In order to calculate the dEPBT, the GER indicated in Table 5 are used. Table 5 also indicates the cumulative energy demand (CED) results of all cases under study. The results of PV multi-crystalline silicon (multi-Si) for Lebanon (LB) and Palestine (PS) are similar because of the proximity of both countries and therefore the same data are used in the LCA input stage[18]. In general, the results indicate that PV installations for all countries have the lowest CED, estimated to be 4.73 MJ/kWh for Palestine and Lebanon, and 4.71 MJ/kWh for Iraq, followed by the PS national grid (11.6 MJ/kWh), the self-gen for all countries (13.49 MJ/kWh), and last the LB and IQ grids (14.18 and 26.48 MJ/kWh, respectively).

Impact category	Unit	Self-gen Diesel 1 kWh (all 3 countries)	Palestine PV multi-Si Electricity production, 1 kWh	Lebanon PV multi-Si Electricity production, 1 kWh	Iraq PV multi-Si Electricity production, 1 kWh	Palestine Electricity low voltage, 1 kWh	Lebanon Electricity low voltage, 1 kWh	Iraq Electricity low voltage, 1 kWh
Cumulative energy demand	MJ	13.49	4.73	4.73	4.71	11.6	14.18	26.48
GER ($MJ_{embodied}/MJ_{delivered}$)		3.747	1.314	1.314	1.308	3.223	3.939	7.356

Table 5. Cumulative Energy Demand V1.10 and Gross Energy Requirements

The dEPBTs are estimated as 1.59 years for Lebanon, 1.76 years for Palestine, and 1.07 years for Iraq. The results assume a 50-50% operation between the diesel gensets and the respective national grids of the three countries. Therefore, and as per Equation 2, the overall efficiency of the electricity system is taken to be the average GER of the diesel and the utility networks in each respective country. The results indicate that it would take only 1.59, 1.79 and 1.07 years of

[18] The proximity of Lebanon and Palestine enables the same transport logistic assumptions to be used in the LCA, and their respective average global horizontal irradiances are similar (Lebanon is endowed with an average of 5.3 kWh/day (UNDP, 2013) and Palestine with 5.4 kWh/day (Omar & Mahmoud, 2018; Saeed *et al*., 2016)).

operating the solar system in Lebanon, Palestine and Iraq, respectively, to displace all the 'primary energy requirements' that it would have taken by the same combination of the diesel genset and utility power of the respective countries to produce the embodied energy within the supply and installation of the solar PV system. Given that the lifetime of the solar PV systems are 25 years, this would leave net energy benefits from the solar PV systems of 23.4, 23.2, and 23.9 years respectively for Lebanon, Palestine and Iraq. Benefits of 'displaced energy payback period' commonly return better results than 'simple energy payback period', as confirmed in other studies as well (Allen *et al*., 2008b; Hammond *et al*., 2012).

3.2 Life-cycle assessment

Results of the life-cycle impact assessment (LCIA) for the three select countries are provided, utilizing the Stepwise2006 LCIA and, alternatively, focusing only on carbon emissions using the IPCC 2013 GWP. These results are specific to the assessment of the hybrid solar PV-diesel system in the three select countries.

Results from the Stepwise2006 LCIA are shown in Figure 2. The externality costs for the diesel self-generators is $0.22 per kWh, while that for the solar PV is $0.02 per kWh for the three select countries, respectively. For the national utility grid, the externality costs equal approximately $0.21 per kWh in Palestine, $0.26 per kWh in Lebanon, and $0.41 per kWh in Iraq.

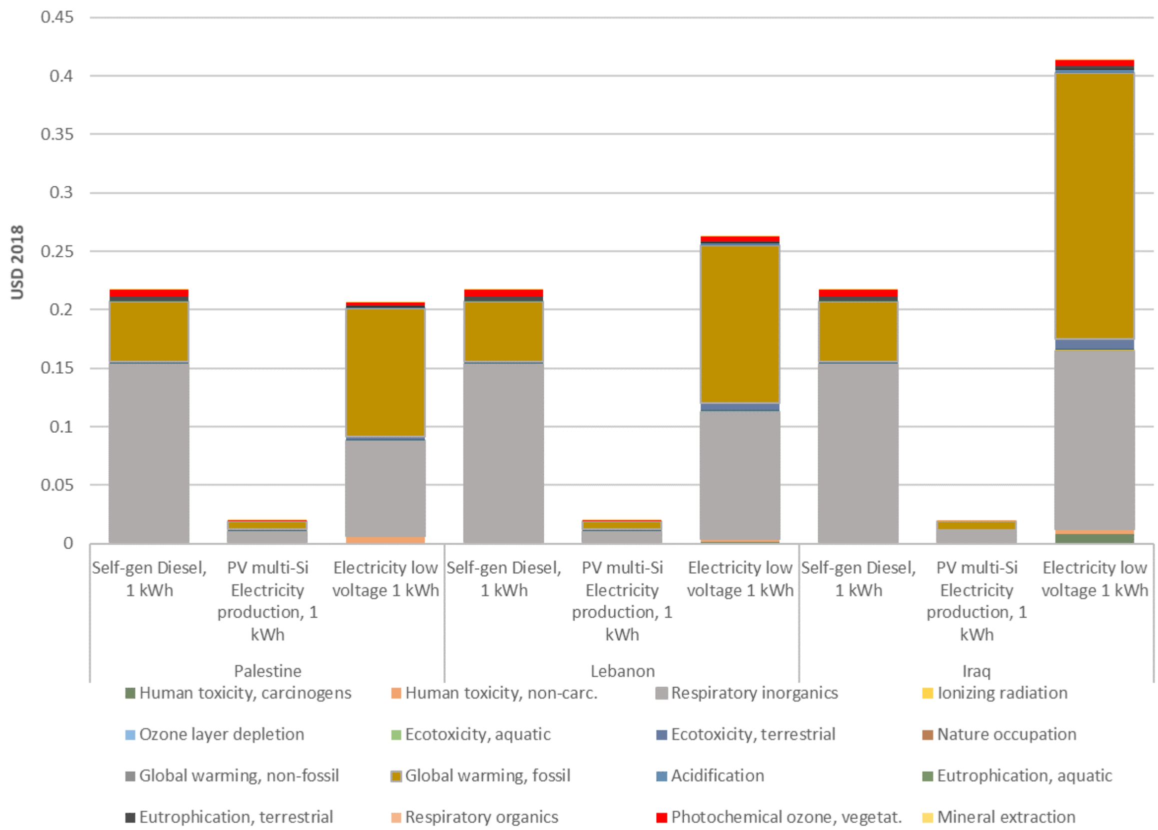


Figure 2. Stepwise2006 V1.05 LCIA single score results (USD 2018) for 1 kWh diesel genset, 1 kWh solar PV, and 1 kWh low voltage electricity for the three select countries

For all three cases in the three select countries, the two highest impact categories are 'respiratory inorganics' (particulate matter with a diameter of ≤ 2.5 mm), and 'global warming fossil', where these two impact categories account for at least 94% of the associated externality costs of the diesel self-generators, and 92 - 93% of the total associated externality costs of their respective national grids.

With respect to isolating and concentrating on greenhouse gas emissions only, Figure 3 indicates the emissions of the life-cycle production, installation, and operation of the diesel gensets, the national grids, and the solar PV systems.

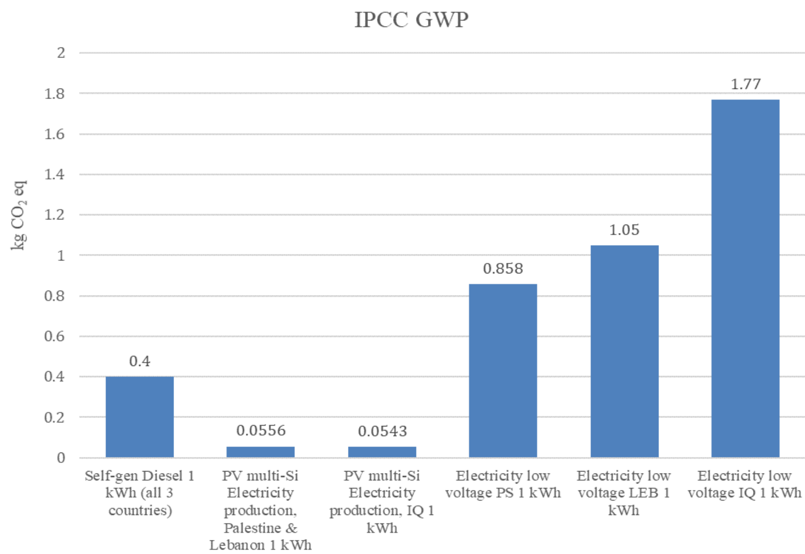


Figure 3. IPCC 2013 GWP 100a V1.03 / Characterization for the three select countries

For the carbon footprint, the results indicate that the solar PV systems (in all countries) have the least carbon footprint, followed by the diesel self-gensets (higher by almost a factor of 10 compared to PV), then the Palestinian, Lebanese and Iraqi grids (in that order).

The differences between the life-cycle environmental externalities of the solar PV, the diesel gensets and the national grid forms the basis of the economic assessment, where each unit (kWh) of solar PV displaces a unit (kWh) of either national utility or diesel power.

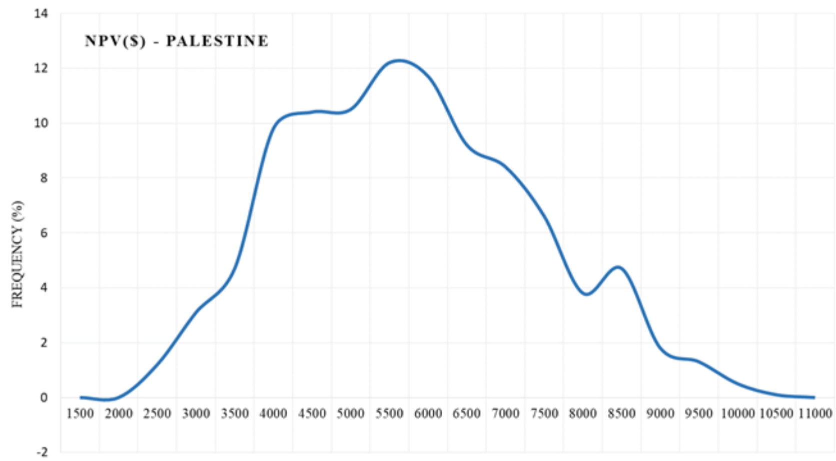
Comparing the results of the life-cycle assessment of the hybrid solar-PV diesel system undertaken in this study to other literature sources was not possible. The only other literature sources to date on life-cycle assessment of energy technologies or energy systems in these three countries focused on other technology types and/or used different LCA inventory databases and LCIA methodologies. For example, Bacenetti *et al.* (2016) assessed the environmental impacts of two anaerobic digestion plants in Palestine, using LCIA mid-point environmental categories. With respect to Lebanon, El-Fadel *at al.*, (2010) modelled various energy systems using the Ecoinvent v2.1 database and using the LCIA mid-point CML2001 method. Kabakian *et al.* (2015) modelled a residential 1.8 kWp solar system in using the Ecoinvent v.2.2 database and using the ReCipe 2008 LCIA method that combines both mid-point and end-point evaluations. Tannous *et al.* (2018) assessed solar street lighting applications using the Ecoinvent v3.3 database and the IMPACT 2002+ LCIA method. For Iraq, the only LCA study found was on a wastewater treatment plant (Alyaseri, 2016).

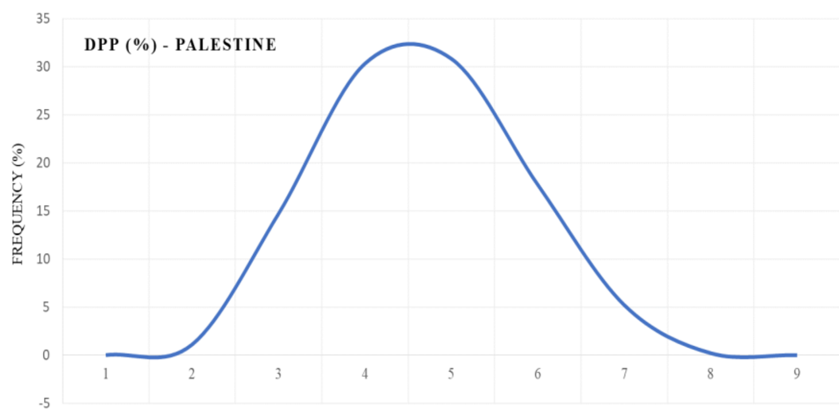
3.3 Financial appraisal and economic assessment

This section provides the results of the financial appraisal and economic assessment using Monte-Carlo simulations and the various data and assumptions indicated in Section 2.4.

3.3.1 Financial appraisal

Results from the financial appraisal, in the form of the net present value (NPV), internal rate of return (IRR), dynamic payback period (DPP) are provided in Figures 4 – 6 for the three select countries. In Palestine, results shown in Figure 4 indicate that integrating the solar PV into the grid and diesel gensets promise favorable financial outcomes. The mean NPV resulting from the 1,000 rounds of simulations is approximately $6,029, the DPP is 3.79 years and the mean IRR is 25%. The 1,000 rounds of simulations on NPV results are all positive and fall within a range between $2,140 - $11,000.





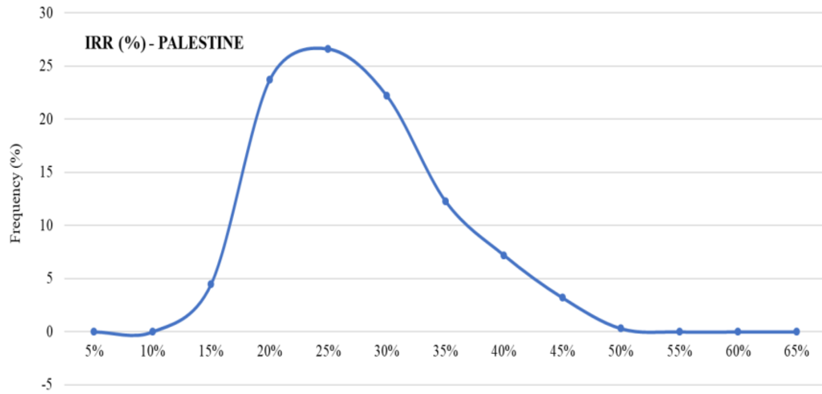


Figure 4. Financial appraisal results (NPV, IRR, DPP per kW invested) for solar PV in Palestine

Results for Lebanon are shown in Figure 5. The added difference is that Lebanon has a subsidized electricity tariff (averaging $c8.6/kWh), whereas the tariff should be at least $c16.5/kWh to cover all the current costs of generation, transmission and distribution (assuming oil price of approximately $65 per barrel). Results from the Lebanese financial appraisal simulation are not as favorable as the Palestinian case where diesel prices are relatively the most expensive and the grid tariff is un-subsidized. Figure 5 reveals a positive mean NPV $2,680 for the subsidized scenario, a mean payback period of 6.1 years, and a mean IRR of 15%. The NPV results show a range of values for NPV that fall between approximately -$405 to $5,946. The negative NPV simulation rounds are extreme cases (0.6% of total simulations) where the average curtailment rate is 17%, the average oil price increase is (0%) and the average capital price is $1,540/kW.

As a case for comparison, the unsubsidized tariffs in the Lebanese scenario yields a mean NPV increases to $5,012, a mean DPP of 4.21 years and a mean IRR of 24%. The NPV results range between $1,162 and $8,912.

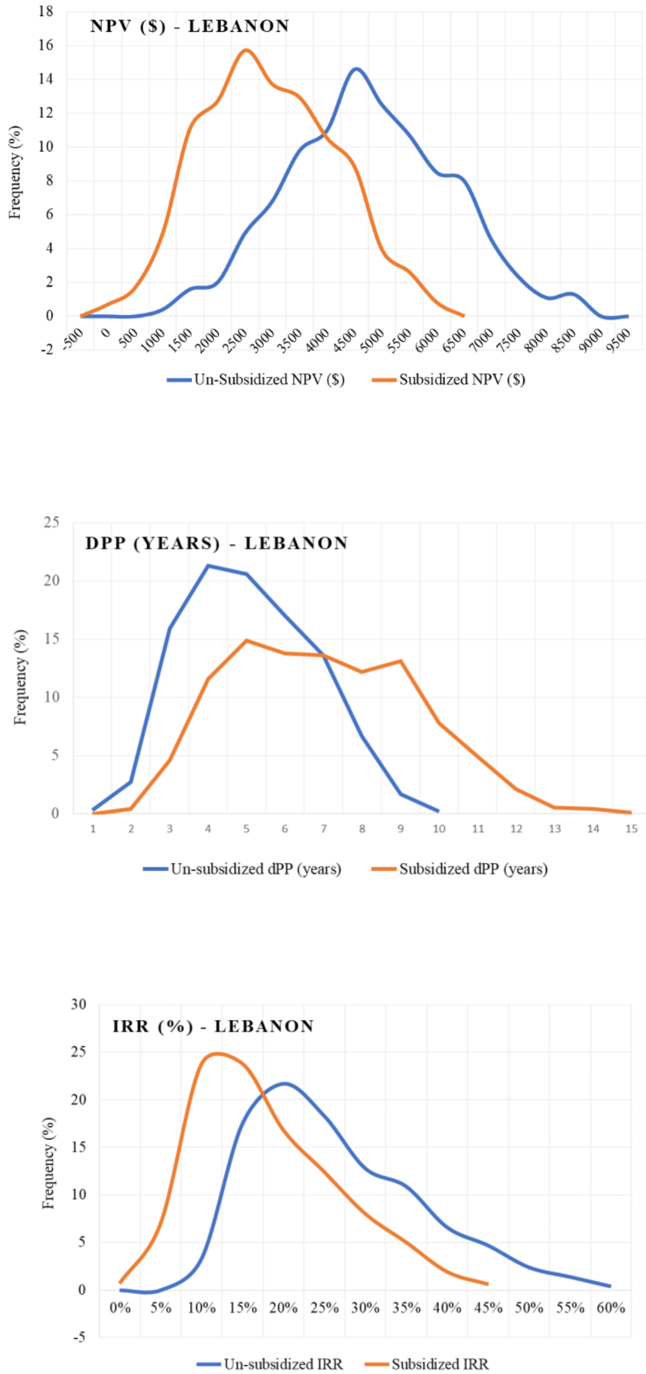
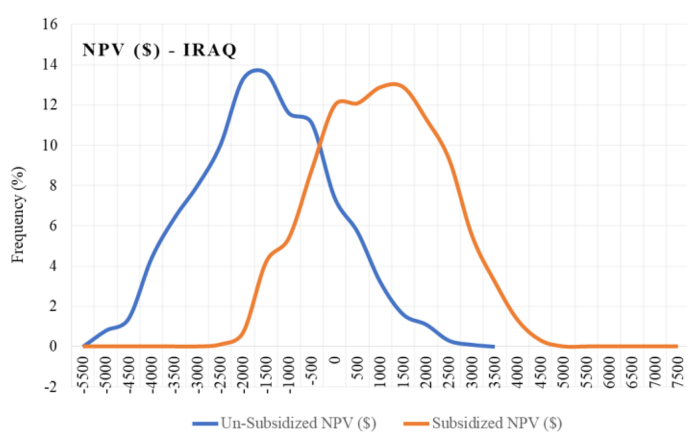
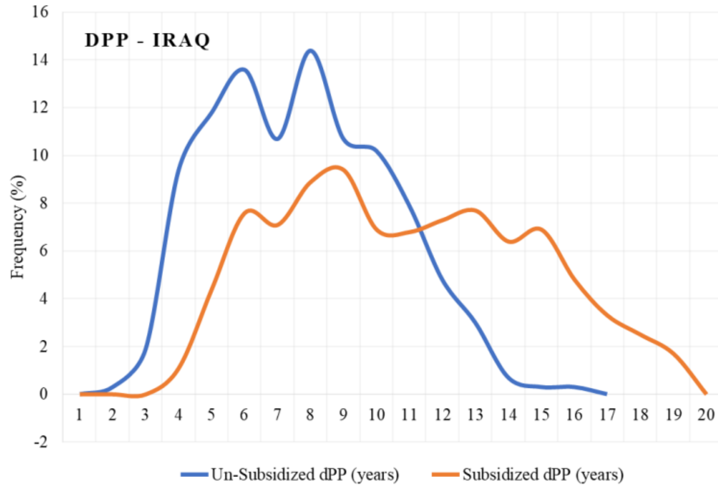


Figure 5. Financial appraisal results (NPV, IRR, DPP per kW invested) for solar PV in Lebanon

Results for Iraq are shown in Figure 6 for the NPV, IRR and DPP indicators. Iraq's subsidized electricity tariff stands an average of $c1.85/kWh, which significantly undermines the performance of the solar PV system. The mean NPV results from the 1,000 Monte-Carlo simulations show a mean NPV for the subsidized tariff scenario of $756, a mean payback period of 10 years and a mean IRR of 5.2%. The NPV results fall in a range of -$2,502 to $4,395. The positive NPV results represent 72.7% of the results with an average 8.63% of curtailment rate, an average oil growth rate of 1.44% per annum and an average capital cost of $1,228/kW. The negative values represent 27.3% of the sample results with an average curtailment rate of 12%, an average oil price growth rate of 0.91% per annum and an average capital cost of $1,871/kW.

For comparative purposes, the unsubsidized scenario (also shown in Figure 6) yields a mean NPV of $2,736, a mean DPP of 6.9 years and a mean IRR of 13.4%. The NPV results range between $-925 and $7,131. The positive NPV results represent 97.0% of the sample size with an average curtailment rate of 9.62%, oil price growth rate of 1.19% per annum and an average capital cost of $1,346/kW. The negative NPV represent just 3% of the sample results with an average curtailment rate of 15%, an average oil price growth rate of 0.24% per year and an average capital cost of $1,798/kW.





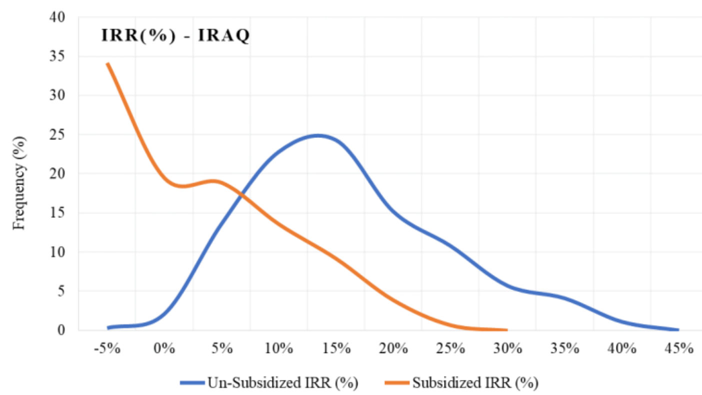
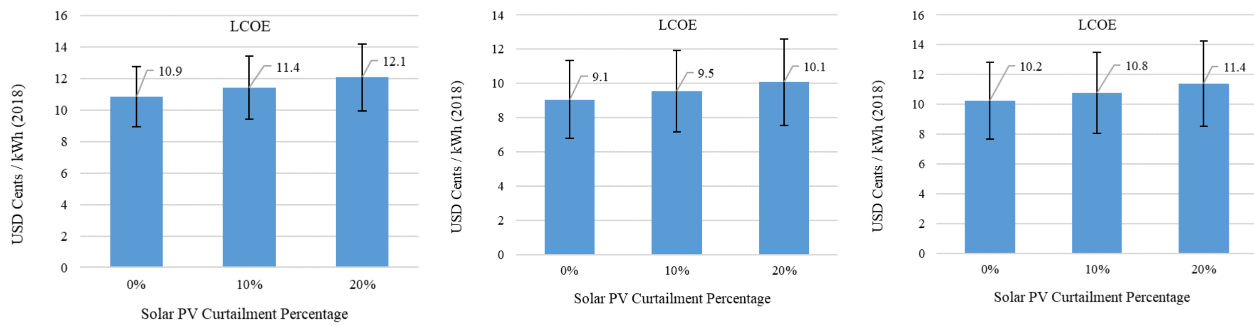


Figure 6. Financial appraisal results (NPV, IRR, DPP per kW invested) for solar PV in Iraq

The levelized cost of electricity (LCOE) from commercial-sized solar PV, integrated into both diesel gensets and the national grid, is provided in Figure 7. This allows for comparative assessment on the unit costs of the solar PV systems in the three select countries with their diesel counterparts operating alone, with the subsidized and unsubsidized national tariffs, and with other electricity generating technologies. The mean-case scenarios indicate an LCOE of $c11.4/kWh for Palestine, $c9.5/kWh for Lebanon, and $c10.8/kWh for Iraq. Comparing the LCOE of commercial-scale solar PV with national tariffs and diesel costs (see Table 2), we find that solar PV is cost-effective when compared to all three countries' diesel fuel costs, per kWh, and more competitive to the un-subsidized tariffs in Lebanon and Palestine. The LCOE of solar

PV is approximately $c1 - $c1.4/kWh more expensive than the subsidized utility tariff rates in Lebanon and Palestine, however much more expensive than the subsidized utility tariff rate of Iraq.



Palestine Lebanon Iraq

Figure 7. LCOE for solar PV system in the 3 select countries (USD cents/kWh – 2018)

In relation to other literature on the financial performance of solar-PV in the three countries, Omar & Mahmoud (2018), for example, assessed a 5 kWp solar system for the residential sector in Palestine. Results indicated a levelised cost of electricity of approximately $c11/kWh, a simple payback period of 4.9 years, and an IRR of 25%. This is within the range specified in this analysis. For Iraq, Muslim *et al.* (2018) assessed the financial performance of a 2 kWp solar system with battery storage through 2 scenarios, one scenario displacing a 2.5 KVA gasoline generator and the other scenario displacing utility electricity only. For the second scenario, a simple payback period of 13 years was estimated if the price of electricity tariffs is raised to $c10/kWh. This is slightly above the mean calculated for solar PV for Iraq in this paper. In Lebanon, Nasr *et al.* (2016), assessed the financial performance of a 140 kWp solar PV diesel system using the IRR indicator. Results indicate the system yielded an IRR of 19% and a simple payback period of 5.4 years. Results from Nasr *et al.* (2016) are more favorable to the mean financial appraisal results of the solar system assessed in this paper where the DPP of 6.1 years and an IRR of 15% was indicated. One reason, as mentioned in Nasr *et al.* (2016), is the reference year of 2014 used for the analysis when the average barrel of oil costs $96.29[19].

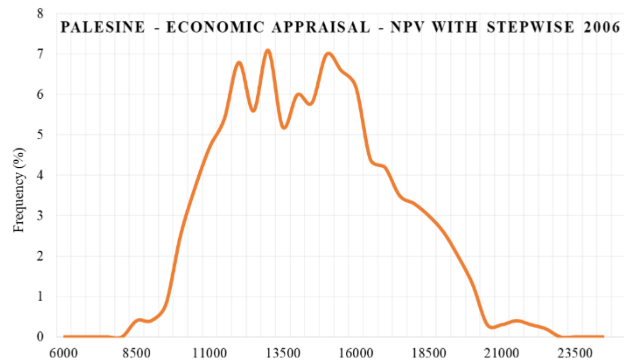
Comparing the financial appraisal results of this study, as shown above, to other existing studies is problematic, given the specificities of the technology analyzed (commercial-scale solar PV-diesel hybrid systems). Second, solar technology costs have dropped significantly over the past 10 years, changing the outcome landscape of the financial appraisal. From 2009 to 2018, solar PV costs have dropped by approximately 88% (Lazard, 2018). Last, the methodology employed in this study, the data and variable assumptions, such as the WACC, are unique to the analysis deployed in this study.

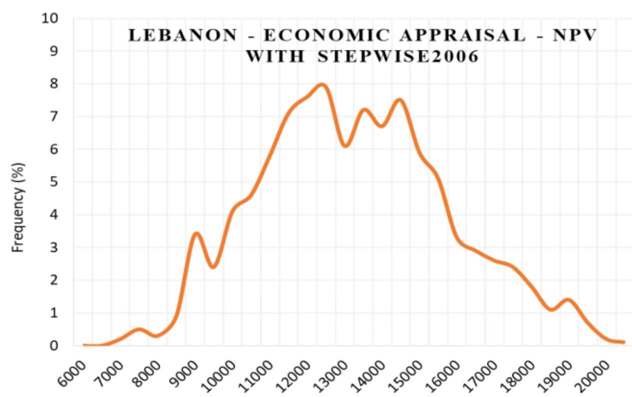
3.3.2 Economic assessment

The economic assessment assumes no taxes on capital costs of the solar PV system, as well as no taxes and/or subsidies for the electricity tariffs. It adopts a social discount rate of 3%. Furthermore, environmental externalities are internalized using the results from two scenarios; the Stepwise2006 LCIA results and the IPCC GWP results combined with two estimates on the SCC, both outlined in section 3.2.

[19] https://www.statista.com/statistics/262858/change-in-opec-crude-oil-prices-since-1960/

Figure 8 presents the outcome of the economic assessment, using the NPV indicator for the three select countries.





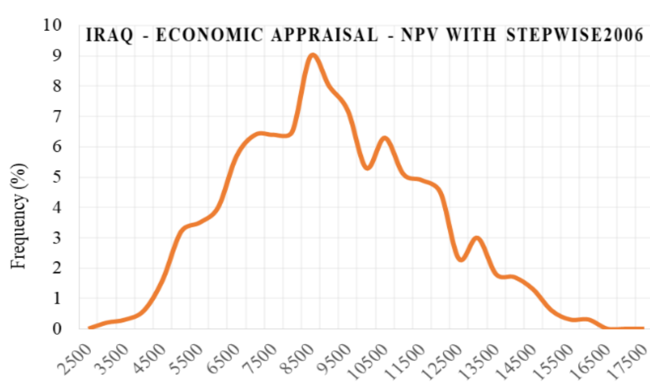


Figure 8. Economic assessment results (NPV per kW invested) for solar PV in the 3 select countries using Stepwise2006 results.

Figure 8 indicates that the solar PV system's economic performance is even more favorable when environmental externalities are internalized, even if curtailment of the solar PV stands at 20% during the operation of the solar PV with the diesel gensets. The mean NPV of the 1,000 rounds of Monte-Carlo simulations in Palestine under the Stewise2006 LCIA assumptions result in a mean value of $14,673 for Palestine. In Lebanon, the results show a mean NPV of $13,468, while in Iraq the mean NPV is approximately $11,187.

An alternative scenario that relies only on greenhouse gas emissions (GHGs) is also assumed for the installations of the solar PV systems and results are shown in Figure 9. As the damages from the release of GHGs are global in nature, they are not site specific and can thus be considered more 'realistic' than the 'potential' impacts of the Stepwise2006 method. It is important to note that the Stepwise2006 method's results include the impacts of climate change, as well as other impacts. In fact, the value of the SCC used in Stepwise2006 is approximately 0.083 Euros per kilogram of CO_2-equivalent (2003 value) and this is approximately equal to the 2018 adopted value under the 100 year 2.5^{o}C constraint. Results reveal a similar positive outlook in terms of the economic costs and benefits of commercial-scale solar PV integrated into both diesel gensets, when national power is cut, and when national power is present. NPV results are slightly lower than the Stepwise2006 method, which is expected given that the environmental externalities are limited to climate change impacts in the IPCC GWP method.

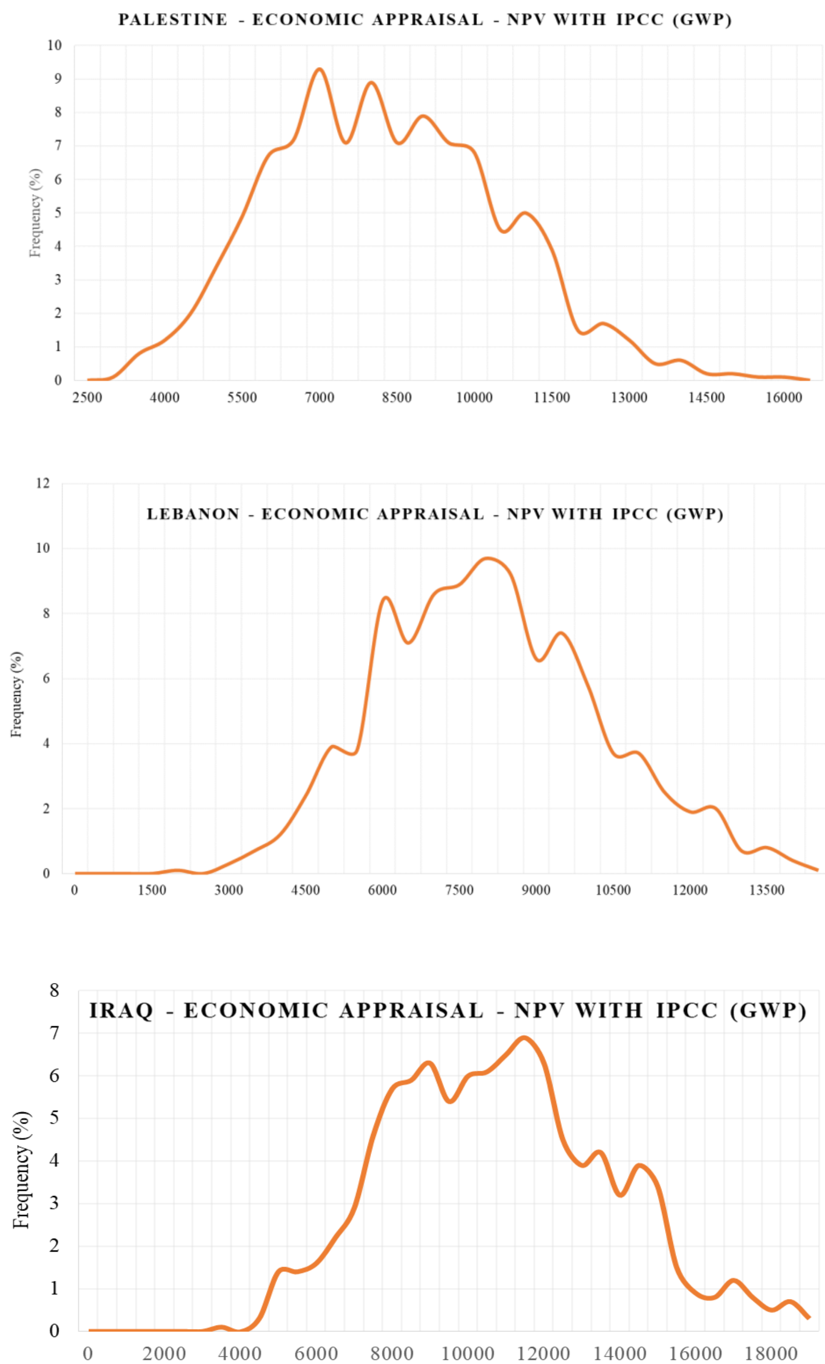


Figure 9. Economic assessment results (NPV per kW invested) for solar PV in the 3 select countries using IPCC GWP method results.

The results of the simulation relying on the IPCC GWP methodology yield a relatively less favorable economic performance than Stepwis2006, although the outcome is positive for all countries. In Palestine the mean NPV is $8,558, while it equates to approximately $7,458 for Lebanon and $7,087 for Iraq. The results indicate a clear societal benefit of integrating solar PV systems.

4 Conclusion and Policy Recommendations

This paper's objective is to present the outcomes of an 'integrated appraisal' that combines energy analysis, life-cycle assessment, financial appraisal and economic cost-benefit analysis of solar photovoltaic-hybrid systems installed in Palestine, Lebanon, and Iraq, three countries that are categorized with 'weak' grids. This objective has been met in the analysis. Uncertainties in the economic assessment are inherent in the uncertainties of the adopted values of the life-cycle impact assessment methods utilized, the values for the social cost of carbon and the social discount rate. However, providing a monetary value for environmental impacts is an integral part of the 'integrated appraisal', and enables a more complete picture of the cost and benefits of energy generating technologies than one that excludes such impacts. This is especially the case when displacing national and local power systems that depend mainly on fuel oil and diesel.

The results of the study indicate a positive outcome for all the commercial-sized solar PV installations in the three countries from an energy and environmental perspective. This is mainly due to the fact that the solar PV displaces either the use of diesel fuel to power distributed generators, or the relatively environmentally inferior utility grids of the three countries.

The energy payback period of the solar PV installations, when considering the energy displaced (diesel fuel and utility grid), are estimated to be less than 2 years for Lebanon and Palestine, and just over 1 year for Iraq. With respect to environmental damages, every kWh generated from solar PV that displaces the use of fuel from the local gensets saves \$0.2 in environmental damage costs emanating from each of the three countries and saves \$0.19, \$0.24, and \$0.39 per kWh in environmental damages if displacing a unit (kWh) of utility power in Palestine, Lebanon, and Iraq, respectively (adopting the life-cycle impact assessment method of Stepwise2006). When concentrating only on impacts of climate change, installing the commercial-scale solar PV system will save \$0.014 per kWh generated for the three countries when displacing the local diesel genset (using the climate change 'baseline' impacts only), whereas the savings in climate change damages increase to approximately \$0.05 per kWh when adopting the 100 year 2.5^{o}C constraint values for the social cost of carbon (SCC). On the other hand, when solar PV displaces grid electricity, the savings on climate change damage costs range from \$0.031 - \$0.113 per kWh for Palestine, \$0.04 - \$0.14 per kWh for Lebanon, and \$0.069 - \$0.24 per kWh for Iraq, depending on whether the 'baseline' or the 100 year 2.5^{o}C constraint values are adopted for the SCC.

Results from the economic assessment (EA) return positive and highly favorable net present value (NPV) results across all cases in the three countries. This shows the importance of integrating environmental damage estimates into economic modelling. Likewise, the results from the financial appraisal indicate positive outcomes in terms of NPV, internal rate of return (IRR), and dynamic payback period (DPP) for the solar PV installations in Palestine and Lebanon. However, Iraq's financial appraisal results are less optimistic, given Iraq's highly subsidized electricity tariff. A negative NPV is likely in Iraq under current conditions, especially when and if there is any curtailment of the solar PV power when operating with the diesel genset.

To expedite the uptake of commercial solar-PV systems integrated into the utility grids and the diesel gensets of the select countries, several policy initiatives are required. In Iraq, the government subsidizes both electricity and diesel fuel consumption, while in Lebanon only electricity purchased from the grid is subsidized. In Palestine there are no subsidies on energy. This is one of the key reasons why commercial solar-PV hybrid systems return the best financial outcomes in Palestine, followed by Lebanon and Iraq. Energy subsidies are therefore one barrier to a more robust growth of commercial scale hybrid PV systems in intermittent grids. In Lebanon, in the latest update of the electricity policy paper (MEW, 2019), the government plans to increase the electricity tariff starting 2020 to avoid paying between $1.5 - $2 billion per annum in subsidies (Lebanon MoF data[20]). The planned increase in tariffs will be accompanied by an increase in the utility power supplied so that the new tariff will not exceed the total average cost of electricity consumption currently being paid by subscribers on utility electricity and generators combined. With respect to Iraq, the World Bank indicated that "removing electricity subsidies (in Iraq) would have no overall negative effects on the economy and on the poor… a fourfold increase in the electricity tariffs suggest that the subsidy reform would result in an overall increase in real GDP of 1.6 percent" (World Bank, 2018b). Iraq loses between $5 and $6 billion annually from subsidies (World Bank, 2018b). Removing subsidies as part of overall reforms, however, should not be adopted without special attention to the more vulnerable groups of society that benefit from subsidized energy tariffs and costs. One recommendation is to re-

[20] The Ministry of Finance in Lebanon publishes annual reports on the fiscal performance of the country since the year 2000, including an expenditure line that specifies the electricity subsidies to EDL. Please see http://www.finance.gov.lb/en-us/Finance/EDS/FP/Pages/default.aspx [100]

channel some of the financial resources that are allocated to energy subsidies towards social safety nets that can mitigate against 'perceptions of social injustice' of tariff reform (Yemtsov & Moubarak, 2018; Flochel & Gooptu, 2018). Energy safety net measures can 'either reduce the price of energy directly or make it easier for recipients to afford the market price, and this can come in the form of delivering fuel, electricity or equipment' (Scott & Packard, 2018).

Secondly, all three selected countries can further accelerate commercial-solar PV installations if net metering policy is enacted (Iraq) or adequately implemented (e.g. Lebanon and Palestine) (RECREE & UNDP, 2016). Most commercial and industrial institutions are not (or only just partially) operational for 52 - 104 days per year. Enabling the investors to account for the solar power fed back into the grid is critical to improve the overall financial viability of the systems. However, this requires relatively proficient institutional capabilities and smart metering and billing technologies, especially within the national utilities of the three countries, respectively.

Third, tax exemption on renewable energy components need to be applied to decrease the initial cost of financing. The Palestinian case showcases the highest financial return of integrating solar PV systems with diesel and grid electricity. The removal of 16% value added tax (VAT) on renewable energy components is easily implementable and will result in even better financial returns and increase in the total number of systems installed, which in turn would improve the environmental performance of the overall electricity system. In Lebanon, similar initiatives need to be followed, the removal of the 11% VAT will lower capital investment required and result in better financial and environmental returns.

Fourth, support in overcoming the upfront investment cost barrier for solar-PV installations can significantly increase the uptake of this technology in the commercial and/or industrial sectors. Lebanon is a good case in point. Of the total 35 MW of solar PV power installed to date, approximately 64% were enabled through the soft loan program initiated (see Section 1.3) (UNDP DREG, 2018). Soft loans with grace periods enable a positive cash flow throughout the loan's tenure, meaning that the loan payments are likely to be less than the payments that would have been made to purchase electricity from the grid and diesel fuel for the gensets in the absence of the solar PV installations. Such a mechanism can thus be useful to extend in Palestine and Iraq.

Last, the paper touches on the importance of the optimal integration of the solar PV system with the diesel generator. The '0%' curtailment option results in better fiscal, economic and environmental outcomes in all the cases studied in this assessment. This directly calls for the improvement in the design of such systems to keep the solar curtailment at its lowest. Better design is subject to the experience and objectives of designers, installers and operators in each country. Innovative technologies can also be targeted, specifically in energy management systems (see, for example, Olatomiwa *et al.*, 2016) and variable speed drive gensets (an example on the performance of the later can be found in Thomas *et al*., 2014). Providing education and vocational training is crucial for the development of the sector especially when it comes to the large number of jobs expected to be created during the energy transition. Public support of R&D is lacking in general in the region[21] both in technological and implementation terms. The hybrid solar PV-diesel-grid system is a unique area of expertise that the region may be well positioned

[21] According to World Bank data the average share expenditure on R&D as a percentage of GDP in Arab states is 0.9% while the world average is around 2.2%; (https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS?locations=ZQ&name_desc=false)

to play an important role on an international level but would require collaboration between government institutions, energy companies and research institutes to succeed.

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Table(s)

Country	Capital expenditure (EPC) ($/kW) - Inputs to economic assessment[1]			VAT (%)	Custom Duties (%)[2]	Capital expenditure (EPC) ($/kW) - Inputs to financial appraisal		
	Low	Medium	High	Current	Current	Low	Medium	High
Lebanon	780	1,090	1,400	11%	0%	866	1,210	1,554
Palestine	1,000	1,250	1,500	16%	0%	1,160	1,450	1,740
Iraq	1,000	1,400	1,800	0%	0%	1,000	1,400	1,800

Table 1. Solar PV capital cost values (2018 data)

[1] Lebanon: Data from UNDP CEDRO Project "http://www.cedro-undp.org/"; Palestine: National Beverage Company (Alaa Esawi -Technical Department Coordinator), and Najah University Hospital (Imad Ibrik); Iraq: UNDP Iraq - Environment, Energy and Climate Change (Tarik Islam - Program Manager and Mohammed Faez Al-Attar - Solar Engineer).

[2] Lebanon: Lebanese Customs "http://www.customs.gov.lb"; Palestine: Palestinian Investment Promotion Agency "http://pipa.ps/"; Iraq: Iraqi budget law report for 2017.

Table(s)

Country	Electricity tariff rates ($c/kWh)[1]		Marginal diesel genset electricity tariffs ($c/kWh)[2]
	Current tariff	Unsubsidized tariff	
Lebanon	8.51	16.5	20
Palestine	15	-	29
Iraq	1.85	9.42	19.7

Table 2. Current electricity tariffs and marginal diesel genset costs

[1] Lebanon: Summary of power sector report (Lebanon CoM, 2018); Palestine: IEC "https://www.iec.co.il"; Iraq: Values adopted from two academic articles: (Istepanian, 2014) and (Al-Rikabi, 2017).
[2] Lebanon and Iraq based on the local cost of diesel adopted from "https://www.globalpetrolprices.com", Palestine based on minimum diesel fuel cost (Nassar & Alsadi, 2019).

Table(s)

Country	Average GHI (kWh/m2/day) [1]	Average specific yield for commercial scale PV system (kWh/kWp) [2]	Solar PV displacement assumption (diesel power vs. utility power)	Curtailment percentage (with diesel self-gen only)		
				Low	Medium	High
Lebanon	5.3	1,670	50:50	0%	10%	20%
Palestine	5.4	1,670	50:50			
Iraq	5.7	1,712	50:50			

Table 3. Solar power output and curtailment values

[1] Lebanon average GHI: UNDP CEDRO Project "Photovoltaic Plants in Lebanon" report "http://www.databank.com.lb/docs/Photovoltaic%20plants%20in%20Lebanon-Cedro%202013.pdf"; Palestine average GHI: (Saeed *et al*., 2016); Iraq average GHI: adopted from (Juaidi *et al*., 2016).

[2] Specific yield for all countries based on the average GHI was imported from "https://globalsolaratlas.info".

Table(s)

Country	FA discount rate (WACC) (%)			Adopted WACC (%)[1]	EA discount rate (SDR) (%)[2]
	Debt cost[3]	Equity cost[4]	WACC (70-30)		
Lebanon	9	16	11	10	3
Palestine	7	16	10	10	3
Iraq	15	16	15	10	3

Table 4. Discount rate assumptions
(weighted average cost of capital and the social discount rate)

1 This study adopts a 10% WACC to take a longer view, noting the IRR is also included that can be used to compare the financial outcome of the solar PV systems with the current existing 'unstable' investment climate (which may thereby change) as reflective in the high WACC value of Table 4 (especially for Iraq).

2 A review on the social discount rate (SDR) concluded that 'more than 90 percent of experts are comfortable with a SDR somewhere in the interval of 1 percent to 3 percent' (Drupp *et al*., 2018). We adopt the higher range of the SDR values.

3 The average value for up to the last 15 years of available lending interest rate data from the World Bank was calculated "https://data.worldbank.org/indicator/FR.INR.LEND?locations=IQ-PS-LB".

4 Based from UNDP's De-Risking Renewable Energy Investments Report (UNDP, 2017).

Table(s)

Impact category	Unit	Self-gen Diesel 1 kWh (all 3 countries)	Palestine PV multi-Si Electricity production, 1 kWh	Lebanon PV multi-Si Electricity production, 1 kWh	Iraq PV multi-Si Electricity production, 1 kWh	Palestine Electricity low voltage, 1 kWh	Lebanon Electricity low voltage, 1 kWh	Iraq Electricity low voltage, 1 kWh
Cumulative energy demand	MJ	13.49	4.73	4.73	4.71	11.6	14.18	26.48
GER ($MJ_{embodied}/MJ_{delivered}$)		3.747	1.314	1.314	1.308	3.223	3.939	7.356

Table 5. Cumulative Energy Demand V1.10 and Gross Energy Requirements

Figure(s)

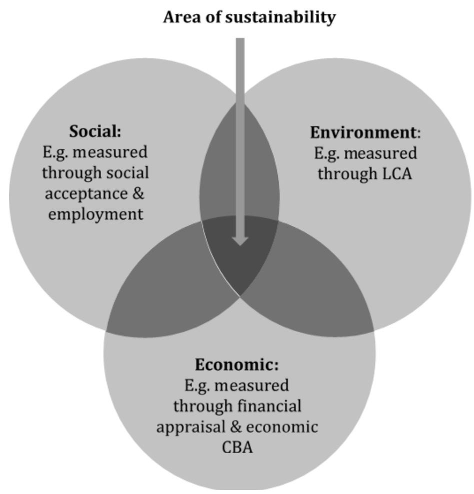


Figure 1. Sustainable development Venn diagram and related evaluation tools and indicators (adapted from Allen *et al*., 2008a)

Figure(s)

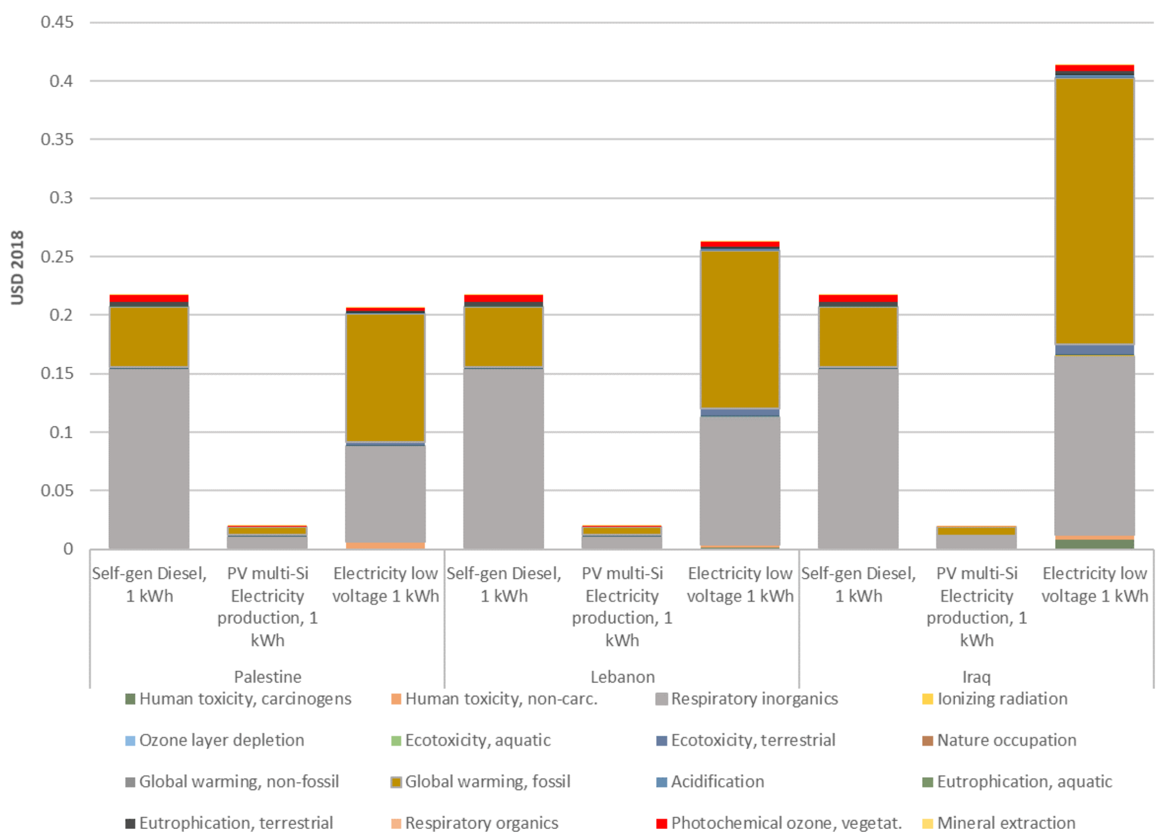


Figure 2. Stepwise2006 V1.05 LCIA single score results (USD 2018) for 1 kWh diesel genset, 1 kWh solar PV, and 1 kWh low voltage electricity for the three select countries

Figure(s)

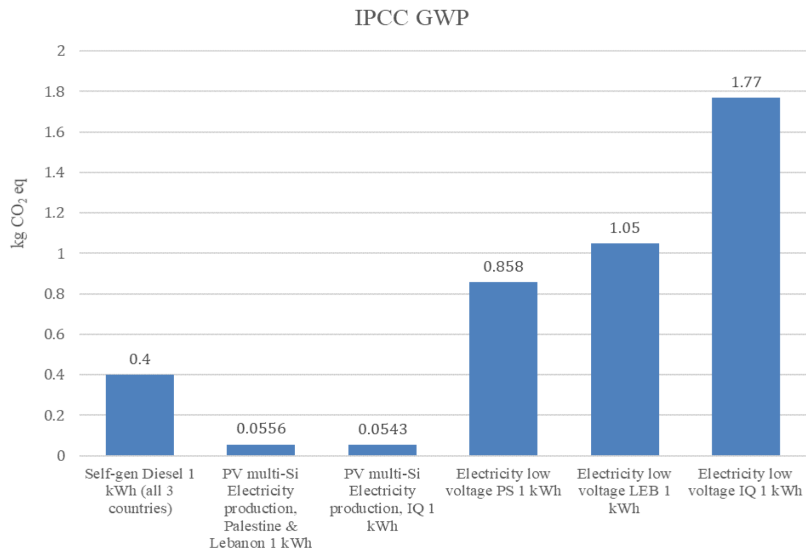


Figure 3. **IPCC 2013 GWP 100a V1.03 / Characterization for the three select countries**

Figure(s)

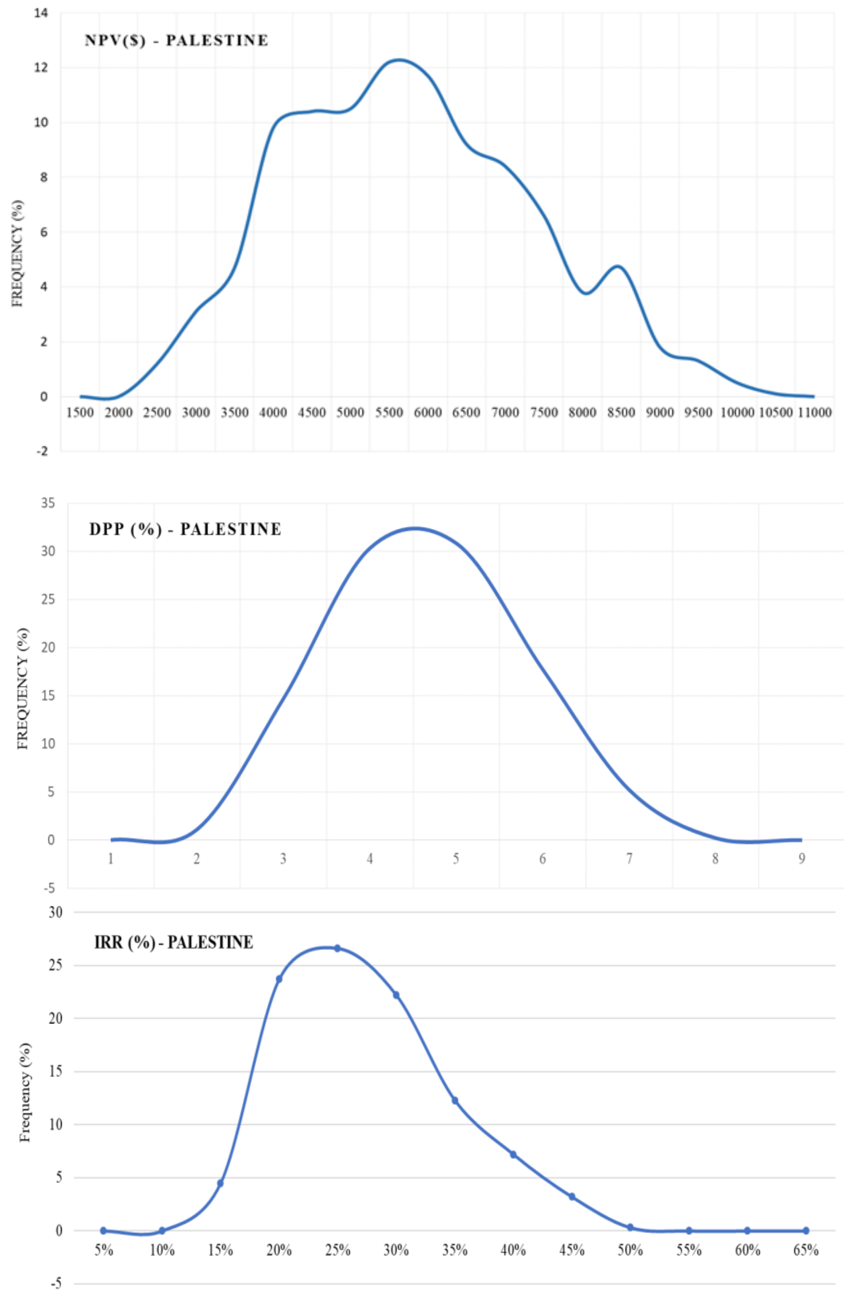


Figure 4. Financial appraisal results (NPV, IRR, DPP per kW invested) for solar PV in Palestine

Figure(s)

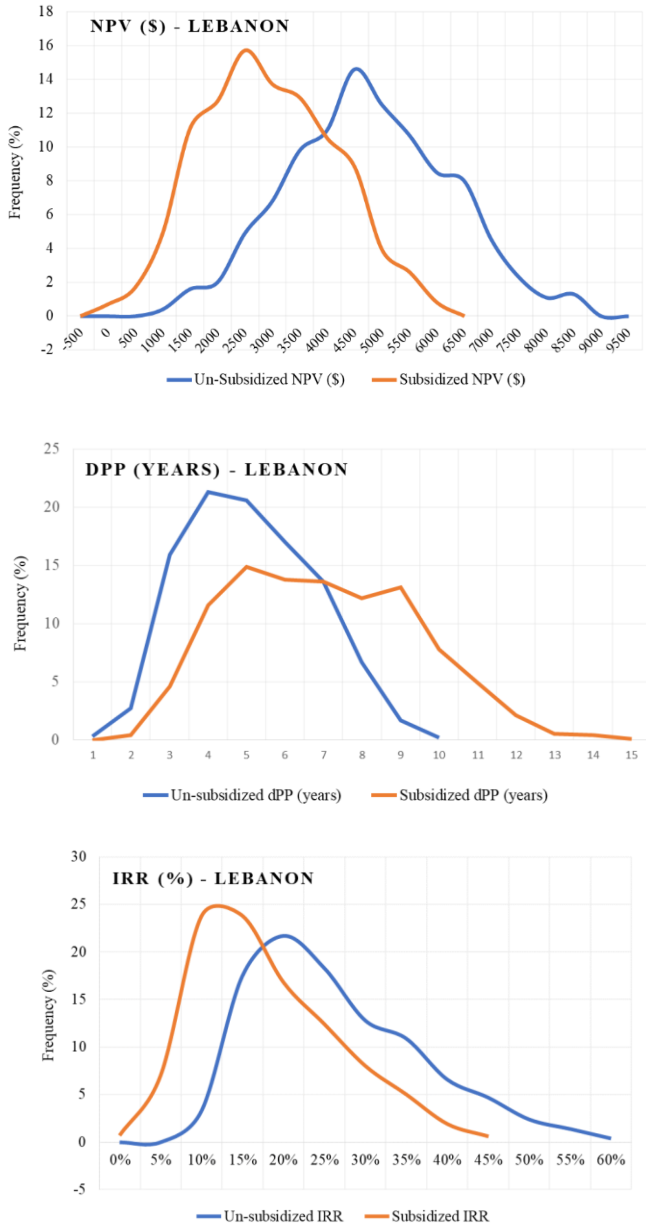


Figure 5. Financial appraisal results (NPV, IRR, DPP per kW invested) for solar PV in Lebanon

Figure(s)

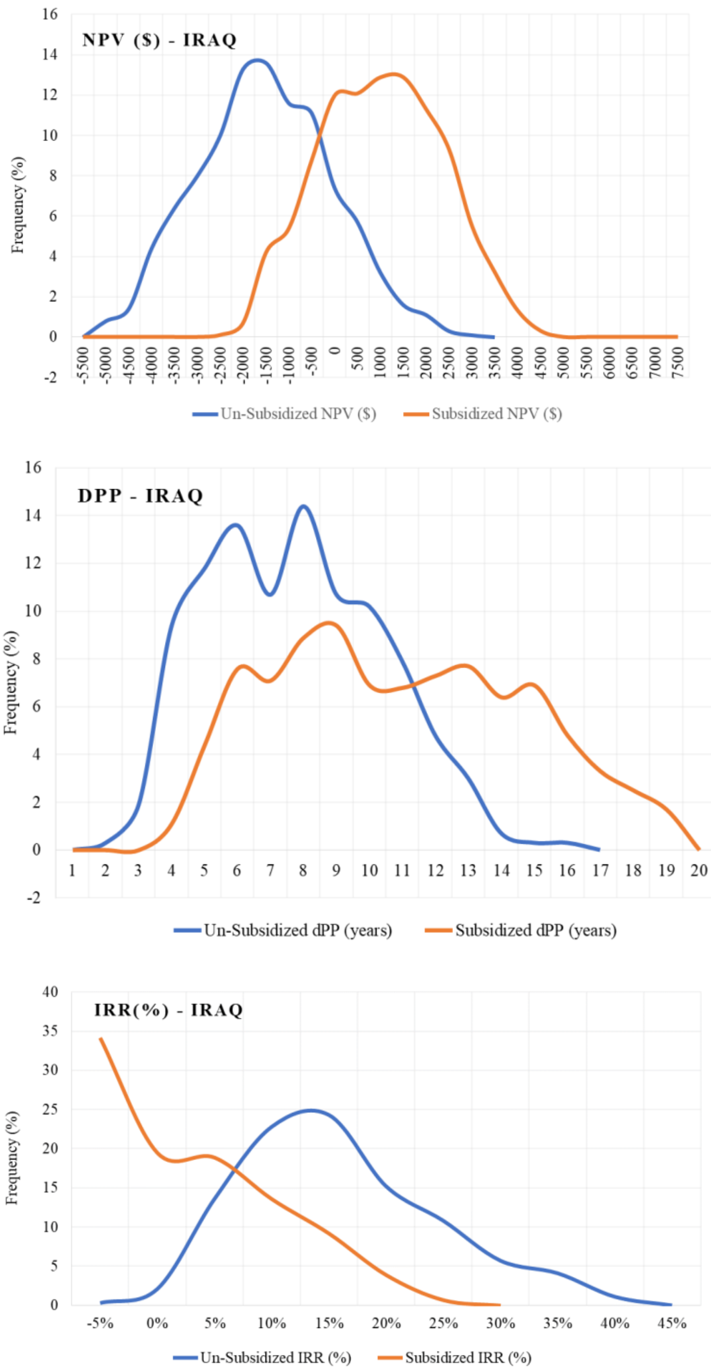


Figure 6. Financial appraisal results (NPV, IRR, DPP per kW invested) for solar PV in Iraq

Figure(s)

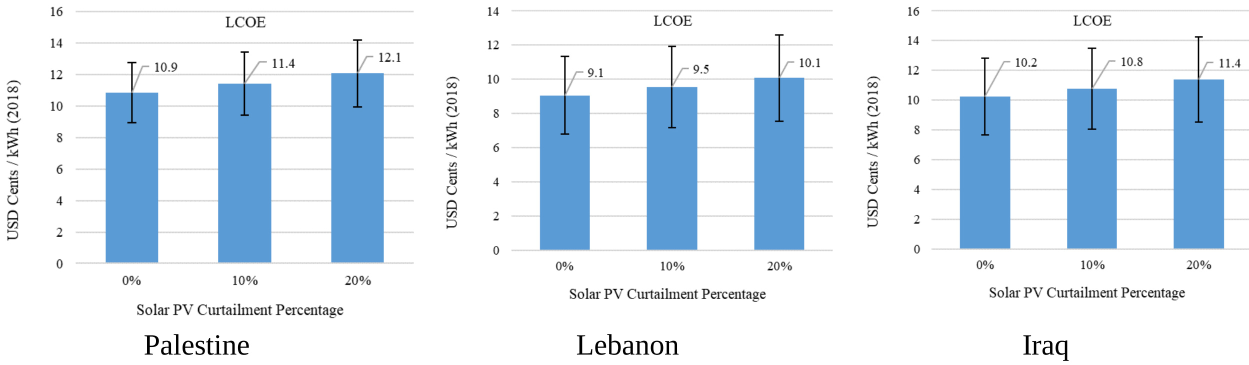


Figure 7. LCOE for solar PV system in the 3 select countries (USD cents/kWh – 2018)

Figure(s)

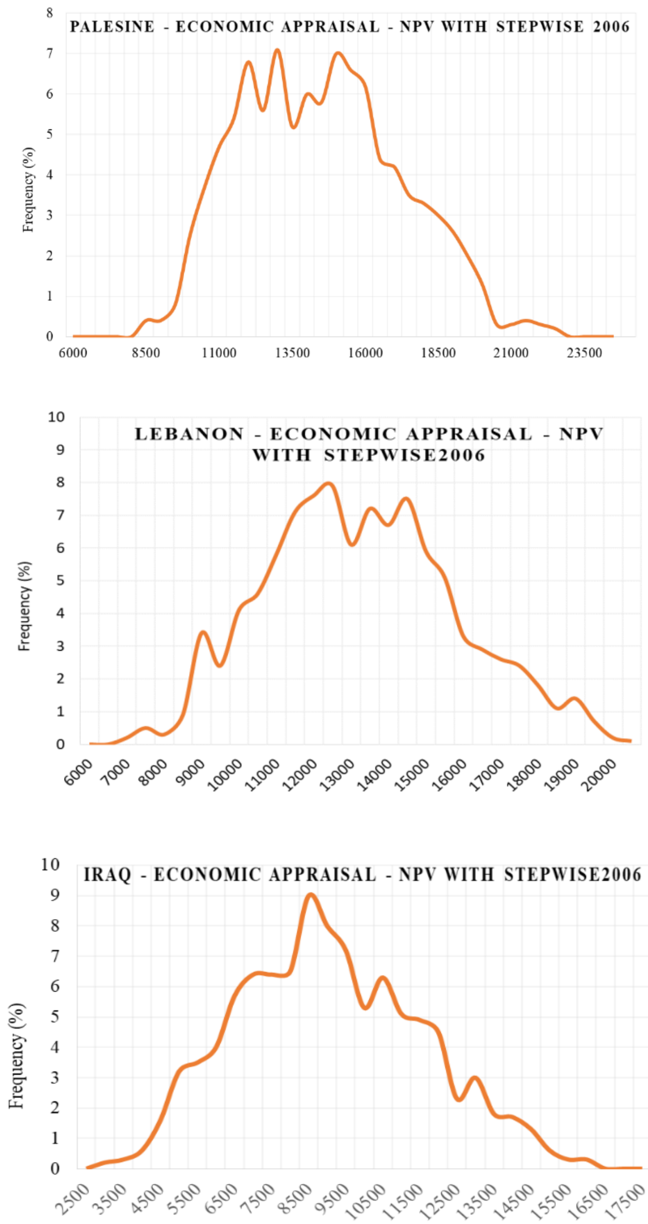


Figure 8. Economic assessment results (NPV per kW invested) for solar PV in the 3 select countries using Stepwise2006 results.

Figure(s)

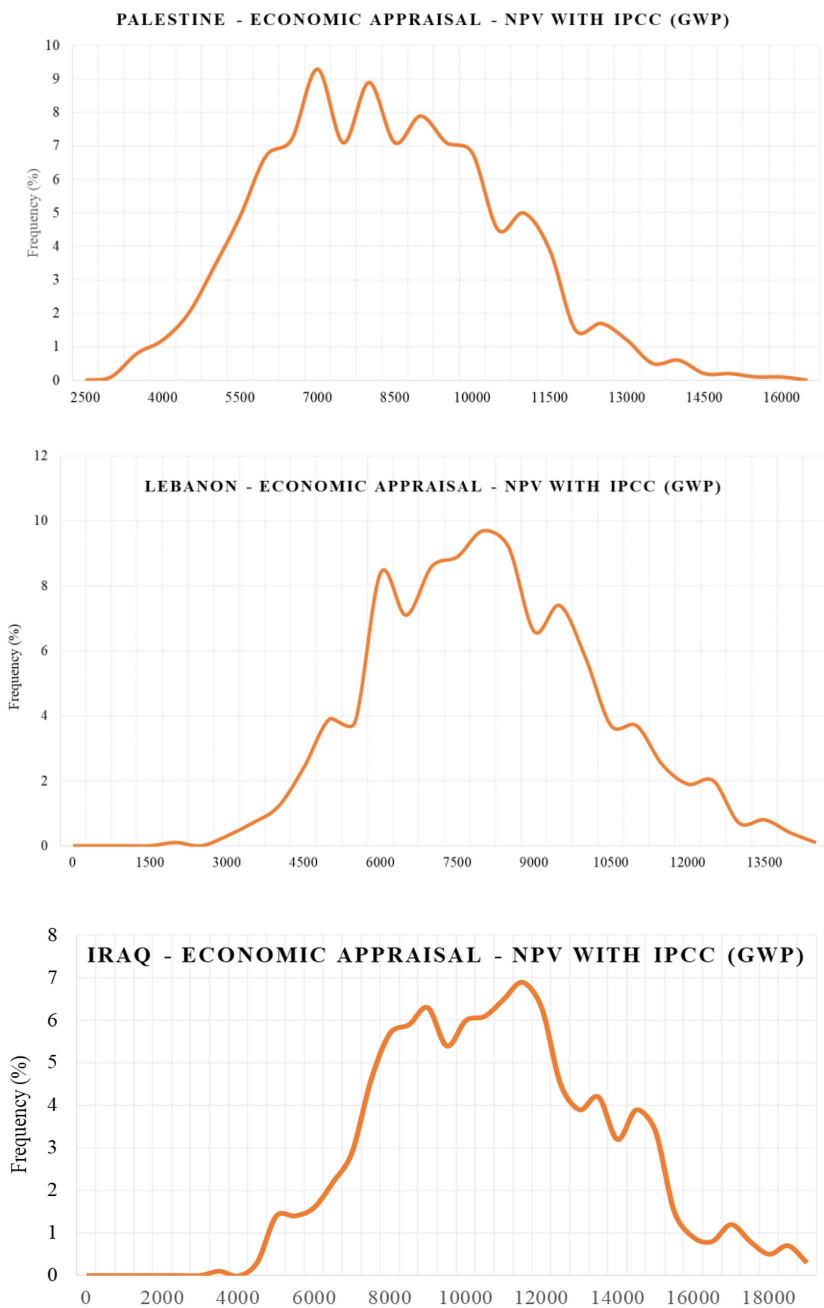
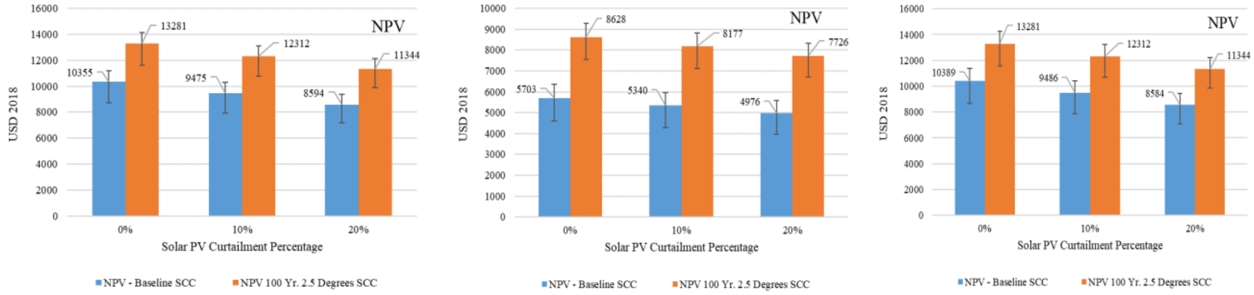


Figure 9. Economic assessment results (NPV per kW invested) for solar PV in the 3 select countries using IPCC GWP method results.

Figure(s)



Palestine Lebanon Iraq

Figure 10. Economic assessment results (NPV per kW invested) for solar PV in the 3 select countries using IPCC GWP method results.