Light at the End of the Tunnel in Lebanon's Electricity Crisis?
A Feasibility Assessment of Rooftop Solar

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Abstract

Solar energy offers Lebanon a unique window of opportunity to mitigate its endemic electricity woes. The country's power sector has long been constrained by problems ranging from ailing infrastructure to a rising demand exacerbated by an enormous influx of Syrian refugees. To meet demand, a decentralized sustainable energy strategy is needed to address the supply shortages and rising pollution while bypassing government inaction. This study aims to advance the understanding of the potential of PV rooftop technology as a viable power generation alternative for the city of Saida, Lebanon. An examination into the feasibility of the technical, financial, governmental and environmental potentials was conducted using a range of quantitative methods. The results of the study suggest a promising high yield generation capacity potential close to 16 MWp with a PV output of 1633 KWh per KWp. Financial results revealed solar achieving 'price parity' with fossil-fuel-based power with a number of incentives to improve its affordability. The Lebanese policy examination showed growing support for renewable energy generation, while environmental results offered insights into the GHG abatement and pollution decline due to solar transition. Overall, the study showed a strong support for rooftop solar to provide reliable, affordable and clean 24/7 electricity to Saida's residents. A recommended framework is provided to enable collaborative action to empower residents and local municipalities adopt sustainable on-site solar power generation. Future research may include replicating this study in other developing countries with similar context of electricity challenges.

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Acronyms and Abbreviations

AMPs	Amperes
BDL	Banque Du Liban (Central Bank of Lebanon)
BaP	Benzo[a]pyrene
CEDRO	Country Energy Efficiency & Renewable Energy Demonstration Project for the Recovery of Lebanon
CHP	Combined Heat and Power
CoM	Lebanese Council of Ministers
DHI	Diffuse Horizontal Irradiation
DNI	Direct Normal Irradiation
DO	Diesel Oil
EAPI	Energy Architecture Performance Index
EDL	Electricitè du Liban
FITs	Feed-In-Tariffs
GDP	Gross Domestic Product
GHG	Green House Gases
GHI	Global Horizontal Irradiation
GIS	Geographic Information System
GoL	Government of Lebanon
GTI	Global Irradiation for Optimally Titled Surface
GW	Gigawatts
HFO	Heavy Fuel Oil
IARC	International Agency for Research on Cancer
IMF	International Monetary Fund
INDC	Intended Nationally Determined Contribution
IRR	Internal Rate of Return
KG	Kilo-grams
KWh	Kilowatts-hour
KWp	Kilowatts peak or power peak
LBP	Lebanese Pound
LiDAR	Light Detection and Ranging

MoE	Ministry of the Environment in Lebanon
MoEW	Ministry of Energy and Water in Lebanon
MSW	Municipal Solid Waste
NG	Natural Gas
NEEREA	National Energy Efficiency and Renewable Energy Action
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
PAHs	Polycyclic aromatic hydrocarbons
PV	Photovoltaics
PVGIS	Photovoltaic Geographical Information System
RES	Renewable Energy Standard
ROI	Return on Investment
tCO_2	Tonnes of CO_2
UNDP	United Nations Development Program
VAT	Value Added Tax
WHO	World Health Organization

CHAPTER 1. INTRODUCTION

In the quarter of a century since the Lebanese civil war, the country's power sector has suffered from chronic problems ranging from supply deficits to a crumbling infrastructure. The widening gap between the supply and the demand for electricity has made blackouts a regular part of the Lebanese life. This is so prevalent that there is even a phone app for tracking the power rationing scheduling and the outages (Baalbaki, 2015). Having a reliable continuous supply of electricity has remained a fundamental challenge to the country's infrastructure.

This prolonged electricity predicament stems from a myriad of issues. First, the demand for electricity has been steadily increasing by an average rate of 7% per capita per year (Bouri & El-Assad, 2016). The country's peak generation capacity is 1.6 GW compared to a peak demand of 3.1 GW (Dubin, 2017). This significant shortage in meeting this demand (see Figure-1) is leading to daily power outages of 3 to 12 hours depending on area, and people are resorting to the use of the unregulated private diesel generators at an exorbitant cost of around 300% of the rates provided by the national power utility (World Bank, 2017), Electricitè du Liban (EDL) and is leading to further pollution as a result. To exacerbate the problem, the recent displacement of Syrian refugees into the country has resulted in an increase of approximately 25% to the existing population before the Syrian war (European Commission, 2017). A recent study has estimated the generation demand attributed to the displaced Syrians alone at 480 MW, which is equivalent to a cost of $330 million per year (AEMS, 2017).

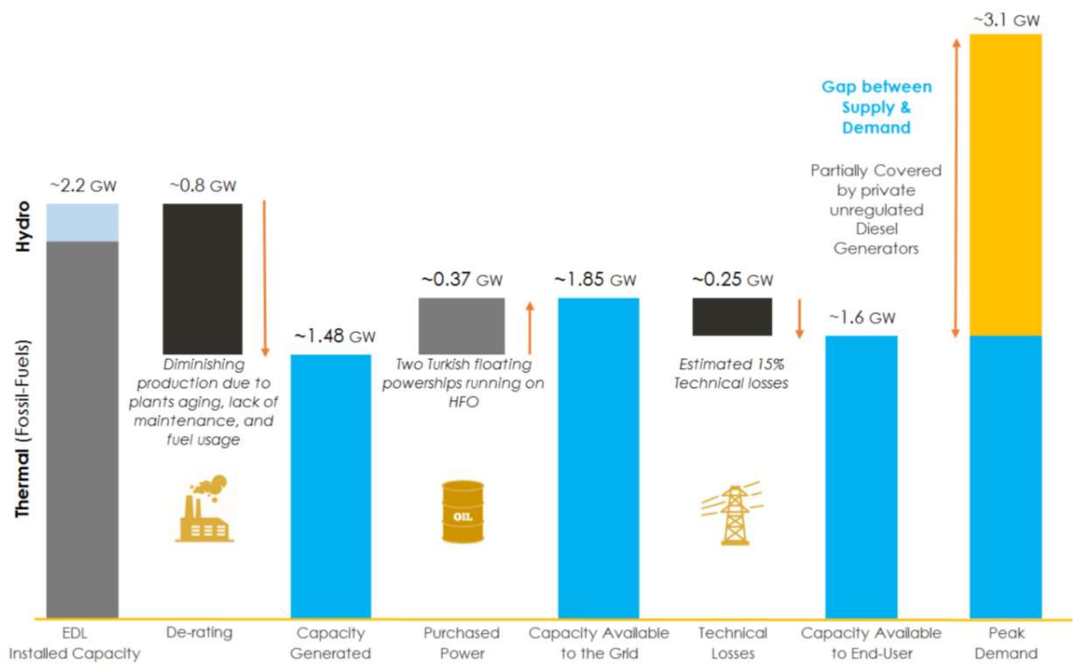

Figure 1. Supply and Demand of the Lebanese Power Sector. *Data Sources: Dubin (2017), EDL (2017), Karpowership (2017), Ministry of Energy and Water (2017), Ziade (2012).*

Another factor undermining the electricity stability in Lebanon is the country's ailing infrastructure (power plants, sub-stations, high power lines, etc.). Lebanon ranked 125th out of 127 countries on the global Energy

Architecture Performance Index (EAPI, 2017). The majority of Lebanon's fossil-fuel power plants are nearing the end of their lifetime, thereby losing efficiency and reducing their output capacity. Lack of maintenance puts yet another strain on the system. Finally, the use of a sub-optimal fuel mix dampens the efficiency of the original installed capacity due to a decision to use heavy fuel oil (HFO) to operate a turbine designed for natural gas (Ziade, 2012). Such inefficiencies have strained the outdated grid resulting in systematic blackouts ranking Lebanon 3rd globally in the number of power cuts per month (Figure 2).

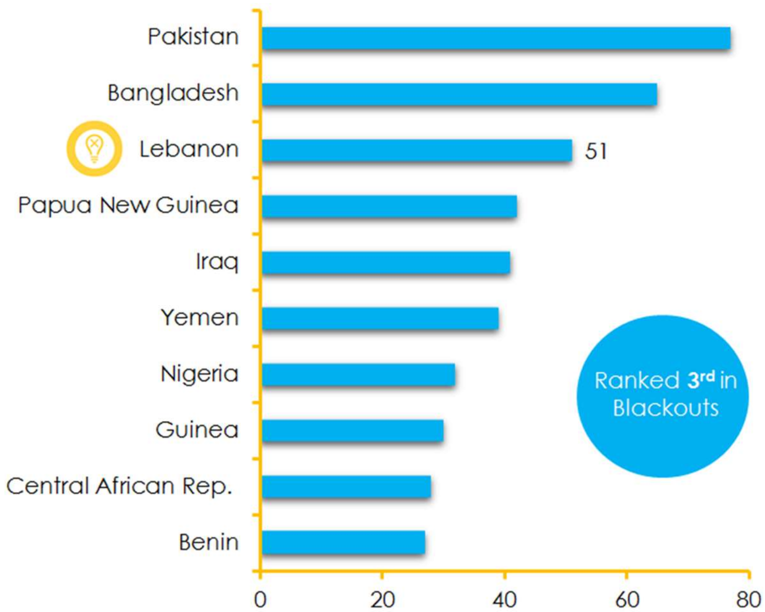

Figure 2. Top 10 Countries in Number of Cuts per Month. *Data Source: The World Bank and Enterprise Surveys (2016).*

A third factor fueling the Lebanese electricity malaise can be attributed to the political gridlock and oligarchical corruption ingrained in the governmental system of the country. This poses a key impediment to any reform in the power sector either through EDL rehabilitation or through privatization. Consequently, the country's national electricity utility, EDL, had been incurring large financial losses annually (cumulative $27 billion deficit year-over-year since 1992, Baalbaki, 2015) while failing to meet demands. The consumer has also been suffering exorbitant prices for electricity. Not to mention, the Lebanese people spend on average 14% of their median household income (19.6 Million LBP in 2014) on electricity expenditures - one of the highest per capita (Gallop, 2014).

The aforementioned factors contribute directly to the tumultuous state of electricity in Lebanon along with the adverse economic and environmental implications they carry. A significant potential improvement in this dire situation would be the replacing of the centralized fossil fuel dependency with decentralized renewable production. Chief among the renewable options is energy derived from solar photovoltaic - the primary focus of both this immediate research and the longer-term proposed strategy of the Lebanese power sector.

Purpose of the Study

The purpose of this study is to assess the feasibility of photovoltaic (PV) solar as the main source for electricity generation for a representative residential area in Lebanon. The study addresses the need of more research for a viable power production source that is decentralized in nature, particularly in country where severely constrained power generation. The research focuses on the feasibility of rooftop solar as the key renewable energy source of interest driving a decentralized energy generation strategy. The study has the following objectives:

- To review the existing public policy pertaining to energy generation and advocacy programs for renewables including solar.
- To analyze the feasibility of financial assistance for PV projects through comparative cost analysis and cost-benefit evaluation.
- To analyze the environmental implications of solar energy including avoided carbon emissions and mitigated pollution.
- To analyze technical potential of the study's location in terms of meteorological, solar resource, geographic data.
- Draw upon the various disciplines (environmental and energy policy, renewable energy, quantitative research methods, finance, engineering, etc.) to synthesize the results of this study into solid recommendations.

Assumptions and Limitations

The study was conducted with the general assumption that respondents' responses are accurate and free of coercion involved in the participation process. The study's scope was limited to residential consumption scale only and does not cover commercial or industrial sectors. The study was also limited to a representative, mid-sized Lebanese city, Saida which could be utilized as a model for replication across different areas in the country. In addition, Saida is among the cities experiencing higher than average daily power cuts, so it was assumed it is a good representative for this study.

Research Questions

The study aims to explore the overall research question: To what extent can PV rooftop solar be utilized as a viable energy generation solution for the local Lebanese population to achieve electricity independence? To further answer this question, the following sub-questions were developed:

- Policy: To what extent do current public policies support renewable energy and PV installations?
- Financial: To what extent are existing solar loans fiscally sound?
- Environmental: To what extent can the possible PV displacement of fossil fuel power impact carbon emissions and diesel pollution?
- Technical: To what extent is Saida well-suited geographically for solar development?

Significance of the Study

This study sheds light on the supply of a fundamental necessity for a country suffering from electricity instability for decades. Reliable and affordable electricity has been at the core of the economic growth and global competitiveness for all countries (World Bank, 2008). For the Lebanese, having a viable renewable source of energy that can help mitigate the current economic and social disruption is a quintessential development goal. The long term implications of such renewable solution might include:

- Social: Empowering the local-residents to generate their own electricity, thereby improving their quality of life, by bypassing the failed public utility and the private generator “mafia”, as it is commonly termed.
- Environmental: Elimination of the diesel pollution currently overwhelming local neighborhoods from the private diesel generators and reduction of carbon emissions from the use of fossil fuel.
- Economic: Enhancement of economic development as a result of more infrastructure stability and a financial savings from current electricity costs.

CHAPTER 2. BACKGROUND

To anchor an understanding of how viable autonomous renewable energy can be to bridge the power gap in Lebanon, it is necessary first to examine the literature on the subject. This chapter reviews a gamut from the profile of the study's site to the application of solar energy in developing countries.

Lebanese Power Sector

The phenomenon of daily electricity outages has been ingrained in the Lebanese way of life. The country has been suffering due to the failures of the power sector for the past 25 years (Thornton, 2016), while witnessing the government paralysis on the issue since then. The crux remains around the country's failing sole public utility Electricitè du Liban (EDL).

The public utility, EDL, shows an alarming trend of operational losses that are typically covered through annual bailouts averaged at $1.4 billion from the state treasury (Halawi, 2017). The soaring EDL deficit is close to 40% of the national public debt (World Bank, 2017) leading to fiscal deterioration. Global organizations monitoring the fiscal condition in Lebanon like The World Bank and the International Monetary Fund (IMF) have long advocated for power sector reform as a key strategy to achieve fiscal stability (IMF, 2017). The EDL operational shortcomings reflect not only financial losses, but also other inefficiencies including billing non-collection, governance failures, and illegal gird connection (IMF, 2014).

Despite the hefty support from the Lebanese government, EDL covers a fraction of the power needed per seasonal demand (see Figure 1; EDL, 2017). The epidemic shortage has pushed the residents to resort to the neighborhood diesel-run generators that are exceedingly expensive and notoriously polluting (Aziz, 2015). The lucrative business of private generators adopts a territorial monopoly model involving practices like price-gauging, tampering with supply, and using firearms for own-turf protection (The Economist, 2015). Consumers are saddled with high costs of electricity access, paying two monthly bills for the pricey diesel generator subscription, and also for EDL's erratic power.

Saida City Profile

Saida (*Sayda* or *Sidon*), the third largest Lebanese city, is located on the eastern basin of the Mediterranean just at southern coastal part of Lebanon. It lies approximately on Longitude 35.3° and latitude 33.5°

(SolarGIS, 2017). With a surface area of 7 Km^2, the population density is around 774 inhabitants per Km^2 (Hammoud & Hijazi, 2013) excluding the recently added 42,213 Syrian refugees in the city (AMES, 2017). As a result, such population upsurge puts a strain on the resources of the city.

Figure 3. Saida City Location.
Source: MapaMundial (2015)

Despite being dubbed as the capital of South Lebanon, Saida's power infrastructure continues to lag behind its peers. The city suffers from power rationing ranging from 6 to 8 hours per day. Problems like overloading the distribution transformers and sporadic low-voltage networks in densely populated areas pose a hazard, poor voltage quality, and spontaneous power breakdowns (Barthel, 2014). Saida receives its power mainly from the Zahrani combined cycle power plant operated by EDL. The plant turbines were optimally designed for natural gas, however, the turbines were repurposed to use dirty oil fuel leading to considerable degradation in efficiency and higher fuel consumption costing $0.21 per KWh (Bouri & El-Assad, 2016; Ziade, 2012). From insufficient generating capacity to technical gird losses, the state of chronic electricity has pushed residents in Saida to resort to private neighborhood diesel generators at a hefty cost of $0.29 per KWh. According to the local municipality (2017), Saida has 33 operators of power diesel generator covering 48 neighborhoods. These unregulated generators remain as an unnecessary source of pollution due to noise and diesel exhaust.

Apart from the fossil fuel power generated from the public utility and private neighborhood generators, the city's Municipal Solid Waste (MSW) treatment center generates combined heat and power (CHP) from close to 300 tons of waste daily. The generated biomass power is used only to run the treatment center plus street lighting (Saadeh & Mikhael, 2015). Finally, the solar power share of Saida's power mix is negligible (under 0.11%, UNDP, 2016).

Climate Change

Saida has a Mediterranean climate characterized by hot dry summers and cool wet winters (MoE, 2016). The warm and temperate typical climate of Saida averages more than 300 sunshine days a year (Karam, 2016). The average annual temperature of the city is at 20° C (Climate-Data, 2017). However, temperatures are projected to rise by the end of the century.

The Lebanese Ministry of the Environment (MoE, 2016) published results predicting an increase of up to 2 °C by 2050 and up to 5 °C by 2100. The predictions also reveal a precipitation decline suggesting seasonal prolongation of hotter and drier conditions leading to adverse impacts. Climate change presents a diverse set of implications for the City of Saida including the following vulnerability (MoE, 2016):

- Water accessibility: Climate disruptions will impact water availability in the summer while increasing floods in the winter exacerbating the existing water challenges facing the region.
- Droughts: Extended hotter and drier periods will lead to draughts which will in turn require additional resources to mitigate its effects.
- Increased energy demand: Higher temperature in the summer translates into increased the need for cooling. This puts a strain on an already stretched supply.
- Sea level rise: Based on the historical sea rise rate of 20 mm per year, the higher sea levels mean increased coastal flooding and inundation. This poses as a risk for the coastal city.
- Public health effects: Higher temperatures increase the risk of infectious diseases, morbidity, and mortality.
- Food security: Climate impacts will lead to fewer crops due to aridity of land and increased infestation.

One of the key contributors to anthropogenic GHG emissions is the energy sector dominated by electricity production. More than half of the country's total GHG emissions are attributed to energy (MoE, 2015). Fossil fuel power generation using outdated inefficient technologies is mainly responsible for 98% of the energy sector carbon footprint (MoE, 2016). Therefore, transitioning to renewable energy (e.g. solar) offers an enormous window of opportunity for GHG abatement.

Rooftop Solar

Southern Lebanon's adoption of PV Solar is nascent (11% of the country's already insignificant MW capacity), lagging behind the nation's other major cities (UNDP, 2016). A survey of Lebanese residents on solar technology had revealed that 68% of the respondents are unaware of PV solar for power generation (LCEC & UNDP 2014). Among those who knew about PV solar, only 4% had rooftop solar installed. This dearth of solar usage is mainly attributed to the cost perception barrier (e.g. 75%) or other minor factors like maintenance requirements and rooftop space constraints (LCEC & UNDP 2014). Note that the cost of PV solar systems has been falling drastically in the past 7 years in Lebanon. According to the latest solar status report for Lebanon (UNDP, 2016), the turnkey price of Solar PV systems in 2015 has plummeted by 66% from the 2010 levels. The price is expected to further drop ameliorating the outdated consumer perception of solar affordability.

The falling cost of solar coupled with the various configurations of PV solar systems, can provide tailored energy options for residents choosing from numerous types (Zipp, 2015). The PV residential-scale configuration most suitable for Saida is the grid-connected rooftop PV systems with a battery bank backup. This provides the resident with solar energy that can be used during the day or during the public utility rationing periods. The PV system also includes net metering, a recent service enabled by EDL, that can credit any excess solar energy to the resident's account as it passes through the bi-directional meter and into utility grid (EnergySage, 2017). Figure 4 demonstrates how the rooftop solar system works.

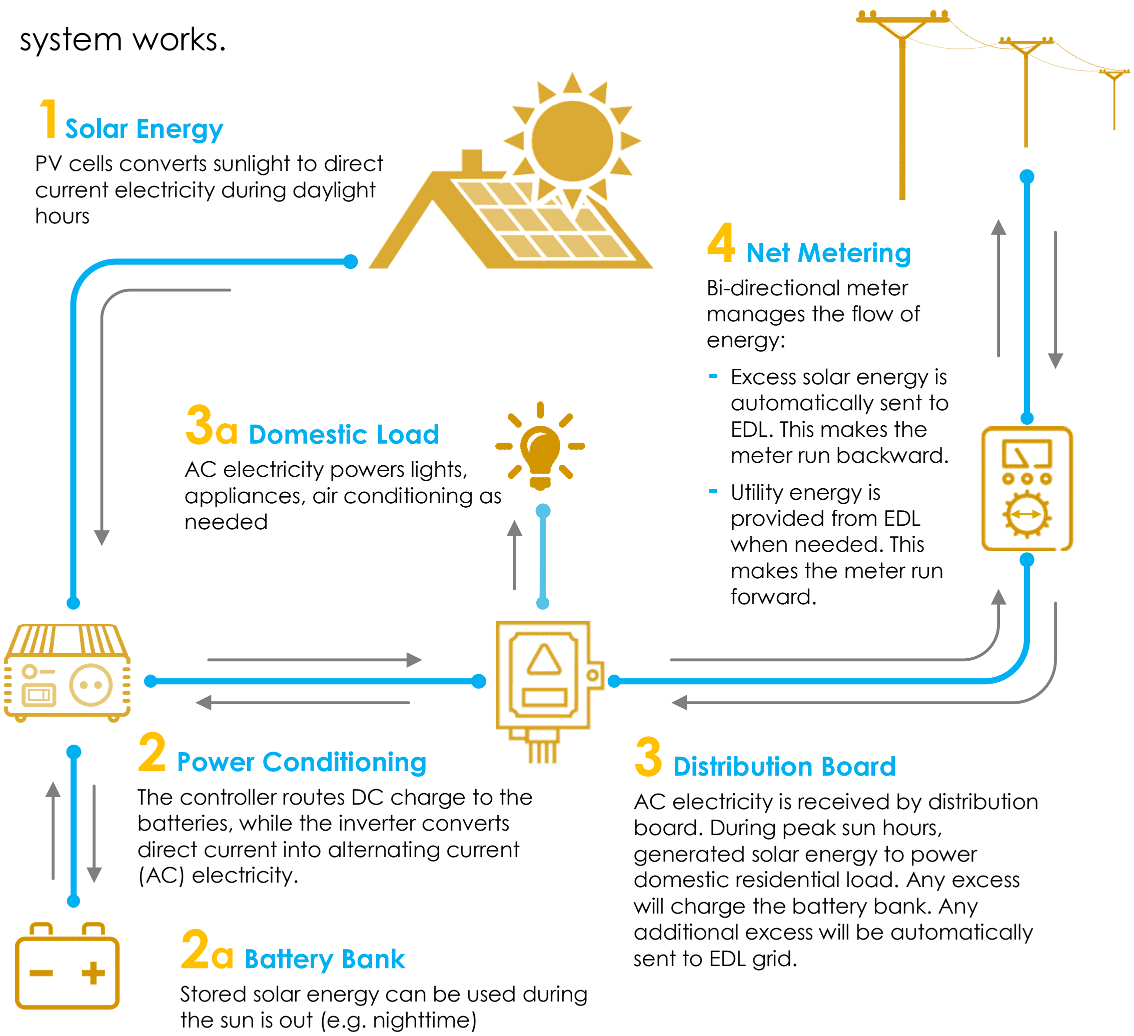

Figure 4. How the Grid-Tie PV Hybrid System Work? *Icon Sources: Noun Project, Shutterstock.*

The strategy of using rooftop solar for residential energy generation to address the electricity shortcomings is consistent with other developing countries. Applications of rooftop solar in other developed parts of the world include displacement of diesel generators in Kenya (Rose, Stoner, Perez-Arriaga, 2016), electricity access for rural residents in India (Dhiman, Chaudhury, Deb, & Chakrabati, 2017), mitigating GHG emissions in China (Duan et al., 2016). Rooftop solar helps eliminate costly investments in fossil fuel thermal plants, reduce the reliance on overloaded electric grids, and displace more expensive diesel generation. All of the latter benefits are much needed to solve the existing electricity challenges in Lebanon, which makes rooftop solar as a promising energy generation option. The remaining question is to explore the implementation feasibility of such an option.

CHAPTER 3. METHODS

The purpose of this study is to explore the extent to which rooftop solar systems pose a viable, decentralized solution for power production in the City of Saida, Lebanon. To do so, several factors are examined solar potential feasibility, including financial, technical, and environmental factors. This chapter outlines the various procedures, tools, and the data utilized for this study.

Financial Analysis

To assess the financial feasibility of residential photovoltaic (PV) solar, two different analyses have been conducted: (a) a comparative analysis consumer's cost of kilowatts-hour (KWh) consumed, and (b) a financial soundness assessment for an average residential rooftop solar project. The two financial analyses address the sub-questions as to what degree solar is affordable for the residents in Saida and how to embark financially on a rooftop solar project. The results calculations are presented in chapter 4.

For the comparative analysis, the current prices of local electricity have been obtained through the published tariffs (EDL, 2017) and other sample power bills issued by Electricitè du Liban (EDL). These prices were then examined, along with recent articles and studies, in order to derive the effective cost paid by the consumer in KWh for both power purchased from EDL and from the private diesel generators.

The cost of solar power has been derived from the total cost of a 3-kilowatts-peak (KWp) rooftop solar system along with its power generation yield over the course of its lifetime. A degradation of performance is factored into the extrapolation along with the cost of a one-time backup battery replacement. The cost of the three power sources (public utility, diesel generator, PV solar) is based on 10 amperes (AMPs) baseline of an average residence with moderate electricity usage. The derived solar cost per KWh was then graphed to compare it with the previously obtained consumer costs of EDL and neighborhood diesel generators.

For the financial evaluation of a rooftop solar project, four parameters have been identified to determine the financial soundness of rooftop solar. The parameters Net Present Value (NPV), Internal Rate of Return (IRR), Return on Investment (ROI), and Simple Payback are commonly used to assess the financial benefits and costs of infrastructure projects and are therefore paramount to the decision-making process important to the residents of the city. The parameters are defined as the following:

- NPV: the Net Present Value is the tool of choice for assessing the financial worthiness of a project as it translates the future benefits expected from investment in today's dollars (Gallo, 2014). In this case, the NPV was calculated by adding the discounted cash flows of avoided power subscription for 25 years, the assumed lifespan of the solar system. The cash flows calculation included any avoided electricity costs resulting from either the fixed rate paid for any diesel electricity that would be generated or the public utility electricity rates.
- IRR: the Internal Rate of Return is the rate used to measure the breakeven point of a proposed project. This measure is important in order to compare the rate of return of an investment with a hurdle rate, hence determining the attractiveness of the proposed project compared to other undertakings requiring the same financial investment (Gallo, 2016). The IRR is calculated by finding the rate at which the cumulative NPV of the solar project is equal to zero.
- ROI: the Return on Investment ratio indicates the degree of profitability of a project based on the return realized from the project versus the initial investment made on the project.

- Simple Payback: the calculation of a repayment period is the time needed for the accumulated savings from the project to become equal to the initial cost of the investment.

The feasibility assessment for this study utilized a 3.1 KWp hybrid system as a baseline for the assessment. The complete system includes 10 solar panels, an inverter, controller, monitor, and backup batteries. A Microsoft Excel macro is used to develop the calculations for the four financial parameters. The discount rate used for this analysis was 6%, while the inflation rate is assumed at 2.6% (World Data Atlas, 2017). Five iterative scenarios were considered for parameters calculations:

- Outright purchase: The scenario assumes the resident pays for the PV rooftop system upfront with no incentives involved.
- Subsidized financing: The scenario assumes the financing of the PV system over the course of 10 years and a 1% interest rate.
- Tax credit: The scenario assumes the resident pays for the PV rooftop system upfront and receiving a 10% tax credit.
- Net metering: The scenario assumes the resident pays for the PV rooftop system upfront and receiving a net metering benefit of 500 KWh annual offset with EDL.
- Incentivized Mix: This is a cumulative scenario of all the three incentives of subsidized financing, tax credit, and net metering.

Technical Analysis

To assess the technical feasibility of solar power in the City of Saida, the study employed various tools in order to obtain the data needed. The Global Solar Atlas (2017) and SolarGIS (2017) were used to derive the area solar characteristics of the study's geographic location (33.56° N, 35.39° E). This includes the following parameters (Global Solar Atlas, 2017; NREL, 2017):

- Global horizontal irradiance: Measured in KWh/m^2, GHI is the total amount of solar radiation received by a horizontal surface.
- Direct normal irradiance: Measured in KWh/m^2, DNI is the total amount of solar radiation received by a surface perpendicular to the falling rays.
- Diffuse horizontal irradiance: Measured in KWh/m^2, DHI is the scattered or diffused solar irradiance received by earth surface.
- Global tilted irradiance: Measured in KWh/m^2, GTI is the sum of both direct and diffuse solar irradiation received by an optimally tilted surface.
- Optimum inclination angle: Optimal inclination angle of a PV panel for a specific azimuth.
- PV output: Amount of electricity generated by the PV system in KWh per KWp.

- Temperature: air temperature at 2 meters above the surface.
- Elevation: Terrain altitude above the sea level in meters.

In addition, the annual power generation potentials were derived using a number of solar models (EU PVGIS, 2014; Global Solar Atlas, 2017; IRENA, 2017; NREL PV Watts, 2017; ONYX Solar, 2017; Solar Med Atlas, 2010; Sunmetrix, 2017; System Advisor Model, 2017) covering the Middle East and North Africa (MENA) region. The KWh/y calculations are based on a 3.1 KWp rooftop solar system. Finally, the results from the model outputs along with the average monthly global tilted irradiance were graphed for comparison.

WorldMap (2015) software was utilized to for rooftop isolation, where roof footprints were assessed using Light Detection and Ranging (LiDAR) technology. The City of Saida was divided into 11 districts featuring residential buildings identified for rooftop measurement that could be leveraged for solar installation. Once the geographic information system (GIS) rooftop digitization was completed, the high yield generation potential was extrapolated. It is assumed that only 50% of the estimated rooftop area is usable, accounting for the existing obstacles (water tank, solar water heater, fire code safety setback, etc.). Using the average footprint and the baseline 3.1 Kwp PV systems selected for the study, the megawatts (MW) high yield capacity potential for solar was calculated using the estimated rooftop footprint and the PV output averaged from the aforementioned solar models. Finally, the collected data utilized ArcGIS software to build the solar map of the City of Saida districts.

Policy Analysis

To analyze to what extent the current public Lebanese policies support renewable energy, particularly PV installations, all the recent major laws pertinent to energy policy are analyzed. This study also comparatively examined the existing laws to show the public policy support of fossil-fuel energy versus other renewables. Each law was evaluated in terms of the following parameters:

- Legal: Establishment of a legal framework in order to encourage parties to the generation, distribution or transmission of electricity sourced from various energy sources (e.g. renewable energy standards or RES).
- Financial: Advocacy for solar energy through tax incentives, credits, subsidized loans or any other monetization form.
- Standards: Providing guidelines for operation, net metering, feed-in-tariffs (FITs), and other schemes pertinent to renewable energy.
- Environment: Containing any policies that would reduce emissions, mitigate pollution, or implement sustainability measures.

- Effectiveness: Assessment of the overall effectiveness of the introduced policy in terms of meeting its objectives and promotion of solar energy.

The results were tabulated for each law or policy along with a side-by-side comparison of the two energy categories. Below is the listing of all the main regulatory measures in relation to the government's strategy of the power sector.

- Law 462 - Electricity Sector Organization: A law that established the governance for electricity sector including a framework to start the privatization of power generation, transmission, and distribution (Government of Lebanon, or GoL, 2002).
- Circular # 236 Banque Du Liban (BDL): A memorandum of understanding between the Lebanese Central Bank and the United Nations and Development Program (UNDP) that launched and supported the National Energy Efficiency and Renewable Energy Action or NEEREA (BDL, 2010).
- Law 132 - Offshore Petroleum Resources Law: A law to establish the framework for offshore drilling, exploration, and rights for petroleum activities within Lebanese territorial waters (GoL, 2010).
- The 2010 Policy Paper for the Electricity Sector: A plan set by the Lebanese Ministry of the Energy and Water (MoEW) to revamp the

electricity sector by increasing its capacity through resource diversification (MoEW, 2010).

- National Energy Efficiency Action Plan: Prepared by the Lebanese Center of Energy Conservation (LCEC), a comprehensive sustainability roadmap includes several efficiency strategies and future targets of renewable energy generation and greenhouse gas (GHG) emissions (LCEC, 2011; LCEC, 2016).

Environmental Analysis

Potential environmental benefit was assessed through comparative analyses of the carbon emissions of solar-generated electricity versus other existing fossil-fuels sources. The input data of the evaluation exercise was gathered from various sources, including the Lebanese Ministry of the Environment. The emissions intensity of each of the electricity sources (i.e. Zahrani HFO power plant and the neighborhood diesel generators) in the City of Saida was compared against the PV solar measured in grams CO_2 eq. per KWh. Next, the GHG emissions were calculated using the emission intensity factors and the previously derived rooftop footprint feasible for solar installation. The avoided GHG emissions results were tabulated in two formats – 1 and 25 year spans.

CHAPTER 4. RESULTS

This chapter summarizes the outcome of the qualitative and quantitative analyses. The results were presented in four thematic areas – financial, technical, environmental, and policy. Note that the results are discussed in the next chapter in relation to a broader context of the study.

Financial Results

To assess the financial feasibility of residential PV solar, two different analyses were conducted: (a) a comparative analysis of consumer's cost of KWh consumed, and (b) a financial soundness assessment for an average environmental benefit.

Electricity Cost

The state-owned Electricitè du Liban (EDL) has residential tiered tariffs that have remained unchanged since 1994, when oil was at $20 a barrel. The tariffs range between $0.02 and $0.13, depending on user's consumption (EDL, 2017). Samples of ten recent local electricity bills were analyzed for the price of average KWh. After factoring in the monthly subscription fee, rehabilitation fee, stamp fee, and a value added tax

(VAT), the average KWh is at $0.11. This is comparable to other sources whose range of EDL KWh pricing between $0.094 (Ibrahim, Fardoun, Younes, & Gualous, 2013) and $ 0.13 (World Bank, 2017). In addition, the Lebanese Ministry of Energy and Water (MoEW) has announced recently that tariffs will gradually increase by 40% over the next 2 years. Similarly, the neighborhood diesel generator bills were examined to derive the KWh cost. As a result, the equivalent of 10 amperes (AMPs) capacity can be averaged to be $0.29. Note that pricing hikes in certain areas can reach up to $0.4 (Assi & Kaaki, 2016) and even $0.5 (Tisdall, 2013) per KWh.

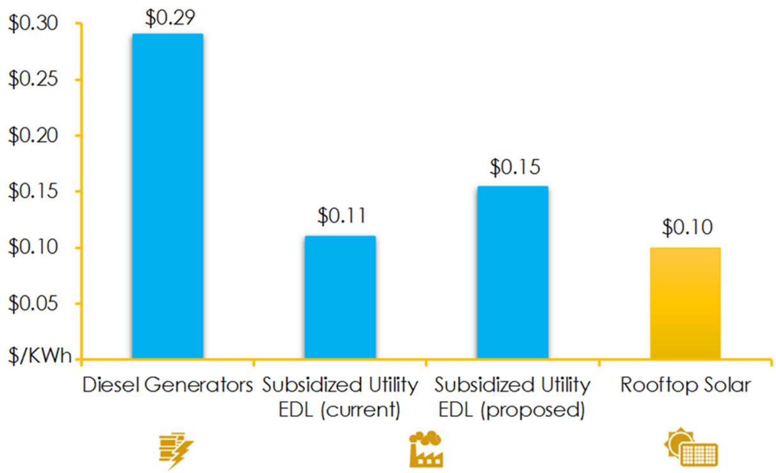

Figure 5. Comparative Power Cost Analysis per KWh in Saida, Lebanon.

Finally, the solar KWh pricing can be extrapolated from the cost of the initial rooftop module system plus the operation and maintenance (O&M) fees over the lifetime of the module. This puts the proposed solar generated power at $0.1 per KWh. Figure 5 shows the comparative pricing analysis of the consumer's power cost from diesel generators, current EDL cost, proposed EDL cost reflecting the announced 40%, and rooftop solar.

Financial Evaluation

The four parameters - NPV, IRR, ROI, and simple payback - were calculated to evaluate the financial soundness of a 3.1 KWp grid-connected rooftop solar system. The evaluation analysis constituted of five different scenarios tabulated below.

Scenario	NPV	IRR	ROI/yr.	Payback
Outright Purchase (pay for system at installation - no other benefits)	$11,452	13%	15%	8 years
Subsidized financing (1% interest for 10 years)	$14,168	13%	15%	8 years
Tax Credit (10% tax subsidy)	$12,584	14%	17%	7 years
Net Metering (500 KWh grid fed)	$11,488	13%	15%	8 years
Incentivized Mix (Tax Incentive + Subsidized Financing + Net Metering)	$15,335	15%	16%	7 years

System Considered: 3.1 KWp with an average generated output of 5062 KWh. Discount Rate = 6%. Inflation Rate = 2.6%. Estimated Diesel Electricity Rate = $0.29 per KWh. System Cost = $12,000. O&M = 10% of SC. System Lifetime = 25 yrs.

Table 1. Financial Evaluation of a Grid-Connected 3.1 KWp Solar System Installed in Saida.

Technical Results

Solar Potential

The result from the Global Solar Atlas simulation provides a summary of the estimated PV solar potential of the city of Saida. The following SolarGIS maps represent the annual averages from 1999 to 2015 for the solar potential parameters (Global Solar Atlas, SolarGIS, 2017).

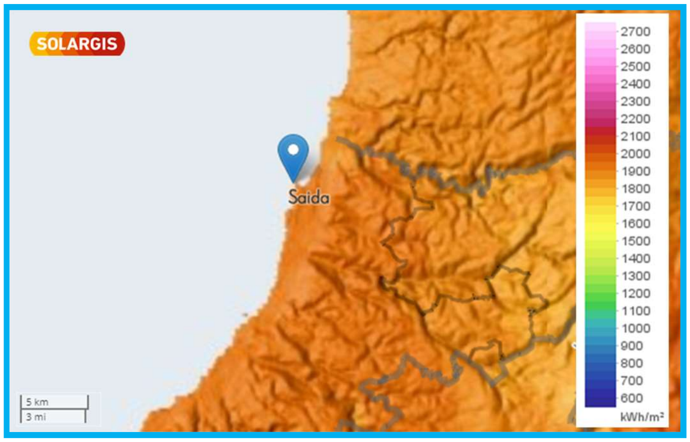

Figure 6. Global Horizontal Irradiation (GHI) in KWh/m^2 of Saida, Lebanon.

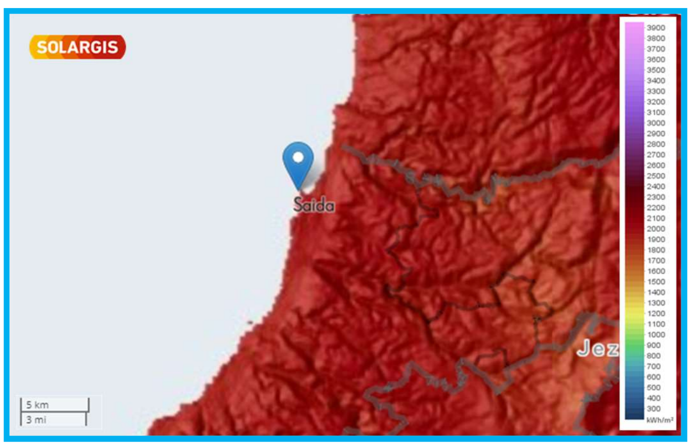

Figure 7. Direct Normal Irradiation (DNI) in KWh/m^2 of Saida, Lebanon.

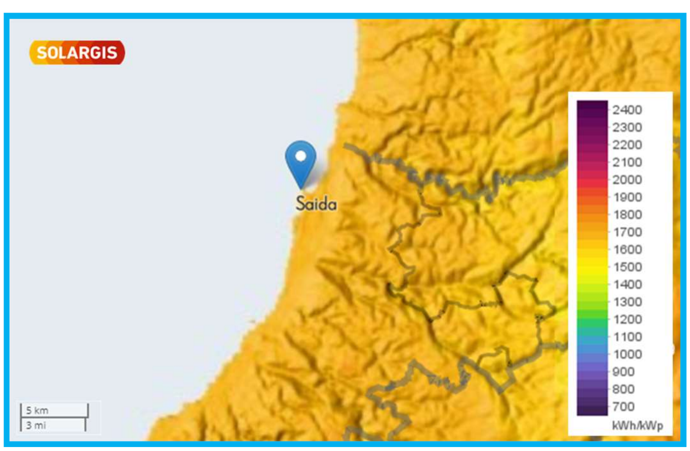

Figure 8. PV Power Potential in KWh/KWp of Saida, Lebanon.

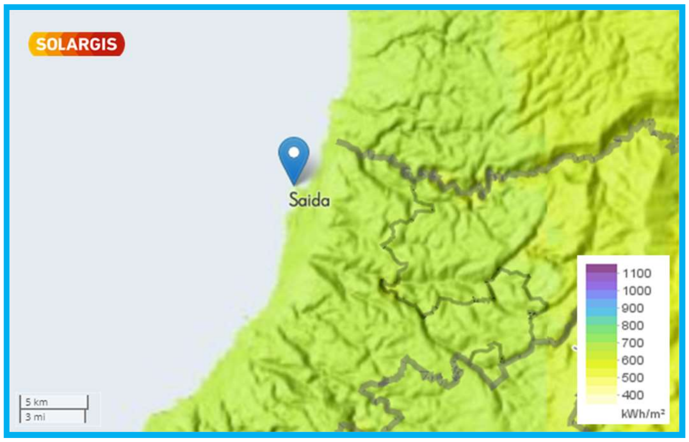

Figure 9. Diffuse Horizontal Irradiation (DHI) in KWh/m^2 of Saida, Lebanon.

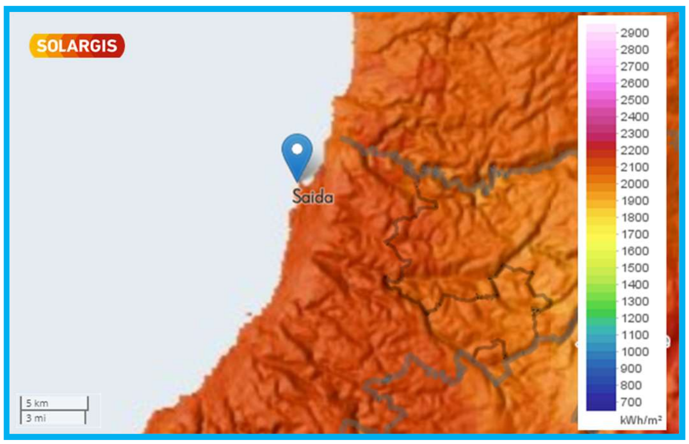

Figure 10. Global Irradiation for Optimally Titled Surface (GTI) in KWh/m^2 of Saida, Lebanon.

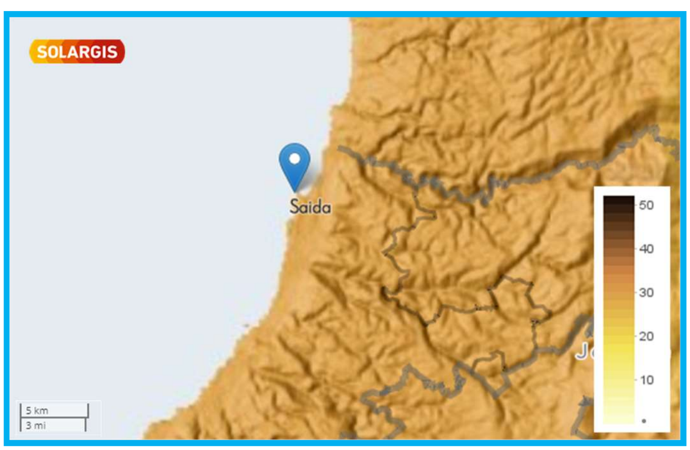

Figure 11. Optimum Inclination Angle [°] (OPTA) of a PV Module in Saida, Lebanon.

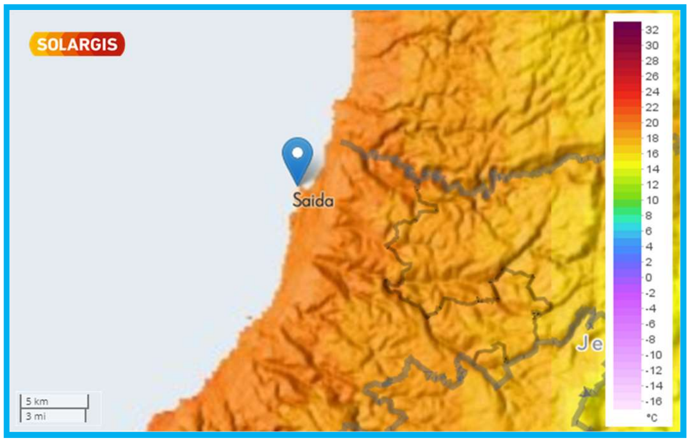

Figure 12. Average Temperature in °C of Saida, Lebanon.

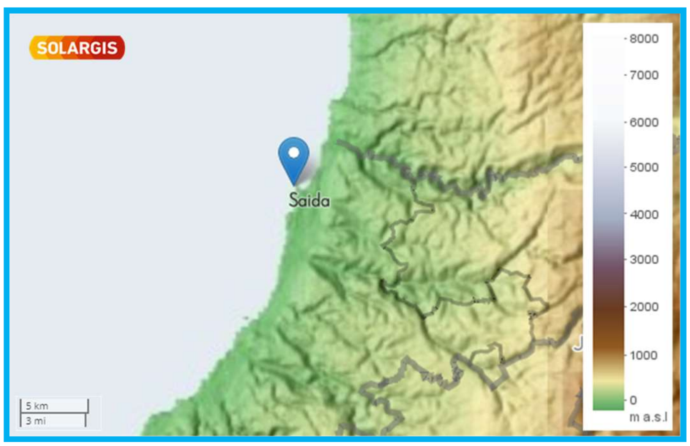

Figure 13. Terrain Elevation Relative to Sea Level (meters) of Saida, Lebanon.

The annual electricity potential results derived from the eight different solar potential models with MENA coverage that were graphed in Figure 14 below. The KWh/y calculations are based on a 3.1 KWp rooftop solar system connected to the grid with same rooftop configurations and comparable system losses.

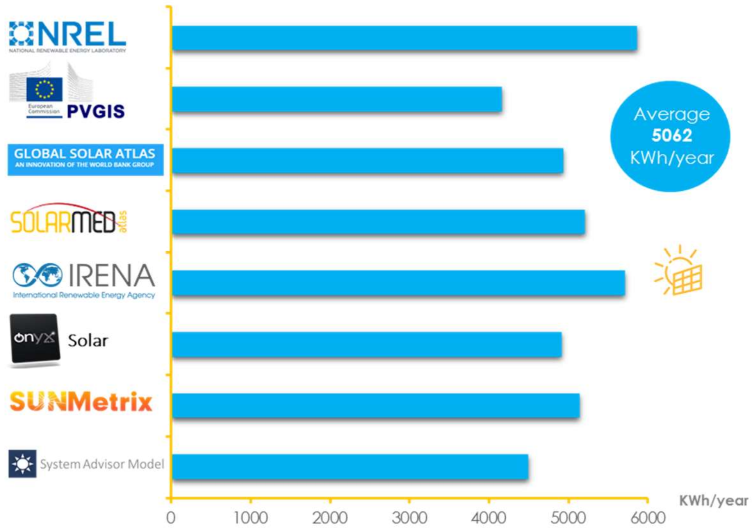

Figure 14. Annual Electricity Potential (KWh) in Saida of a 3.1 KWp Rooftop PV System by Different PV Estimation Models.

The global tilted irradiation (GTI) data from all of the utilized solar potential estimation models was averaged to derive the sum of the monthly global irradiation per square meter (Figure 15). The temperature averages of the location were sourced from Climate-Data (2017).

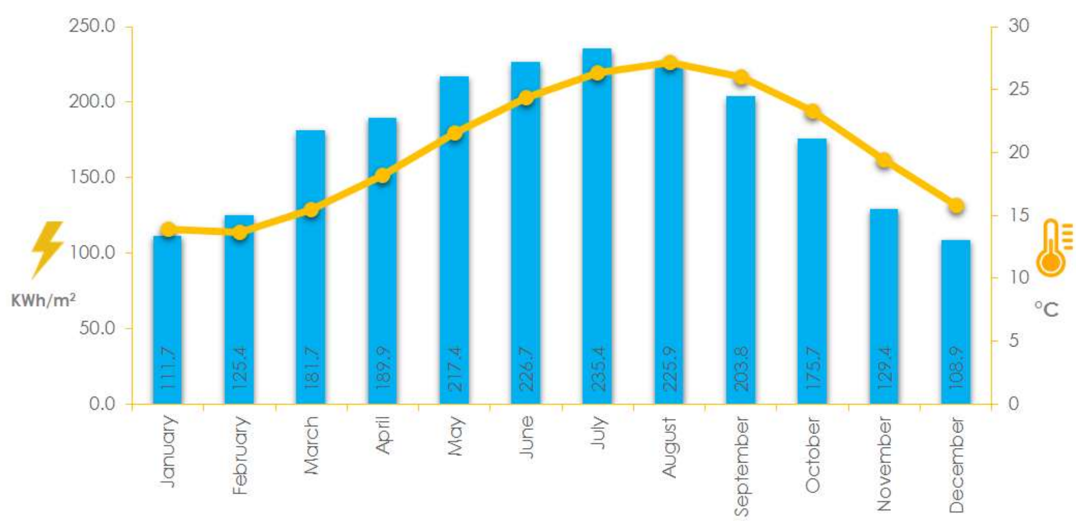

Figure 15. Average Monthly Global Titled Irradiation in KWh/m^2 and Average Monthly Temperatures of Saida.

Capacity Potential

Using the ArcGIS model to estimate the gross available rooftop area for the 11 identified districts of Saida, the total rooftop area was tabulated below (Table-2) along with the derived PV capacity and power generation potentials. A solar map for the city was also constructed based on the extrapolated generation potential from the rooftop footprint (Figure-16).

	Rooftop Footprint (m^2)	Average Footprint (m^2)	Number of Structures	Region Area (Km^2)	Rooftop Utilization Ratio	Rooftop PV Area Potential (m^2)	PV Capacity Potential (KW)	PV Generation Potential (MWh/yr.)
D1	9240	264	35	0.91	50%	4620	716	1155.00
D2	13993	145	96	0.60	50%	6997	1084	1749.13
D3	8624	172	50	0.27	50%	4312	668	1078.00
D4	37750	221	171	0.42	50%	18875	2926	4718.75
D5	18460	217	85	0.41	50%	9230	1431	2307.50
D6	11640	220	53	0.26	50%	5820	902	1455.00
D7	26305	244	108	0.28	50%	13153	2039	3288.13
D8	40610	242	168	0.30	50%	20305	3147	5076.25
D9	5470	161	34	0.17	50%	2735	424	683.75
D10	9440	29	330	0.24	50%	4720	732	1180.00
D11	20925	182	115	2.50	50%	10463	1622	2615.63
	202,457	163	1,245	6.36	50%	101,229	15,690	25,307

Table 2. Identified Rooftop PV Area Along with the Extrapolated Capacity Assessment. *Icons Sources: Noun Project and Shutterstock.*

Figure 16. Rooftop solar Map for Saida Created in ArcGIS.

Policy Results

The qualitative evaluation of the five key energy policies is summarized in the table below.

Policy	Law 462 - Electricity Sector Organization	Circular # 236 Banque Du Liban (Central Bank)	Law 132 - Offshore Petroleum Resources Law	EDL 2010 Policy Paper for the Electricity Sector	National Energy Efficiency Action Plan
Year	2002	2010	2010	2010	2011 & 2016
Legal	X				X
Financial		X			
Standards					X
Environment		X		X	X
Effectiveness	Low	High	N/A	Low	High
Legal	X		X	X	
Financial				X	
Standards	X		X		
Environment					
Effectiveness	Low	N/A	Low	Low	N/A
Implications	Law aims to kick-off privatization effort, but it was never implemented due to political gridlock. Law does not include any policy related to renewable energy sources. However, it sets the legal grounding for any resident to generate own electricity (but not sell).	Because of the new agency creation, residents seeking solar installations can obtain subsidized loans from commercial and retail banks as close to zero interest rates.	Law aims to regulate the fossil fuels activities and rights within the Lebanese territorial waters. Fossil fuel gas offshore extraction is a priority of the government.	The policy entails a plan that is heavily oriented around fossil fuel generated electricity. However, it does cover sustainable energy measures to reduce demand. Majority of the policy plans went unimplemented.	The 2011 and 2016 roadmaps action plans provide the first ever framework to the government to integrate energy sustainability measures and renewable power generation. It sets the 12% solar power goal for Lebanon by 2020.

Table 3. Lebanese Policy Comparative Analysis.

Environmental Results

The carbon emission factors of the current electricity sources (utility & diesel generators) are presented below in comparison to PV solar. Figure 17 shows the ranges estimated from various sources (EDL, 2016; Ministry of the Environment (2016); & Nugent and Sovacool (2014) revealing the life cycle GHG emission for each generation technology.

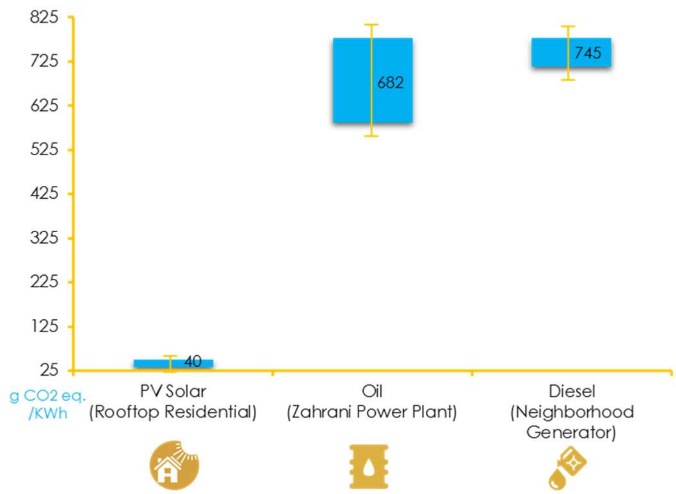

Figure 17. Emissions Intensity (grams CO_2 eq. per KWh) Ranges and Means of the Different Power Sources in Saida. *Sources: EDL (2016), Ministry of the Environment (2016), & Nugent and Sovacool (2014).*

Carbon Emissions

Using the above means for a calculation for emission factors and the previously calculated solar capacity potential, the avoided greenhouse gas (GHG) emissions were calculated and tabulated below in Table 4 per each of the districts of Saida for both the annual and lifetime (25 years) potential generation from solar.

		D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	Totals
	PV Generation Potential (MWh)	1,155	1,749	1,078	4,719	2,308	1,455	3,288	5,076	684	1,180	2,616	25,307
	Energy Mix Scenario												
Annual	Avoided GHG Emissions *Source: 100% Oil* (tonnes CO2 eq.)	742	1,123	692	3,029	1,481	934	2,111	3,259	439	758	1,679	16,247
Annual	Avoided GHG Emissions *Source: 100% DO* (tonnes CO2 eq.)	814	1,233	760	3,327	1,627	1,026	2,318	3,579	482	832	1,844	17,842
Annual	Avoided GHG Emissions *Source: 70% Oil & 30% DO* (tonnes CO2 eq.)	763	1,156	712	3,119	1,525	962	2,173	3,355	452	780	1,729	16,725
Lifetime of PV System	Avoided GHG Emissions *Source: 100% Oil* (tonnes CO2 eq.)	18,538	28,073	17,302	75,736	37,035	23,353	52,774	81,474	10,974	18,939	41,981	406,179
Lifetime of PV System	Avoided GHG Emissions *Source: 100% DO* (tonnes CO2 eq.)	20,357	30,828	19,000	83,168	40,670	25,644	57,953	89,469	12,051	20,798	46,100	446,038
Lifetime of PV System	Avoided GHG Emissions *Source: 70% Oil & 30% DO* (tonnes CO2 eq.)	19,083	28,900	17,811	77,966	38,126	24,040	54,328	83,872	11,297	19,497	43,217	418,137

Table 4. Avoided GHG emissions for Multiple Energy Mix Scenarios Calculated for 1 Year and 25 Years in Tonnes CO_2 Eq.

Diesel Generators Pollution

The results from an existing study on the polluting implications associated with the unregulated neighborhood generators shows the level of polycyclic aromatic hydrocarbons (PAH's) created during the operating hours of a standby unregulated diesel generator. PAHs also comprise of the benzo[a]pyrene (BaP) carcinogen which is also represented in Figure-16.

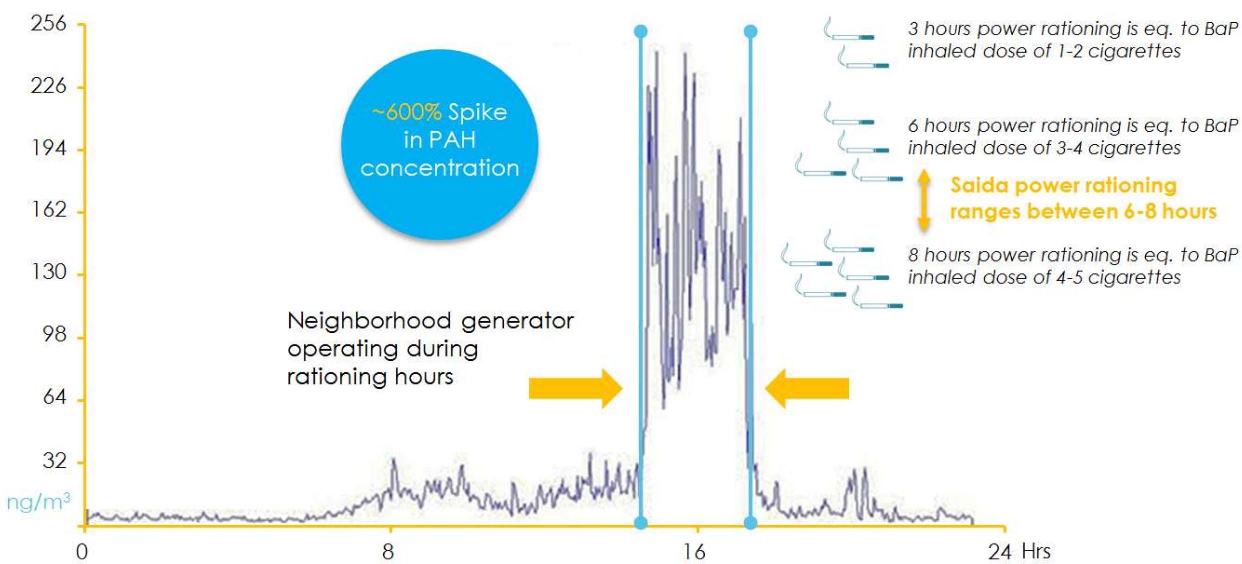

Figure 18. Measured Particle-Bound Poly Aromatic Hydrocarbons During Operating Hours of a Diesel Generator at a Dense Lebanese Neighborhood. *Source: Shihadeh et al. (2013).*

In addition, a myriad of articles have revealed that the same diesel generators are responsible for considerable noise pollution in excess of 63 DBI due lack of silencing enclosures (Armstrong, 2015; Fadel, 2015; & Nasser, 2015).

CHAPTER 5. DISCUSSION AND RECOMMENDATIONS

The main focus of this research is to explore the feasibility of rooftop solar as a viable power generation alternative to mitigate the dependence on the unreliable fossil-fuel power sources in Saida, Lebanon. With the constant increase in electricity rationing from the public utility, EDL, the widening gap between consumption and generation presents an opportunity for solar to becomes the unswerving solution to replace the unregulated monopolized diesel generators. To advance the understanding of solar potential to generate autonomous electricity, this study sheds light on rooftop solar as a main solution.

The findings of the study provide insight into the research questions from four different angles – policy, financial, environmental, and technical. The reported data indicate a strong case for using residential-scale PV solar as a decentralized sustainable power generation option for the local population. Harnessing solar energy is revealed to be technically, legally, financially, and environmentally feasible. Table 5 summarizes the findings per each of the thematic areas.

	P1	P2	P3	P4	Research Questions
Technical					
Solar Potential (annual)	GHI 1914 KWh/m²	DNI 1945 KWh/m²	DHI 673 KWh/m²	PV Output 1633 KWh/KWp/y	To what extent can the study's geographic location be fit for solar?
Generation Capacity (Saida's 11 Districts)	1245 Building rooftops	101,229 m² Rooftop area Potential	15.7 MW Capacity Potential	25,307 MWh Generation Potential	
Financial					
Electricity Cost ($/KWh)	$0.1/KWh of PV Residential Solar, which is lower than other sources (9% of current EDL, 35% of proposed EDL, & 66% of neighborhood diesel generators)				To what extent the existing solar loans are sound financially?
Financial Evaluation (3.1 KWp System Scenarios: outright purchase, subsidized financing, tax credit, net metering, Incentivized mix)	NPV >$11,452	IRR >13% Well above the 6% DF	ROI 16% yoy	Simple payback 7-8 years	
Policy					
Policies (encouraging renewable electricity generation)	- Law 462 sets the legal grounding for any citizen to generate own electricity. - Circular # 236 implemented a loan program to shore up financing for renewable energy installations. - EDL 2010 Policy sets goal for 12% share of renewable energy mix by 2020.				To what extent the current public policies support renewable energy and PV installations?
Environmental					
Carbon Emissions (Annual avoided GHG emissions per energy mix)	100% Oil *(EDL)* 16,247 tonnes CO_2 eq.	100% DO *(Neighborhood Generators)* 17,842 tonnes CO_2 eq.	70% Oil & 30% DO *(EDL & Neighborhood Generators)* 16,725 tonnes CO_2 eq.		To what extent can the PV displacement of fossil fuel power have on the carbon emissions?
Diesel Generators Pollution (PAHs & BaP)	Up to %85 Reduction of PAHs levels during operating hours of neighborhood diesel generators		Reduction of potential inhaled BaP (eq. to 3-5 cigarettes/day)during operating hours of neighborhood diesel generators		

Table 5. Summary of the Study Findings.

Discussion

Technical Feasibility

The meteorological, solar resource, geographic data collected from the Global Solar Atlas confirms the vast potential of the city of Saida to utilize rooftop solar for energy needs. As a coastal Mediterranean city enjoying around 320 days of sunlight annually (Karam, 2016), the Lebanese southern city presents an ideal fit for using PV technology. The GIS solar maps presented in Figures 3 through 10 reveal suitable solar characteristics for the site of the study. For example, the site receives a decent amount of solar irradiation annually (i.e. GHI at 1914 KWh/m^2, DNI at 1945 KWh/m^2, DHI 673 KWh/m^2) that - along with the 20 °C average temperature – resulted an average PV output of 1633 KWh/KWp/year. This creates a tangible opportunity for solar to compensate for the lack of electricity due to shortages.

The second leg of the technical analysis shed the light on the significance of the city's cumulative PV capacity and generation potential. Through the GIS identification of the building rooftops across the city's 11 districts, the estimated high yield footprint available for solar was at 101,229 m^2. The estimated area from 1,246 buildings had the potential of 15.7 MW high yield capacity and 25,307 MWh high yield generation. The technical findings reveal how substantially valuable rooftop solar can be in weaning the reliance on the unreliable public utility and the polluting diesel generators. Moreover, the results address the research sub-question pertaining to the technical viability of PV by demonstrating Saida as a strong fit for the solar power.

Financial Feasibility

The cost analysis of KWh sourced from diesel neighborhood generator, EDL public utility, and solar has revealed a striking 66% difference in solar cost pricing as compared to the subscription of private diesel-run generator. Similarly, solar proved to be 9% lower than the EDL public power, but when the proposed 40% tariffs increase of the EDL kicks in (Habib, 2017), solar is significantly more competitive - at 35% lower. Note that if the government stops subsidizing the EDL budget deficit, the real cost of EDL production of 1 KWh would be $0.21 (Bouri & El-Assad, 2016), which is twice of what solar costs. Therefore, the average 10 US cents per KWh cost of rooftop solar remains more cost-effective than current hybrid subscriptions of the public utility averaging 11 cents and the diesel-run generators running at 29 cents or higher.

While the consumer cost of fossil-fuel sourced power is expected to rise based on the recent EDL announcement of gradual tariff increase (Habib, 2017), onsite solar installation continues to drop. Per a recent report by the United Nations Development Programme (UNDP, 2016), the Lebanese PV market experienced a 66% drop in cost per KWp since 2010. Such competitiveness is expected to increase with the plummeting cost of solar technology globally. Bloomberg's new energy outlook (BNEF, 2017) forecasts a continued plunge in solar cost in the MENA region, which will be enormously cheaper than other competing fossil-fuel sources (see figure 19).

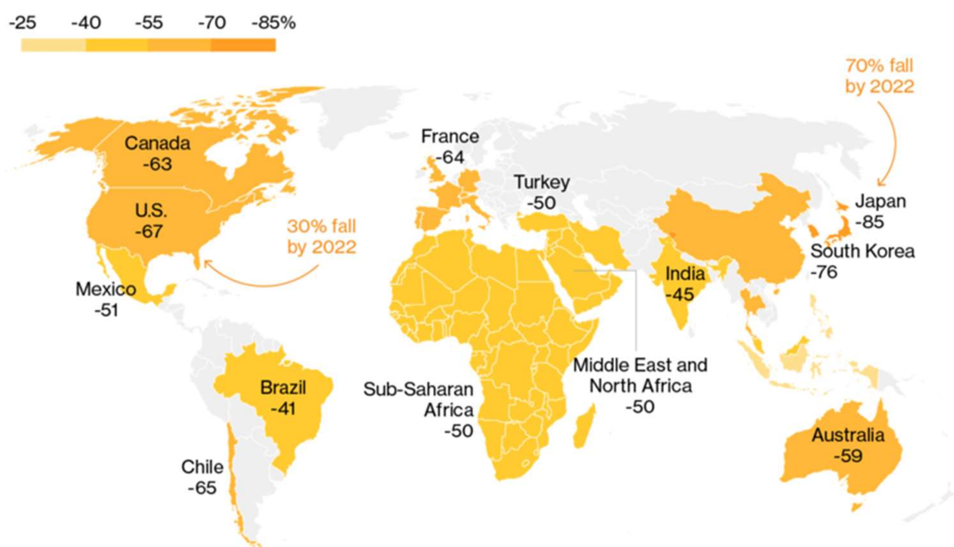

Figure 19. 2040 Solar Cost Outlook by Region reflecting reduction percentages based on 2016 prices. *Source: Bloomberg New Energy Finance (2017)*.

Apart from the comparative cost analysis of power, the financial evaluation of a grid-connected 3.1 KWp rooftop PV system has also proved to be economically sound. Using a 25 years lifespan of the PV system and $0.29 per KWh avoided diesel power cost, the positive NPV of the investment for the baseline residential system turned out to be considerably favorable at $11,452. The IRR was not only positive, but also appeared to be much higher than the 6% discount rate. The ROI was averaged at an annual 16%, which indicates a strong return. Finally, the payback is averaged between 7-8 years, which seems attractive for an investment of 25 years lifespan. The cost-benefit analysis was repeated 4 times for scenarios like adding subsidized financing, tax incentives, and net metering.

Adding the tax incentive to the same PV system yielded an overall positive investment with higher NPV, maximized rate of return, and shorter payback period. The 10% tax credit to the overall PV system initial cost has slightly has proved to improve the overall benefit to the end user. This is in line with a myriad of studies that revealed the encouraging role of tax incentive programs on the affordability and the rapid deployment of grid-tied solar modules (Mendelsohn, Kreycik, Bird, Schwabe, & Cory, 2012; Sarzynski, 2009; Sarzynski, Larrieu, & Shrimali, 2012).

Similarly, providing BDL subsidized lending to residents installing rooftop solar showed even greater financial advantage. The evaluation for this exercise had an NPV of $14,168 reflecting an added benefit from the 10 years loan at 1% low interest with zero money down. The Central Bank of Lebanon or BDL has instituted the National Energy Efficiency and Renewable Energy Action (NEERA) to provide a financial vehicle to promote sustainable energy projects including residential-scale solar. Such lending programs help the residents to avoid steep upfront costs of the PV system and allow them to swap the monthly neighborhood generator subscription fees with the proposed monthly solar loan installment. The only difference is that the latter monthly installment costs less, ends after ten years, and entails ownership for the resident as compared to the diesel generator subscription. Such benefits are corroborated by the National Renewable Energy Laboratory (NREL) study on low-interest solar loans demonstrating greater long-term savings for power generation (Feldman & Lowder, 2014).

The net metering scenario also yielded a financially positive investment given the added benefit from the public utility electricity bill reduction. Introduced by EDL, bi-directional metering entails feeding the excess solar power onto the grid offsetting the cost of the electricity drawn from the public utility. However, if the power fed exceeds the one drawn from the grid within the same calendar year, the end user cannot cash the excess balance. Note that the scenario for this study suggested an annual offset of 500 KWh with EDL at a cost of 11 cents per KWh. However, this conservative assumption does not factor the actual cost of production of 21 cents per KWh (Bouri & El-Assad, 2016) nor the proposed EDL tariff hikes (Habib, 2017). In addition, more surplus solar power are likely to be produced in winter and fall seasons given the household demand usually dips outside of the summer seasons (CEDRO, 2017). Therefore, the benefit of net metering can be further stretched by a factor of 2 to 3 than the estimate of this study.

The last scenario of the financial evaluation involved an incentive mix of all the preceding three scenarios (e.g. tax credit, subsidized financing, and net metering). As expected, the cost-benefit analysis of this scenario demonstrated the most favorable financial outcome with a $15,335 NPV, annual ROI averaged at 16%, and payback of 7 years. For the Saida residents, this financial scenario reveals that rooftop PV is highly feasibly for decentralized power generation.

Policy Feasibility

The examination of the 6 major Lebanese policy artifacts (Table-3) has revealed a great deal of support for fossil fuel energy ranging from the expanding HFO power plants to the regulation of natural gas (NG) offshore extraction. Such notion reflects the heavy reliance on conventional sources to generate power. While fossil fuel power remains ingrained in the country's energy strategy, the United Nations Development Programme (UNDP) has been collaborating with the local government to foster a sustainable energy strategy. This is illustrated by BDL's Circle # 236 that created financial lending programs through

NEERA, EDL's policy paper that set the goal to generate 12% electricity from solar and other renewables, and the National Energy Efficiency Action Plan (NEEAP) that started the first ever framework to the government to integrate energy sustainability measures. Such laws not only confirm the viability of rooftop solar as the alterative power generation vehicle, but also allow the country to reduce public financial burdens related to EDL operational expenditures, increase energy efficiency, and facilitate the transformation towards a green economy (UNDP, 2017).

Environmental Feasibility

The avoided carbon emissions for the current electricity mix for Saida (e.g. 30% diesel oil from private generators and 70% oil at the Zahrani power plant) is calculated to be 418,137 tonnes CO_2 equivalent over 25 years – the system lifetime. That staggering level of offset emissions is equivalent to 1 million barrels of oil saved from burning, 10.8 million trees planted, 1 billion miles driven by an average passenger car (EPA, 2016), offsetting the carbon footprints of 100 thousands Lebanese (Carbon Footprint, 2017), and powering 90,375 average Lebanese homes for a year. Table 6 shows the annual and lifespan emissions offsets for Saida solar capacity potential.

Offset Equivalent	Avoided GHG Emissions (annual) 16,725 tCO_2	Avoided GHG Emissions (25 yrs. Lifespan) 418,137 tCO_2
Trees planted (seedlings grown for 10 years)	433,448	10.8 Million
Light bulbs (Incandescent lamps switched to LEDs)	592,875	14.8 Million
Oil barrels (barrels saved from burning)	38,722	1 Million
Miles driven (by an average passenger car)	40 Million	1 Billion
Carbon footprint of # Lebanese (average carbon footprint of a resident)	4181	104,534
Lebanese Homes powered (based on 7000 Kwh/year average)	3615	90,375

Table 6. Carbon Emissions Calculation Equivalencies. *Source: EPA (2016) & Carbon Footprint (2017)*.

With 53% of Lebanese GHG emissions stemming from the energy sector particularly power generation (MoE, 2016); renewable energy has a strong GHG abatement potential. This study confirms the potential of rooftop solar in contributing to the country's mitigation strategy through displacing GHG emissions from conventional power sources. This will in turn helps the country meet its Paris Agreement targets declared as part of its Intended Nationally Determined Contribution (INDC) – 15% GHG reduction by 2030. Therefore, solar power is found to be environmentally feasible in region that is vulnerable to dire climatic changes (MoE, 2016).

The findings also revealed the negative pollution implications of diesel-run generators in residential neighborhoods. Air levels of carcinogenic polycyclic aromatic hydrocarbons (PAHs) experience rapid increase by a factor of 6 during the rationing hours where generators are operational. Diesel exhaust is classified as an occupational carcinogen by a number of organizations including the World Health Organization (WHO), the International Agency for Research on Cancer (IARC), and National Toxicology Program (Tsai *et al.*, 2010). Rooftop solar can easily replace the approximately 30% rationing gap currently bridged by diesel-run generators in Saida. By ditching diesel-sourced power and replacing it with clean solar power, inhalation exposure to airborne carcinogenic compounds is expected to fall dramatically (Shihadeh *et al.*, 2013). For the neighborhoods of Saida, this translates to more saved lives from lung cancer.

Implementation Framework

There is no doubt that electricity problems are ubiquitous in Lebanon given the supply shortages, rising cost, and fossil fuel pollution. The findings of this study revealed a substantial extent to which solar energy can be a viable decentralized power alternative for solving the electricity dilemma. To support the implementation of this renewable power alternative, the below is recommended as a solar framework (Figure 20).

Rooftop Beneficiary

Local Resident

Financial

- Retail Banks: provide subsidized solar loans with interest subsidized by BDL
- NEERA: facilitate soft loans for rooftop solar
- BDL: subsidize interest rates 1% or less for solar loans

Policy

- Municipality:
  - Support the creation of the solar community association office
  - Regulate the neighborhood diesel private generators to: (a) curtail exhaust pollution, and (b) encourage the generator power providers to transition to solar leasing model

Global Partners

- UNDP: provide expertise, research, studies on solar energy
- NGOs: establish a fund to help provide:
  - Grants for low-income residents for solar installations
  - Direct performance-based incentives for households with track of high energy efficiency

Awareness

- Universities: establish solar internship programs
- High Schools: raise solar awareness through volunteering
- Media: partner with local media to raise awareness on solar benefits and feasibility

Technical

- LCEC:
  - Provide technical expertise and project reviews
  - Rooftop solar codes and standards
- Vendors:
  - Provide PV system sales & installation services
  - O&M annual plans

Other Power Suppliers

- EDL:
  - Public-utility managing the grid
  - Provide bi-directional metering installation
- Discoms:
  - Provide solar power lease services to residents who cannot own PV systems

- Coordinate among various stakeholders
- Provide free rooftop solar assessments
- Protect solar generation rights for local residents
- Manage the permitting and bylaws for building rooftops
- Raise awareness through providing rooftop solar resources and materials
- Has the objective of ensuring solar power decentralized development across the city

Figure 20. Rooftop Solar Recommended Implementation Framework. *Icon Source: Noun Project*.

Limitations and Future Research

The study has several limitations that can be addressed in future research. The first limitation entails the scope geographical limitation where the study was conducted within the city limits of Saida. Expanding to the densely populated suburbs may easily double the potential generation capacity of the metropolitan. To remedy this limitation, future studies can be modeled after this research to replicate across various areas in Lebanon or even the MENA region. The generic methods and formulated framework can be easily applied to other residential sites within the developing countries suffering from fossil-fueled power shortages.

The second limitation involves the rooftop space constraints due to other utilization like water tanks and solar water heaters. This study assumed 50% availability of building rooftops that may be fit for PV panel installation. Such drawback can be ameliorated by using vertical mounts with adjustable tilt that require less space as compared to flat layout. The elevated mounts can be installed on top of existing static objects like water tanks.

Finally, future research may explore how power conservation through energy efficiency can be married to power generation through decentralized solar in the same regional context. Such research can further the understanding of how to maximize clean energy access from both sides – the consumption and production. Furthermore, the application of solar micro-grids as an additional power generation to rooftop solar can be a worthy topic for future research. The lack of current regulations supporting micro-grids poses as an implementation constraint. Future research on the impact of community microgrids may influence the regulatory outcome.

Conclusion

With the strained fossil fuel power supply, the growing need to curtail polluting carbon emissions, and the rising cost of Lebanese electricity, affordable renewable energy poses as a tailored fit to the country's electricity woes. The findings of this study reinforced the main research hypothesis pertaining to highly feasible solar as a viable decentralized power generation alternative for the city of Saida. Given Saida' sunny Mediterranean climate and its ample rooftop footprint, the technical PV capacity is significant, at 25 GWh per year. Combined with the plummeting costs for PV technology, the available subsidized lending has made solar power affordably feasible. Meanwhile, the study demonstrated how green solar energy can improve public health and environmental quality for the local population. Therefore, rooftop PV has emerged as a resilient energy source vital to how Lebanon can address the looming implications of its electricity crisis.

The recommended ‘implementation framework’ for rooftop solar sets the stage for collaborative action to empower residents and local municipalities to adopt sustainable on-site power generation. Rooftop solar power not only allows everyone to have access to electricity, but also offers a societal improvement through affordable, clean, and around-the-clock energy. Solar energy also helps in shoring up the power generation capacity, a much needed step for coping with the socio-economic development of the region. Not to mention, transitioning to solar energy helps the country meet its Paris Agreement commitments through GHG abatement and pollution reduction. In short, rooftop solar appears to be a highly feasible energy generation alternative with significant social, economic and environmental prospects. It is a triple-win proposition.

REFERENCES

AEMS. (2017, February). *The Impact of the Syrian Crisis on the Lebanese Power Sector and Priority Recommendations*. Beirut, Lebanon: Advanced Engineering and Management Services.

Armstrong, M. (2015). *The 'environmental disaster' Lebanon can't afford to fix*. Al-Monitor. Retrieved July 14, 2017 from http://www.al-monitor.com/pulse/originals/2015/06/lebanon-zouk-mikael-pollution-smoke-environment-edl-protest.html

Assi, A. H. & Kaaki, O. A. (2016). *Introducing micro-grids in Lebanon: Renewable-based microgrids to replace diesel generators*. 2016 3rd International Conference on Renewable Energies for Developing Countries (REDEC). DOI: 10.1109/REDEC.2016.7577545.

Aziz, J. (2015). *Lebanon's continued electricity cuts portend disaster*. Al-Monitor. Retrieved July 14, 2017 from http://www.al-monitor.com/pulse/originals/2015/01/lebanon-electricity-supply-debt-disaster.html#ixzz4nRsJxiLB

Baalbaki, M. (2015). *Beirut Electricity app*. iTunes. Retrieved June 28, 2017 from https://itunes.apple.com/lb/app/beirut-electricity/id434106511?mt=8

Baalbaki, N. (2015). *The generator mafia shatters the citizens' dream in Zahle*. Washington, DC: Heinrich Boell Foundation.

Barthel, P. A. (2014). *Cities for a new generation: Report on Saida*. Marseille, France: Center for Mediterranean Integration.

BDL. (2010). *Circular No. 236*. The BDL Intermediate Circulars Database. Beirut, Lebanon: BDL.

Dhiman, B., Chaudhury, M., Deb, S., & Chakrabarti, D. (2017). *Micro solar energy systems: Product design intervention facilitating sustainable development for rural North East India*. Research into Design for Communities, V 2: Proceedings of ICoRD 2017, pp 117-125.

Duan, H., Zhang, G., Zhu, L., Fan, Y., & Wang, S. (2016). How will diffusion of PV solar contribute to China's emissions-peaking and climate responses? *Renewable and Sustainable Energy Reviews, 53*, 1076-1085.

BNEF. (2017). *New energy outlook 2017: Bloomberg's New Energy Finance's annual long-term economic forecast of the world's power sector*. New York: Bloomberg New Energy Finance.

Bouri, E., & El-Assad, J. (2016). The Lebanese Electricity Woes: An Estimation of the Economical Costs of Power Interruptions. *Energies,* 9(8), 583.

Carbon Footprint. (2017). *Carbon footprint calculator for individuals and households in Lebanon*. Hampshire, UK: Carbon Footprint Ltd.

CEDRO. (2017). *Guidelines of net metering: The case of Lebanon*. Beirut, Lebanon: CEDRO-United Nations Development Programme.

Climate-Data. (2017). *Climate model data for Sidon*. Retrieved July 14, 2017 from https://en.climate-data.org/location/4859/

Dubin, R. (2017, February 22). Refugee crisis strains Lebanon's deficient electricity network. *The Daily Star*, p.3.

EAPI. (2017). *Global energy architecture performance index report 2017*. Cologny, Switzerland: World Economic Forum.

EDL. (2017). *About us*. Retrieved June 28, 2017 from http://www.EDL.gov.lb/aboutEDL.htm

EnergySage. (2017). Net metering for home solar panels. Retrieved June 28, 2017 from https://www.energysage.com/solar/101/net-metering-for-home-solar-panels/

EPA. (2016). *Greenhouse Gas Equivalencies Calculator*. Retrieved July 3, 2017 from https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

EU PVGIS. (2014). *Geographical Assessment of Solar Resource and Performance of Photovoltaic Technology* [PV potential tool]. Ispra, Italy: Joint Research Centre - Institute for Energy, Renewable Energy Unit. Available from http://re.jrc.ec.europa.eu/pvgis/

European Commission. (2017). *Lebanon: Syrian Crisis*. Brussels, Belgium: Humanitarian Aid and Civil Protection.

Fadel, A. (2015). *30 thousands generators threaten Lebanese in their health: 7 killer pollutants … and the "controls" of government decisions are without* *censorship*. Beirut, Lebanon: Lebanese Company for Information & Studies.

Feldman, D., & Lowder, T. (2014). *Banking on solar: An analysis of banking opportunities in the U.S. distributed photovoltaic market* (Report No. NREL/TP-6A20-62605). Golden, CO: National Renewable Energy Laboratory.

Gallo, A. (2014). *A refresher on net present value*. Harvard Business Review. Retrieved July 1, 2017 from https://hbr.org/2014/11/a-refresher-on-net-present-value

Gallo, A. (2016). *A refresher on internal rate of return*. Harvard Business Review. Retrieved July 1, 2017 from https://hbr.org/2016/03/a-refresher-on-internal-rate-of-return

Global Solar Atlas. (2017). *Solar potential maps* [Open Source Platform]. Washington, DC: The World Bank and the International Finance Corporation. Available from http://globalsolaratlas.info/

GoL. (2002). Law of electricity sector organization. *Government of Lebanon*. Retrieved July 2, 2017 from www.taqaway.net/sites/default/files/Electricity%20Law%20(2002).pdf

GoL. (2010). The Offshore Petroleum Resources Law. *Government of Lebanon*. Retrieved July 2, 2017 from http://www.lpa.gov.lb/pdf/OPRL%20-%20English.pdf

Habib, O. (2017, March 30). Lebanon's summer electricity ambitions met with skepticism. *The Daily Star*, p.4.

Halawi, D. (2017, April 1). Ministry to launch tender for power barges. *The Daily Star*, p.4.

Hammoud, D., & Hijazi, M. (2013). Saida City: the historic city on the Mediterranean basin. *Prevention Web - UNISDR*. Retrieved July 2, 2017 from http://www.preventionweb.net/files/31093_mostafasaida.pdf.

Ibrahim, O, Fardoun, F., Younes, R., & Gualous, H. L. (2013). Energy status in Lebanon and electricity generation reform plan based on cost and pollution optimization. *Renewable and Sustainable Energy Reviews. 20*, 255-278.

IEA. (2014). *CO2 emissions by country. International Energy Agency, online data service*. Retrieved July 2, 2017 from http://www.iea.org/statistics/topics/CO2emissions/

IMF. (2014). *2014 Article IV consultation* (Report No. 14/237). Washington, DC: International Monetary Fund.

IMF. (2017). *2016 Article IV consultation* (Report No. 17/19). Washington, DC: International Monetary Fund.

IRENA. (2017). *Global Atlas for Renewable Energy* [PV potential tool]. Abu Dhabi, UAE: International Renewable Energy Agency. Available from https://irena.masdar.ac.ae/

Karam, M. (2016, October 11). Solar can fill Lebanon's persistent power gap. *The National*, p. B8.

Karpowership. (2017). *Project Lebanon*. Retrieved June 28, 2017 from http://www.karpowershiplebanon.com/

LCEC. (2011). *The national energy efficiency action plan for Lebanon 2011-2015*. Beirut, Lebanon: Lebanese Center for Energy Conservation.

LCEC. (2016). *The second national energy efficiency action plan for the republic Lebanon 2016-2020*. Beirut, Lebanon: Lebanese Center for Energy Conservation.

Mendelsohn, M., Kreycik, C., Bird, L., Schwabe, P., & Cory, K. (2012). *The impact of financial structure on the cost of solar energy* (Report No. NREL/TP-6A20-53086). Golden, CO: National Renewable Energy Laboratory.

MoE. (2014). *The Lebanese power sector*. Retrieved July 3, 2017 from http://climatechange.moe.gov.lb/viewfile.aspx?id=64

MoE. (2015). *National greenhouse gas inventory report and mitigation analysis for the energy sector in Lebanon*. Beirut, Lebanon: Ministry of the Environment.

MoE. (2016). *Lebanon's third national communication to the UFCCC*. Beirut, Lebanon: Ministry of the Environment.

MoEW. (2010). *Policy Paper for the electricity sector. Lebanese Ministry of Energy and Water*. Beirut, Lebanon: Ministry of the Energy and Water.

MoEW. (2017). *Project Lebanon*. Beirut, Lebanon: Ministry of the Energy and Water.

Nasser, Z. (2015). *High pollution rates due to generators … rationing causes cancer*. Beirut, Lebanon: Lebanese Company for Information & Studies.

NREL. (2017). *Glossary of solar radiation resource terms*. Retrieved July 20, 2017 from http://rredc.nrel.gov/solar/glossary/

NREL. (2017). *NREL PV Watts* [Version 5]. Golden, CO: National Renewable Energy Laboratory. Available from http://pvwatts.nrel.gov/

Nugent, D., & Sovacool, B. K. (2014). Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. *Energy Policy, 65*, 229-244.

ONYX Solar. (2014). *Photovoltaic Estimation* [PV potential tool]. Avila, Spain: ONYX Solar. Available from http://www.onyxsolar.com/photovoltaic-estimation-tool.html

Rose, A., Stoner, R., & Perez-Arriaga, I. (2016). Prospects for grid-connected solar PV in Kenya: A systems approach. *Applied Energy, 161*, 583-590.

Saadeh, L., & Mikhael, M. (2015). *Solid waste management in Lebanon part 2: How to solve Lebanon's waste crisis*. Beirut, Lebanon: BlomInvest Bank.

Saida Municipality (2017). *Municipality published rates of private electricity generators*. Retrieved July 21, 2017 from http://saida.gov.lb/news/details/news-1944#prettyPhoto

Sarzynski, A. (2009). *The impact of solar incentive programs in ten states*. Washington, DC: Institute of Public Policy at the George Washington University.

Sarzynski, A., Larrieu, J., & Shrimali, G. (2012). The impact of state financial incentives on market deployment of solar technology. *Energy Policy, 46*, 550-557.

Nieuwenhout, F., Dijik, A., Lasschuit, P., Roekel, G., Dijik, V., Hirsch, D., … Wade, H. (2001). Experience with solar home systems in developing countries: A review. *Progress in Photovoltaics: Research and Applications, 9*, 455-474.

Shihadeh, A., Al-Helou, M., Saliba, N, Jaber, S., Alaeddine, N., Ibrahim, E., … Chiit, M. (2013). *Effect of distributed electric power generation on household exposure to airborne carcinogens in Beirut*. Beirut, Lebanon: The Issam Fares Institute for Public Policy and International Affairs.

Solar Med Atlas. (2014). *Solar Atlas for the Mediterranean* [PV potential tool]. Golden, CO: National Renewable Energy Laboratory. Available from www.solar-med-atlas.org/

SolarGIS. (2017). *Solar potential data* [Solar data database]. Bratislava, Slovakia: SolarGIS. Available from https://solargis.info/

Sunmetrix. (2017). *Solar Preview* [PV potential tool]. Montreal, Canada: Sunmetrix. Available from http://sunmetrix.com/discover/

System Advisor Model. (2017). *SAM Software* [Version 2017.1.17]. Stuttgart, Germany: Project Consortium led by German Aerospace Center. Available from https://sam.nrel.gov/

The Economist. (2015). *Lights, handguns, action In Lebanon's fractured society, even keeping the lights on is a battle.* Retrieved July 21, 2017 from https://www.economist.com/news/middle-east-and-africa/21645233-lebanons-fractured-society-even-keeping-lights-battle-lights

Thornton, W. (2016). Strategic niche management of the solar electricity sector in Lebanon. *Exchange Issue*. Beirut, Lebanon: CEDRO.

Tisdall, S. (2013, April). The Turkish 'power ship' keeping the lights on in Lebanon. *The Guardian*. Retrieved July 21, 2017 from https://www.theguardian.com/world/2013/apr/11/turkish-power-ship-lights-on-lebanon

Tsai, J., Chen, S., Haung, K., Lin, Y., Lee, W., Lin, C., & Lin, W. (2010). PM, carbon, and PAH emissions from a diesel generator fueled with soy-biodiesel blends. *Journal of Hazardous Materials, 179*, 237-243.

UNDP & LCEC. (2014). *Lebanon's first national survey study of the solar water heaters market*. Beirut, Lebanon: United Nations Development Programme & Lebanese Center for Energy Conservation.

UNDP. (2016). *Solar PV status report for Lebanon*. Beirut, Lebanon: United Nations Development Programme.

UNDP. (2017). *Expanding sustainable energy in Lebanon*. Beirut, Lebanon: United Nations Development Programme.

World Bank. (2008). *Republic of Lebanon: Electricity sector public expenditure review* (Report No. 41421-LB). Washington, DC: Sustainable Development Department of Middle East and North Africa.

World Bank. (2017). *Doing business 2017: Equal opportunity for all*. Washington, DC: World Bank. DOI: 10.1596/978-4648-0948-4.

World Bank. (2017). *Lebanon economic monitor: GMFDR*. Washington, DC: World Bank Group.

World Bank. (2017). *Priority reforms for the government of Lebanon: World Bank Policy Paper* (Report No. 116428-LB). Washington, DC: World Bank Group.

World Bank & Enterprise Surveys. (2016). *Power outages in firms in a typical month*. Retrieved June 27, 2017 from http://data.worldbank.org/indicator/IC.ELC.OUTG

World Data Atlas (2017). Lebanon - Average consumer prices inflation rate. Retrieved July 20, 2017 from https://knoema.com/atlas/Lebanon/Inflation-rate

WorldMap. (2015). *Harvard WorldMap* [Open source mapping platform]. Boston, MA: Center for Geographic Analysis at Harvard University. Available from http://worldmap.harvard.edu/

Ziade, M. (2012). Technical challenges to 24/7 electricity in Lebanon. Lebanon 24/7 – A Carboun Initiative. Retrieved June 20, 2017 from http://www.carboun.com/carboun-projects/lebanon-247/

Zipp, K. (2015). What are some common types of solar PV and storage installations? Retrieved June 20, 2017 from https://www.solarpowerworldonline.com/2015/10/what-are-some-common-types-of-solar-pv-and-storage-installations