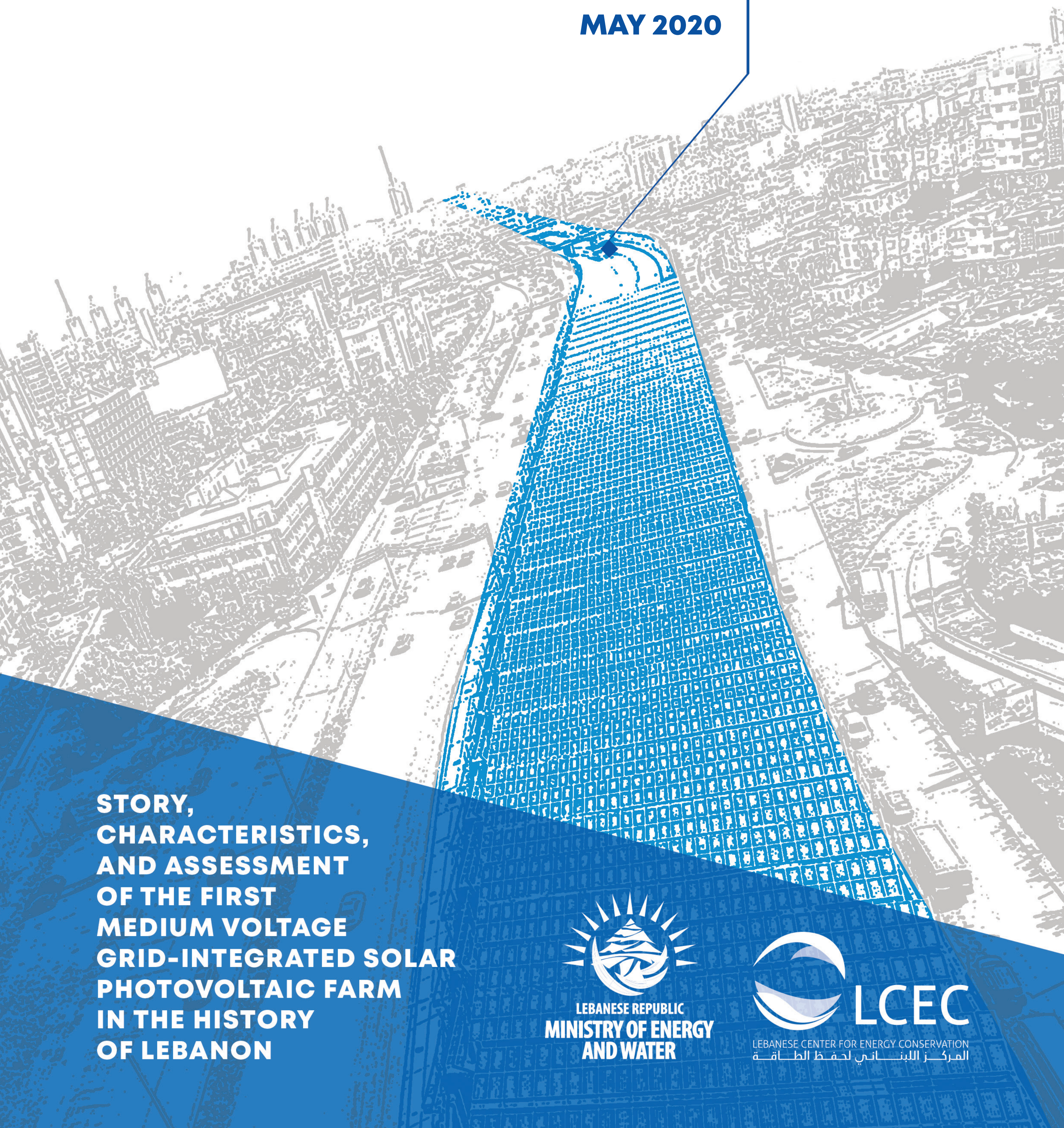
BEIRUT RIVER SOLAR SNAKE

THE DAWN OF THE SOLAR MARKET IN LEBANON

MAY 2020



STORY, CHARACTERISTICS, AND ASSESSMENT OF THE FIRST MEDIUM VOLTAGE GRID-INTEGRATED SOLAR PHOTOVOLTAIC FARM IN THE HISTORY OF LEBANON

LEBANESE REPUBLIC
MINISTRY OF ENERGY AND WATER

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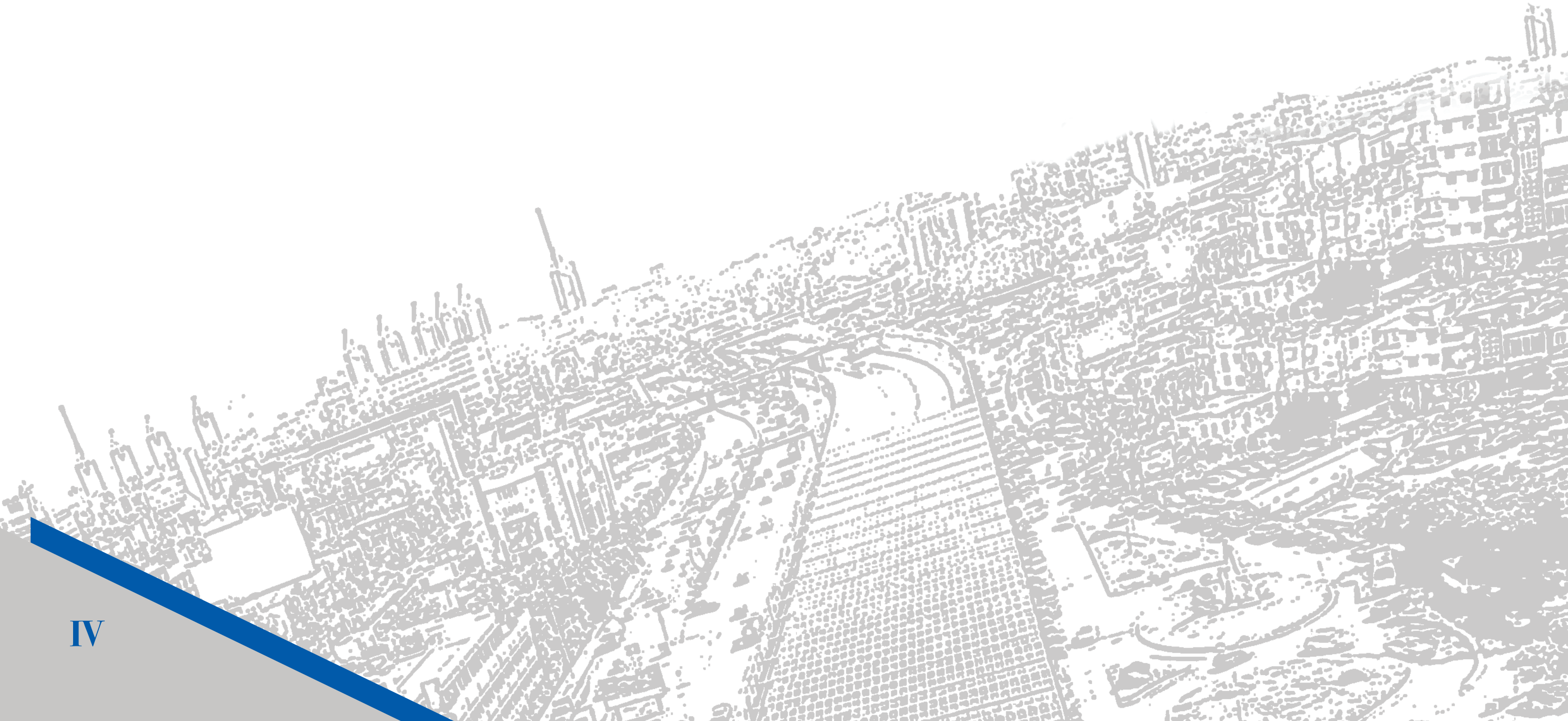

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Foreword

Back in 2013, building a solar photovoltaic (PV) farm with an installed capacity of 1 MW in Lebanon was kind of a dream. Yet, with the support of the Ministry of Energy and Water (MEW) and the engagement of the various stakeholders in the field, the 1 MW Beirut River Solar Snake (BRSS) project was built in 2015 by a private sector consortium and is still operational to date. Since then, more than 60 MW of solar PV farms have been installed all over Lebanon, while the country's national target was set at 100 MW of decentralized solar PV farms installed by 2020 in addition to 150 MW of solar PV farms based on public-private partnerships. Furthermore, around 3,000 MW of solar PV farms are planned to be installed between 2021 and 2030.

In fact, the BRSS has set the pace for a quick development of the solar PV market all over Lebanon. According to the "2018 Solar PV Status Report for Lebanon", the cumulative installed solar PV capacity grew by an average rate of 95% per year from 2010 until the end of 2018. This is quite an impressive increase, but definitely more needs to be done.

This report presents all the details about the development of the BRSS project since its inception until its current operation. The objective of this report is not only to showcase a successful project implemented by the MEW through the Lebanese Center for Energy Conservation (LCEC), but rather to offer content that could be used by companies, researchers, university students, and business developers, further supporting the development of the solar PV market in Lebanon.

The LCEC stands ready to coordinate with all interested parties in order to further understand and advance solar PV technologies and develop projects in the country. It is true that the sustainable energy market in Lebanon faces uncertainties and challenges, but it is also true that this market offers huge opportunities for development. As this market is growing rapidly, future decisions and actions should be based on more solid technical ground, and this BRSS report offers potential material for research to drive a prosperous and sustainable future for our country.

LCEC team
May 2020

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Abbreviations*

AC	Alternating current
BDL	Central bank of Lebanon
BRSS	Beirut river solar snake
CF	Capacity factor
CO_2	Carbon dioxide
COP	Conference of parties
COM	Council of ministers
EN	European norm
EDL	Electricté du Liban
EOI	Expression of interest
FACTS	Flexible alternating current transmission system
FRT	Fault ride through
GTI	Global tilted irradiation
IBEF	International Beirut energy forum
IEC	International electrotechnical commission
kt	kilotonne
KVA:	Kilovolt-ampere
kWh	Kilowatt-hour
LCEC	Lebanese centre for energy conservation
MEW	Ministry of energy and water
MV	Medium voltage
MWh	Megawatt-hour
MWp	Megawatt peak
NEEAP	National energy efficiency action plan
NEEREA	National energy efficiency and renewable energy action
NREAP	National renewable energy action plan
PR	Performance ratio
PV	Photovoltaic
RES	Renewable energy system
RFP	Request for proposal
STC	Standard Test Conditions
UNFCCC	United nations framework convention on climate change

Background

In an attempt to contribute to the mitigation of the serious effects of carbon-intensive activities on the planet, and the extensive pollution problems within cities in Lebanon, the Lebanese Government committed in 2009 during the Conference of Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) to increase the share of renewables in the country to 12% of the projected total electricity and heat demand in 2020 (Lebanese Center for Energy Conservation [LCEC], 2016). In line with this commitment, which was reflected in the Policy Paper for the Electricity Sector (Bassil, 2010) and in the National Energy Efficiency Action Plan for Lebanon (NEEAP 2011–2015) and as a first step to reach this goal, the Lebanese Ministry of Energy and Water (MEW) and LCEC prepared and launched a tender for the first grid-connected photovoltaic (PV) plant in Lebanon's history, the iconic Beirut River Solar Snake (BRSS).

The plant aims to generate and supply the national grid of Electricité du Liban (EDL) with clean energy to eventually meet the energy needs of end-user households. Its objectives are to promote renewable energy in Lebanon, drive the solar PV market, and demonstrate the role of renewables in bridging the gap between electrical demand and supply.

The BRSS project initially consisted of different phases which began with a call for expressions of interest (EOI) launched on April 23, 2013. The first phase consisted of an installed capacity of one megawatt peak (MWp) extending from the Yerevan Bridge to the Nahr Bridge over an area of around 10,000 m^2. The execution of the first phase started in July 2014, and the plant has been connected to the grid since September 2015.

One year after its completion, it was clear that the BRSS project positively contributed to the birth of the solar PV market in Lebanon. The National Renewable Energy Action Plan for Lebanon (NREAP 2016-2020) was hence developed to further promote renewables, boost the momentum created by BRSS on the local PV market, and fulfill the international commitments of the country in that field (LCEC, 2016) . Recently, the Updated Policy Paper for the Electricity Sector reaffirmed once again the commitment of the MEW in pushing renewable targets and providing an ambitious 30% of the total electricity expected to be consumed in 2030 from renewable energy (MEW, 2019).

BRSS is continuously contributing to the reduction of CO_2 emissions that would have resulted from equivalent fossil-fuel energy generation, which forms a fundamental initial step in enhancing the air quality in the country. It has also been playing a small but important role in reducing the monetary expenses in the energy sector, thanks to its relatively low cost of energy when compared to local conventional generation units. Its main importance is highlighted in the demonstration of the feasibility and effectiveness of the PV technology in Lebanon and in the contribution to the improvement of the national energy system and its security in terms of fuel diversification; a first small step in the great sustainable energy transition of the country.

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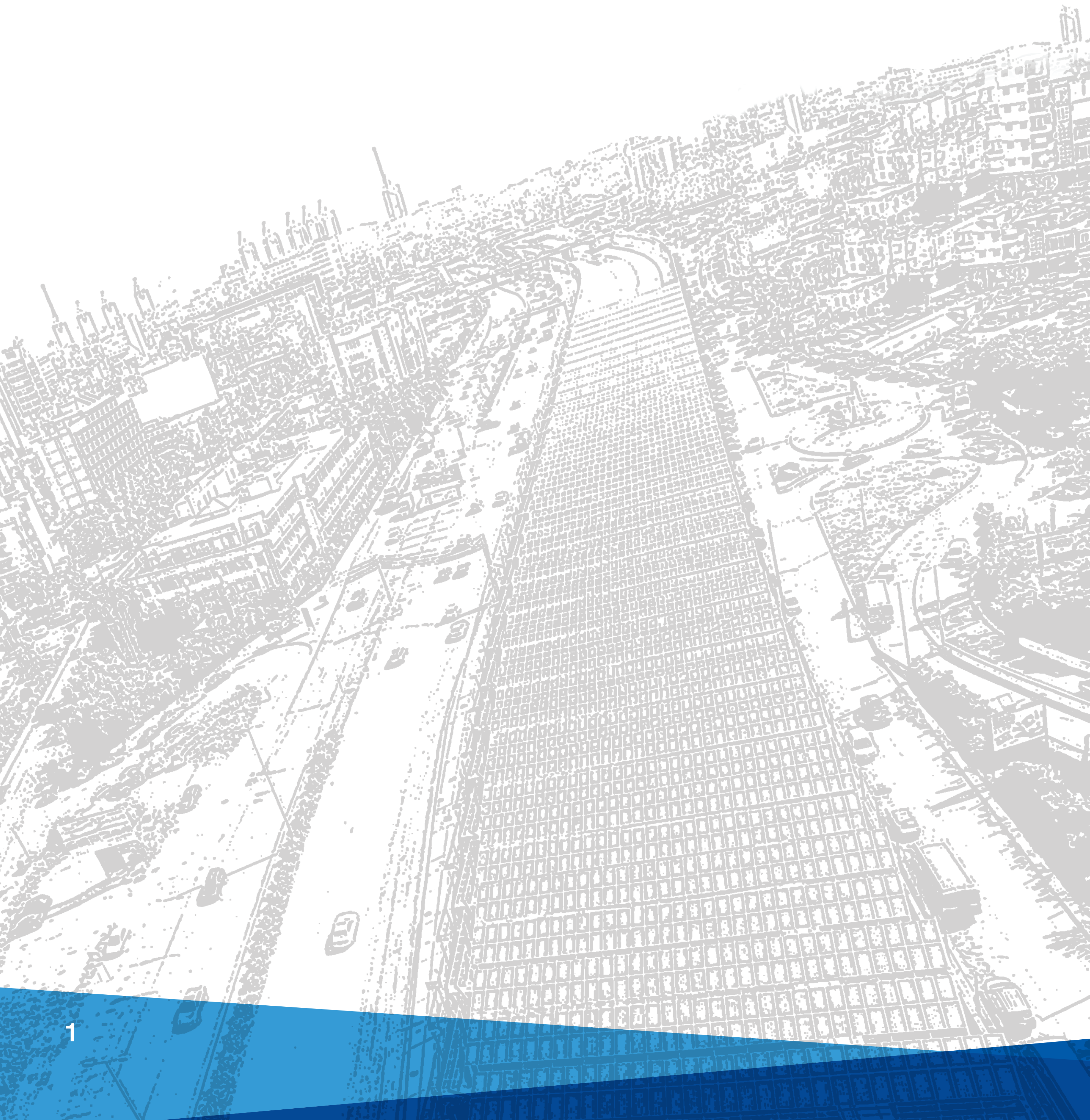

1 | The Beirut River Solar Snake story

1.1 A dream realized

The Beirut River Solar Snake (BRSS) project is the first grid-connected medium voltage (MV) solar photovoltaic (PV) system in the history of Lebanon. The dream of having a solar PV system on the top of the Beirut River bed emerged at the Lebanese Center for Energy Conservation (LCEC) back in 2012 based on a clear concept: if the Lebanese Government, represented by the Ministry of Energy and Water (MEW), is encouraging the private sector to build renewable energy projects, then it should lead by example. At that time, it was essential for the MEW to send a clear and strong signal that Lebanon is committed to reach its 2020 objectives set at the 2009 Copenhagen Summit (Conference of Parties [COP] 15).

When the Lebanese Government launched its famous 12% renewable energy target by 2020, a skeptical national reaction took place. Yet, the MEW reaffirmed this commitment in the Policy Paper for the Electricity Sector that was approved by the Council of Ministers (COM) in June 2018. One year later, the National Energy Efficiency Action Plan for Lebanon (NEEAP 2011-2015), detailed the different paths needed to reach the country's 2020 objectives, where the solar PV technology was one of the main areas of action.

It was clear back then that the private sector would need to implement the largest share of solar PV systems. It was also clear that National Energy Efficiency and Renewable Energy Action (NEEREA), Lebanon's national financing mechanism developed by the Central Bank of Lebanon (BDL), would have a great role in pushing the solar PV market towards impressive growth.

Then came the BRSS dream.

On April 23, 2013 and following the decision of the MEW to fund the initial 1 MWp phase of BRSS, the call for contractors to submit their expressions of interest (EOI) to build the project was launched. Consequently, 32 EOIs submitted on May 7, 2013 were evaluated then shortlisted to 26 interested bidders on June 13, 2013. The request for proposal (RFP) was published on July 12, 2013, and three rounds of questions related to the RFP were answered. A pre-proposal conference was held on September 3, 2013, and 12 offers were submitted on October 4, 2013. After the evaluation of the offers by a team that included two international consultants, one national civil consultant, one legal expert, and representatives from MEW, Electricité du Liban (EDL), and LCEC, the engineering, procurement and construction contract was finally signed, and the construction began on April 17, 2014. The construction of the initial 1 MWp phase of the BRSS project was completed by mid-2015.

And the dream became a reality.

1.2 One project, different phases

The initial objective of the BRSS project was to build a 10 MWp solar PV system, covering seven kilometers of the Beirut River bed, to be owned by EDL. MEW secured the budget needed to build the initial 1 MWp phase over the Beirut River facing MEW's headquarters as shown in Figures 1 to 3.

Figure 1. Panels view, BRSS, Beirut, Lebanon

Figure 2. The one megawatt peak phase of the BRSS project. Adapted from Google Earth

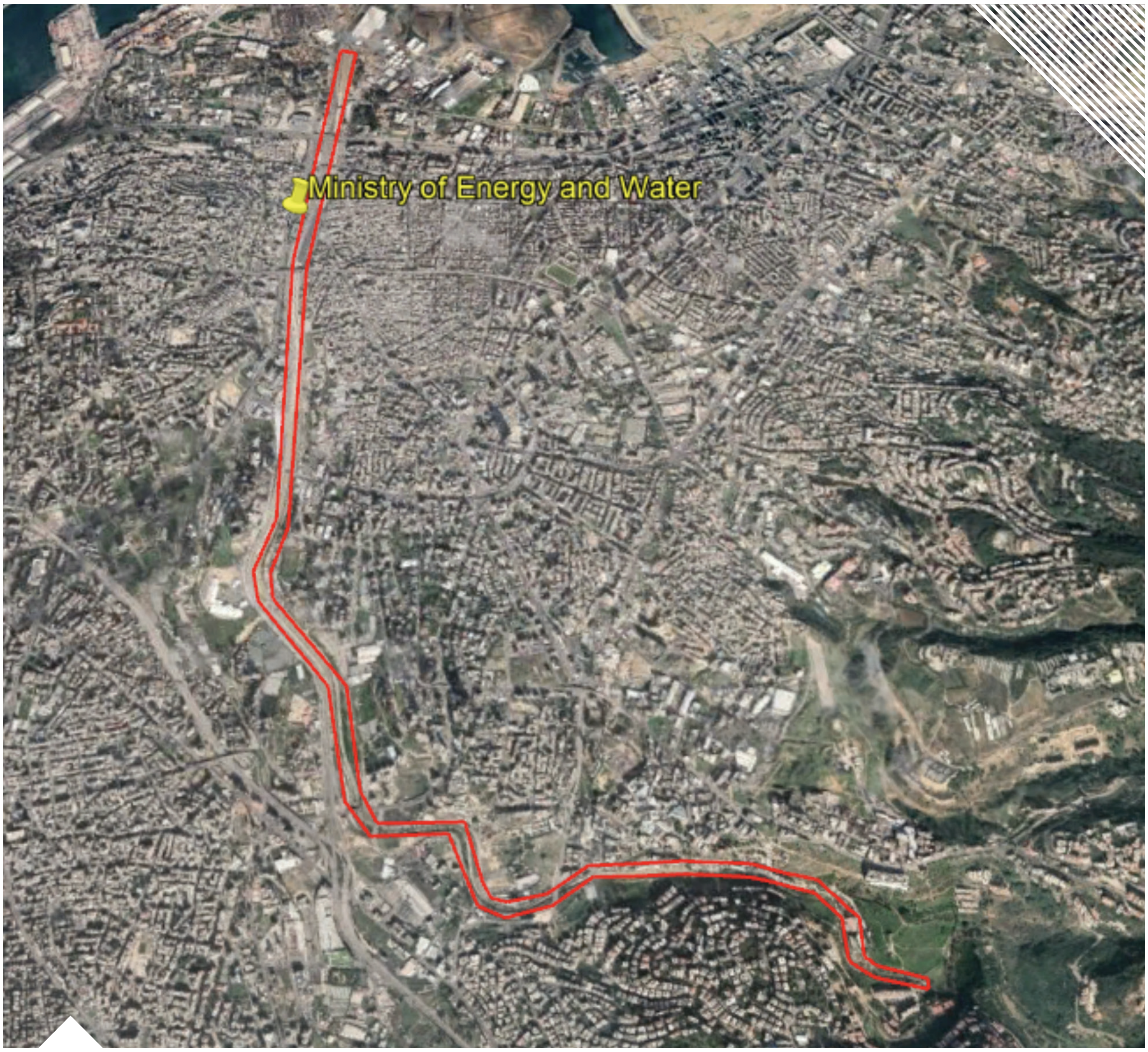

Figure 3. The seven kilometer river bed. Adapted from Google Earth

Following the implementation of the first 1 MWp, the solar PV market witnessed a remarkable growth whereby more than 35 MWp of decentralized rooftop solar PV farms were installed across the country within 3 years of the start of BRSS's construction (Amine & Rizk, 2018). In fact, the Zahrani Oil Installations in Lebanon launched and implemented another 1 MWp solar farm in 2014, which also created an impressive market momentum.

Moving forward with the project, during the International Beirut Energy Forum (IBEF) in 2018, EDL launched a tender for the implementation of a new phase of BRSS which consists of a 7 MWp plant that could be extended to 9 MWp, thus achieving the initial 10 MWp plan.

Accordingly, LCEC decided to conduct a detailed analysis of this iconic project to quantify its benefits and assess its operation before further expansion. This report aims to provide a complete assessment of BRSS operation based on internationally recognized and widely used performance metrics for grid-connected PV farms. This report also discusses the major impacts of medium scale PV grid integration and examines the potential role of renewables, specifically large-scale solar PV, in providing support to the national grid.

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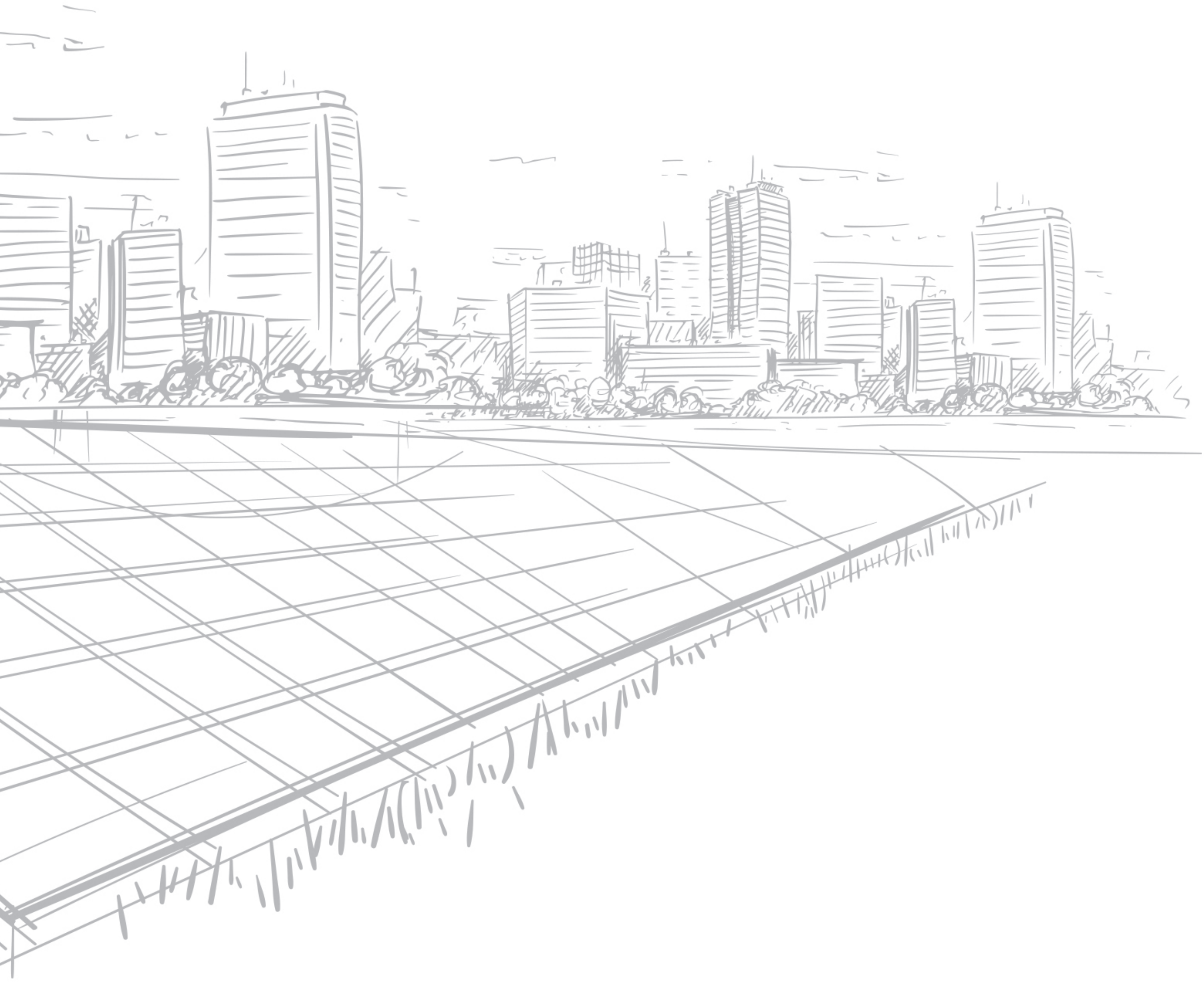

2 | Site description and plant overview

Spanning 10,000 m^2 above the Beirut River bed, the 1 MWp grid-connected BRSS project takes advantage of the unused space to supply green energy to EDL's MV grid through a step-up transformer located in a control room in the backyard of MEW headquarters. The project was built at a capital expenditure of USD 3.1 million, around 20% of which was allocated for the concrete beams spanning the river bed. This results in costs around USD 2,500/kWp for the rest of the system, which is less than the average turnkey price for a solar PV system in 2014, the plant's year of construction (Amine & Rizk, 2018).

The BRSS solar PV plant consists of 3,600 polycrystalline PV panels of 300 Wp each with an efficiency of 15.4%, 60 inverters, and 30 arrays with tilt angle of 10 degrees spanning 31 concrete beams above Beirut River. In fact, BRSS has generated 5,427 megawatt-hour (MWh) of electricity until June 2019. Given that BRSS is connected on the distribution network, these 5,427 MWh would correspond to 6,385 MWh of electricity that would have been generated by an existing power plant connected to the transmission network considering 15% losses on the transmission and distribution network. Accordingly, BRSS has so far reduced around 4.15 kilotonnes (kt) of carbon dioxide (CO2) based on a grid emission factor of 0.56 kt CO2/MWh, and saved USD 894,000 assuming that the average cost of electricity generated from conventional power plants in Lebanon is around 14 US cents/kWh (SMA, July 2019).

Each array in BRSS is composed of six strings of 20 modules in series, and each three strings are connected to a 15 kW inverter, while all 60 inverters are routed to eight alternating current (AC) field combiner boxes. The PV farm can inject active power at unity power factor to EDL's MV grid and supply reactive power if needed. A 1,250 KVA, 435 V/11KV step-up transformer, that meets EDL's requirements, is used to connect BRSS to the grid. A sample schematic drawing of a BRSS single line diagram, which shows its partial configuration and electrical connection architecture, is provided in Figure 4.

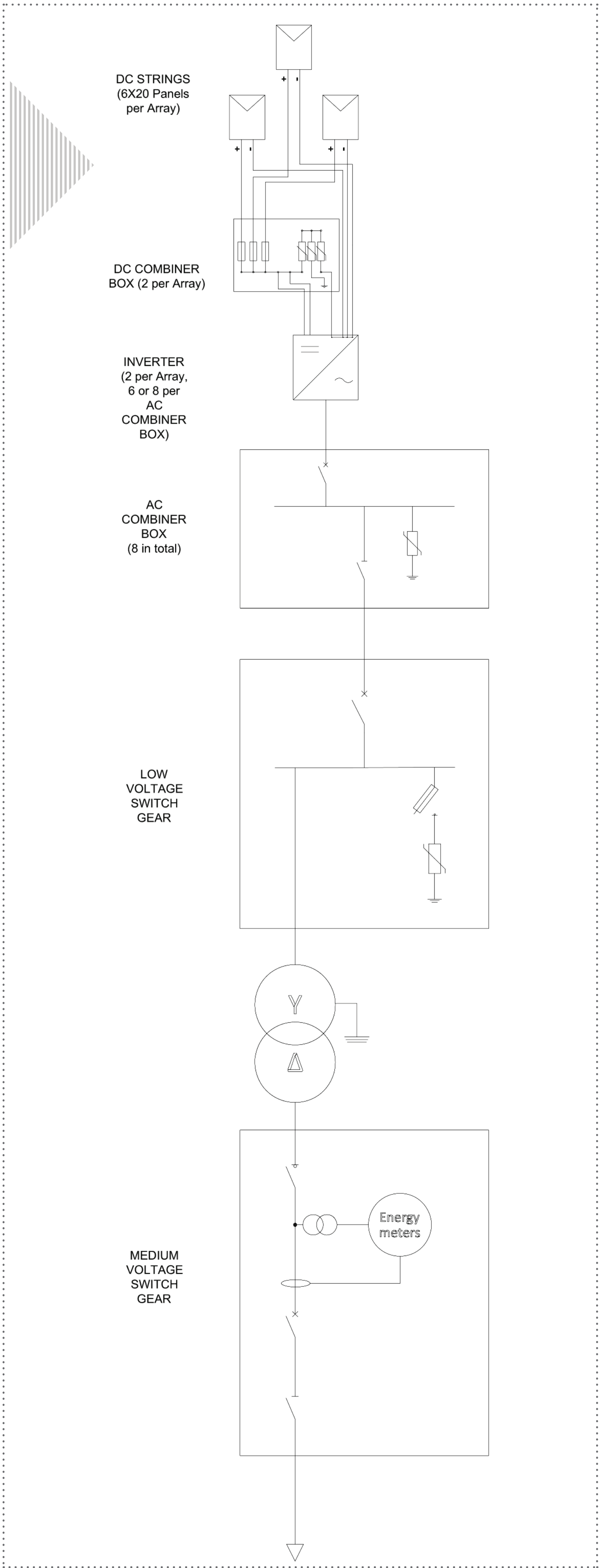

Figure 4. BRSS sample single line diagram

Metering devices

At the time of commissioning of the plant, two metering devices were used to measure the energy produced by BRSS. The first meter provides real-time metering at the AC side of the inverters via interconnected cluster control units linked to a web-based database. The measured parameters such as energy, voltage, and frequency, are first buffered in each inverter and then sequentially transmitted to the main field controller, which stores them in local buffer memory. A copy of these values is instantly transmitted to a dedicated computer in the control room via a file transfer protocol. A duplicate copy is similarly transmitted to a preassigned server on the cloud where the information is stored, analyzed, and displayed. The cluster control units also store measured irradiation levels from four sensors spread across the plant.

The second meter is installed after the MV circuit breaker, which measures the net energy injected into EDL's MV grid. This meter was calibrated in EDL laboratories where its accuracy was verified. The measured energy values can be physically read from the meter's screen or by serial communication on the computer located in the control room. Active and reactive energy, both consumed and generated, are separately measured as well. The meter is also equipped with an electrically erasable programmable read-only memory (EEPROM), a type of non-volatile memory which allows individual bytes to be erased and reprogrammed, and a battery backup that allows it to securely store the measured values.

In 2018, LCEC installed a third energy meter at the low voltage side of the MV transformer, having similar specs as the ones installed initially, to extract, log, display, register, and later-on analyze the interaction of the plant with the national grid.

Currently, the combination of these meters allows data storage, for generated active power at the inverters' side, cumulative energy yield at the inverters' side (before AC losses), net active power at the MV side, reactive power at the MV side, cumulative energy yield at the MV side (after AC losses), tilted irradiation data from four sensors across the plant, ambient temperature data from four sensors, module temperature data from four sensors, grid frequency, total power factor, line voltages, and total harmonic distortion.

3

3 | Performance assessment and analysis

3.1 General review

The performance assessment of a PV farm involves measuring and monitoring the actual performance and comparing it to the expected. Many fundamental performance metrics necessary for the assessment of a PV plant have been defined at the international level, such as the total PV yield, the reference yield, and the performance ratio (PR). This document mainly focuses on the PR to assess the performance of BRSS, since it is a widely used and reflective performance metric in the PV industry. In practice, operating conditions influence the PR of the PV plant, so it becomes necessary to consider several important issues which will be detailed in the next section.

The performance and the efficiency of a solar cell are highly correlated with temperature, which leads to diurnal and seasonal variations in the PR. Relatively low temperatures favor a more efficient module operation, while higher temperatures lower the cell's efficiency, considering the same amount of incoming irradiation. In some cases, the measuring gauge used in the PV plant can be dirty or shaded, which leads to PR values higher than unity. In fact, if the irradiation sensor is soiled, it will report an irradiation value lower than the actual one, thus, the calculated PR could in some cases be greater than unity and will not reflect reality. In addition, a short measurement period would obviously lead to unreliable PR results, since cases reflecting low solar elevations, various temperatures, and shading may not be completely recorded.

AC losses, including voltage drop losses should also be taken into consideration, since they reduce the actual energy injected to the grid. AC losses are typically associated with the transmission of energy from the inverter to the grid injection point. These losses vary according to the type, length, cross section, method of installation, temperature, and material of the used cables, and, therefore, do not really affect the actual operation of the PV cells. It should be noted that all these factors, in addition to inverter losses, were considered in the PR calculation for conservative results.

Solar plant performance metrics

The modern renewable energy industry must overcome serious challenges, because it has to securely supply reliable energy at a competitive price despite the intermittent nature of the renewable resource. This requires accurate information on present and future availability of the solar resource, as well as other data on parameters that affect the energy yield, such as shading and component downtime. Therefore, it becomes necessary to constantly monitor and assess the performance of grid-connected PV power plants via the performance metrics proposed in Table 1 according to different purposes. In addition, these performance metrics can be categorized according to their reflective time span, which can be instantaneous, short term, or long term. Degradation mechanisms and anomalies are usually relevant on the long-term time span, so all time ranges should be considered to perform a detailed assessment.

Table 1. Performance metrics of grid-connected solar PV plants

Metric	Purpose
Performance ratio	Maintenance
Energy performance index	Maintenance, commissioning, and financial
Power performance index	Commissioning and troubleshooting

As defined in IEC 61724: 2017 photovoltaic system performance monitoring, the PR is a widely adopted metric used to assess the performance of solar PV plants. It indicates how effectively the PV plant is converting sunlight to electrical energy. It also quantifies the overall effects of losses due to wiring, cell mismatch, inverter losses, module surface reflection, soiling, system downtime, cell temperature, component failure, and shading. The PR consequently reflects the proportion of energy fed to the grid post energy losses and quantifies the reliability and efficiency of the PV plant while monitoring its operation over the long run. With values ranging from 0 to 1, a high PR reflects a healthy plant operation, while a low PR indicates the opposite. In practice, the PR never reaches unity due to inevitable system losses. It is however common that high-performance PV plants reach a PR averaging around 0.85. Accordingly, it becomes suitable to rely on the PR metric for the sake of BRSS assessment.

3.2 Operation metrics and assessment

As explained in section 3.1, it is critical to perform detailed calculations to obtain reliable results that facilitate the assessment of BRSS performance. Accordingly, the PR was computed on a daily basis using the energy values measured at the low voltage side of the connection point with EDL and recorded at 15-minute intervals for high accuracy results. According to the BRSS engineering, procurement and construction contract, the PR is calculated as follows:

$$PR = \frac{E_{\text{system produced}}}{GTI \times A_{\text{total module area}} \times \eta_{\text{STC module}}}, \quad (3.1)$$

where PR is the performance ratio of the system, GTI is the global tilted irradiation in kWh/m^2, A is the total area of the PV modules in m^2, $\eta_{\text{STC module}}$ is the efficiency of the module expressed as a percentage, and E is the total energy produced by the PV power plant in kWh. Following that:

$$A_{\text{total module area}} = \text{single module area x total number of modules},$$

$$\eta_{\text{STC module}} = \frac{\text{module rating at STC}}{\text{module area}},$$

Plant power = module rating at STC X total number of modules =1,080 kWp.

Substituting the parameters above by their corresponding formulas in equation (3.1) leads to the following:

$$PR = \frac{E_{\text{system produced}}}{GTI \times \text{plant power}} = \frac{E_{\text{system produced}}}{GTI \times 1080}, \quad (3.2)$$

The PR is therefore calculated by simply plugging into equation (3.2) the values of E and GTI measured from the field. The gathered data was processed and refined to remove inadequacies and preserve the consistency of the results. The refined total irradiation and the refined total energy produced were separately summed for each day of each month.

The obtained values were then plugged into equation (3.2), and the PR was obtained for each period of time. The monthly PR was calculated as the average of the daily PR over the corresponding month, and the yearly PR was calculated as the average of the monthly PR over the corresponding year. Ideally, the PR should not be based on averages. However, it was computed as described in this case to avoid data gaps, inconsistencies, and outlying values, and to obtain reliable results.

The capacity factor (CF) is another important parameter used in the assessment of the operation of PV plants. By definition, the CF is the ratio of the actual electrical energy production over a given period of time to the maximum possible electrical energy output during the same time period as shown in equation (3.3) (Renewable Energy Policy Network for the 21st Century, 2017):

$$CF = \frac{\text{actual energy produced}}{\text{maximum nameplate energy produced}} \quad ,(3.3)$$

The monthly CF and yearly CF were computed using the daily values, following the same procedure done for the PR calculation. A summary of the main results can be found in Table 2 and Figure 5.

Table 2. Performance ratio and capacity factor results for BRSS

	2015		2016		2017		2018	
Month	**PR**	**CF**	**PR**	**CF**	**PR**	**CF**	**PR**	**CF**
Jan	—	—	0.92	0.09	0.85	0.10	—	0.09
Feb	—	—	0.87	0.13	0.71	0.14	—	0.11
Mar	—	—	0.86	0.17	0.88	0.15	—	0.15
Apr	—	—	0.89	0.22	0.86	0.21	—	0.17
May	—	—	0.85	0.24	0.87	0.24	0.83	0.20
Jun	—	—	0.81	0.24	0.86	0.23	0.78	0.22
Jul	—	—	0.66	0.20	0.84	0.20	0.75	0.17
Aug	—	—	—	—	0.86	0.21	0.77	0.17
Sep	0.75	0.15	0.71	0.15	0.88	0.16	0.80	0.16
Oct	0.80	0.15	0.69	0.12	0.87	0.13	0.90	0.14
Nov	0.80	0.11	0.62	0.08	—	—	0.86	0.10
Dec	0.81	0.09	0.84	0.08	—	—	0.89	0.07
Average	**0.79**	**0.13**	**0.79**	**0.14**	**0.85**	**0.18**	**0.82**	**0.15**

Note: CF = capacity factor; PR = performance ratio; — = no data

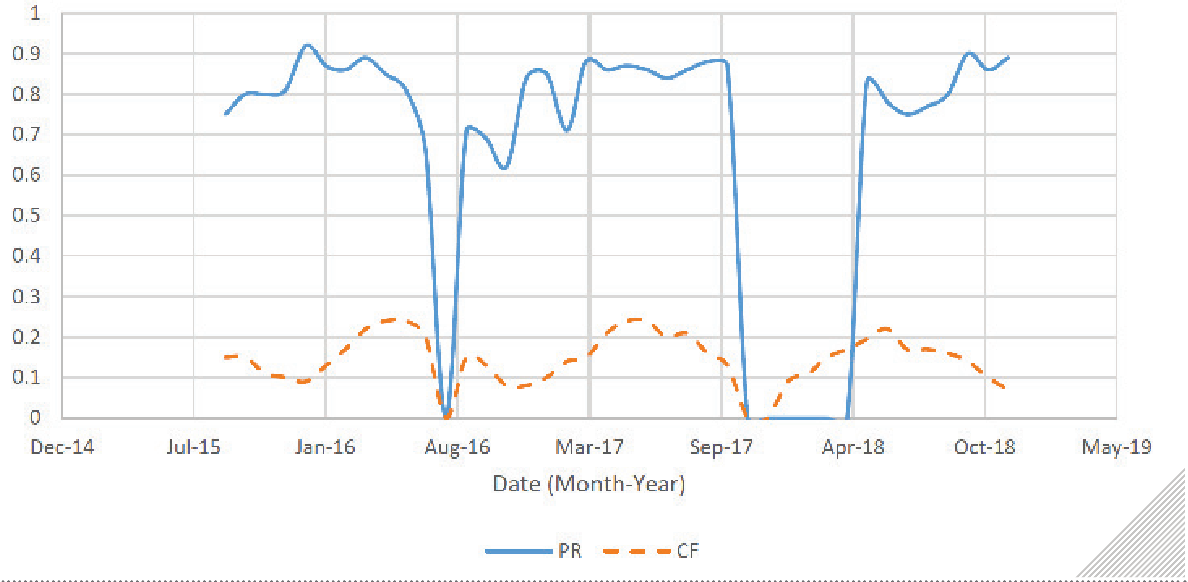

Figure 5. Evolution of the performance ratio and capacity factor for BRSS

Based on the results in Figure 5, the BRSS PR was about 0.79 in 2015 and 2016, increased to 0.85 in 2017, then decreased to 0.82 in 2018. The 2015 and 2016 PR values occurred in the early commissioning phase of BRSS when final modifications were still being performed, but still reflect satisfactory system operation.

The remarkable 0.85 and 0.82 PRs reached in 2017 and 2018 respectively, after the full deployment of the plant, indicate excellent system performance. The data gaps in November and December 2017 and the first quarter of 2018 were due to data logging problems, while the gap in August 2016 was due to a failure of the MV transformer, which was quickly replaced. Despite these issues, BRSS has operated with an overall average PR of 0.81 since its commissioning, which reflects excellent performance compared with the expected simulated PR of 0.815. Following a similar approach to the one used for PR computation and analysis, the BRSS CF was found to be 0.13 and 0.14 in 2015 and 2016 respectively, while it went up to 0.18 in 2017 and fell to 0.15 in 2018.

Due to the large temperature differences between summer and winter in Lebanon and the high correlation of temperature and plant performance, an additional detailed data analysis was performed to visualize the correlation between BRSS performance and the module temperature. Figures 6 and 7, suggest how the PR and the CF of BRSS vary with module temperature changes.

To better visualize the correlation between the PR, the CF, and the module temperature, the missing values for both the PR and the CF were estimated as follows:

- For August 2016, the PR and the CF were estimated as the corresponding average values for July and September.
- For November and December 2017, the values for the PR and the CF were taken as per their corresponding values in the previous year, meaning November and December 2016, assuming similar weather conditions, and similar plant performance.

- For January to April 2018, the data for the PR was taken as per its corresponding values in the previous year, meaning January and April 2017, again assuming similar weather conditions and similar plant performance.

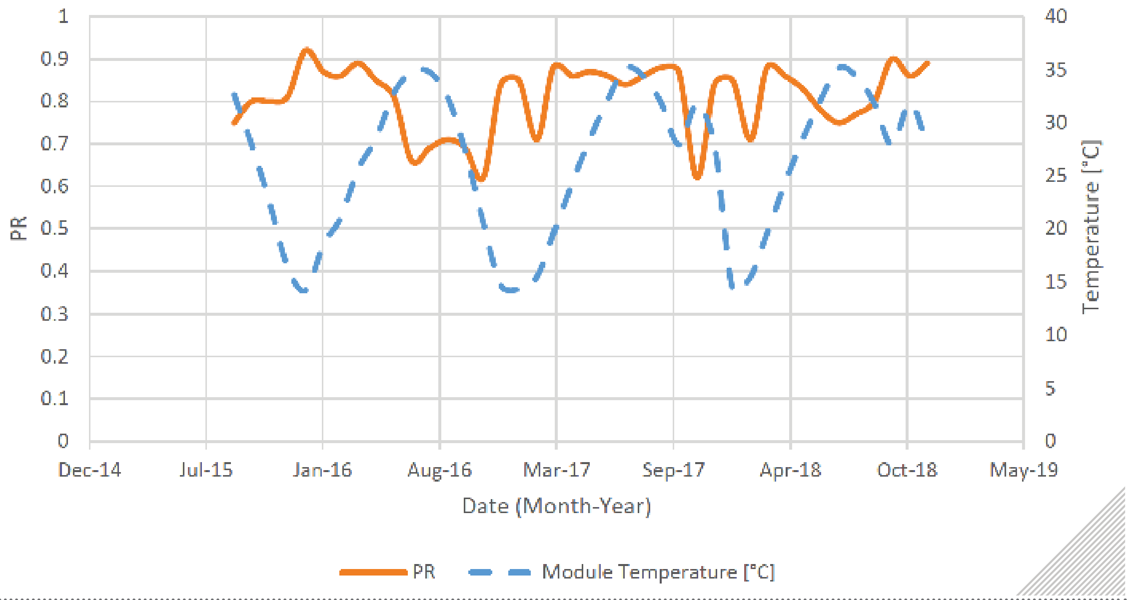

Figure 6. Performance ratio and module temperature correlation for BRSS

As expected, the data displayed in Figure 6 suggests that the PR is inversely proportional to the module temperature. Assuming similar irradiation levels, the higher the module temperature the lower the PR and conversely, the lower the module temperature the higher the PR. These empirical results are aligned with the conduction bandgap theory in semiconductors, which suggests that a higher module temperature reduces the conduction bandgap and hence reduces the PV cell voltage build-up (G. Claudio, personal communication, November 2017).

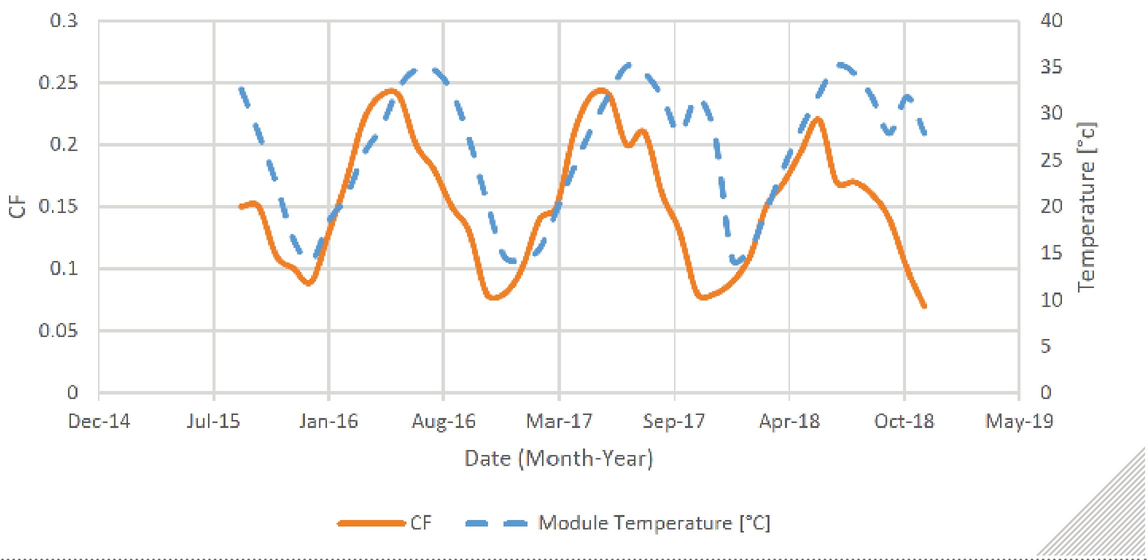

Figure 7. Capacity factor and module temperature correlation for BRSS

Similarly, Figure 7 suggests that CF is directly proportional to the temperature, which is also proportional to the GTI in the case of BRSS. It was noticed that the module temperature and the ambient temperature are directly and closely proportional as the module's temperature is on average a couple of degrees higher than the ambient temperature and follows the same trend as shown in Figure 8.

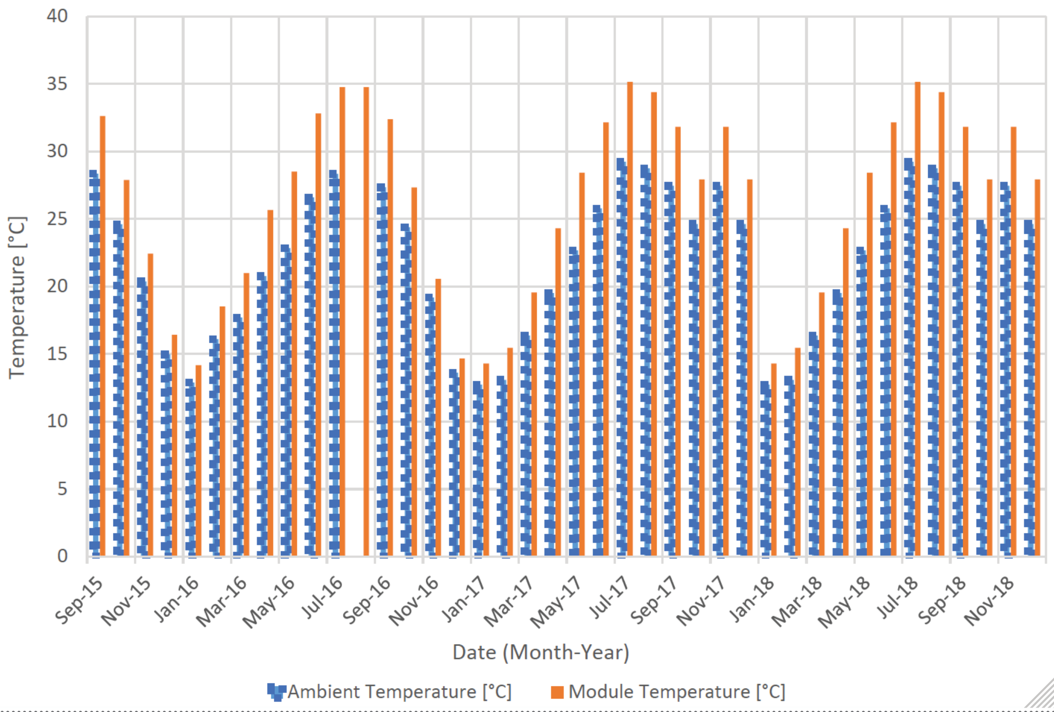

Figure 8. Ambient temperature and module temperature trends for BRSS

3.3 Weather, global tilted irradiation, energy correlation, and seasonal variations

It is well known that weather, GTI, and the plant's generated energy are highly correlated. On the macro level, the average monthly trends in GTI and energy yield based on their recorded daily values are presented in Figure 9. Recall that the data gaps in November and December 2017, and the first quarter of 2018, were due to data logging problems, while the one in mid-July to mid-September 2016 was due to a failure of the MV transformer. Figure 9 shows that the energy yield is proportional to the incoming GTI, which is in turn affected by the seasons. In fact, the highest values for both GTI and energy yield were recorded during summer, while the lowest values were recorded in winter, which emphasizes the seasonal effect on the plant production. Accordingly, the higher the GTI the higher the energy yield and conversely. The high GTI values and low energy yields recorded in July and September 2016 were due to the failure of the MV transformer, which is normal for a grid-connected plant since the point of common coupling to the grid, via the MV transformer, is the only way for the evacuation of the produced energy.

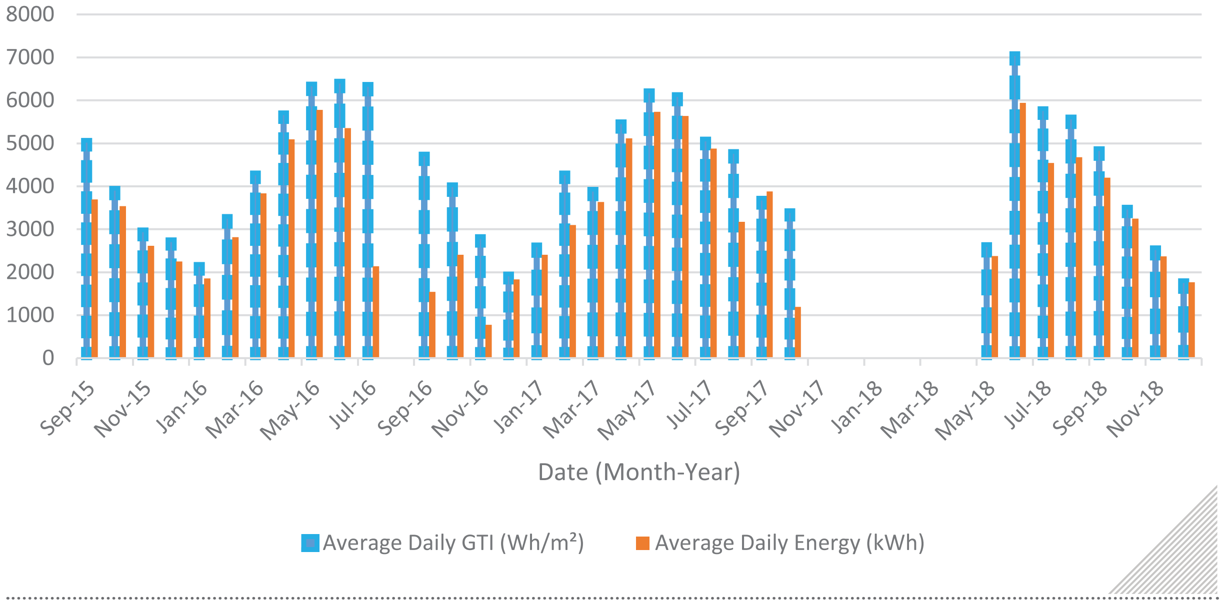

Figure 9. Average monthly trends of the global tilted irradiation and energy

The hourly-based graphs in Figures 10 to 13 reflect the most interesting cases and scenarios under which BRSS was performing. The choice of the dates took into consideration the seasonal effects, the weather variations, the intermittencies, and the unexpected events encountered during the plant's operation.

In fact, figures 10 to 13 suggest that the energy generation pattern of BRSS is aligned with the sun's relative daily pattern. As observed, the system's energy production starts rising slowly in the morning and gradually reaches its maximum value around midday, while it falls slowly to reach zero after sunset as illustrated in Figure 10 to 13 for the different seasons. It should be noted that the energy yield was measured on the AC side of the inverter to account for the conversion losses. Additional graphs (Figure 14 and 15) show the overall seasonal effect on the energy production of the PV plant.

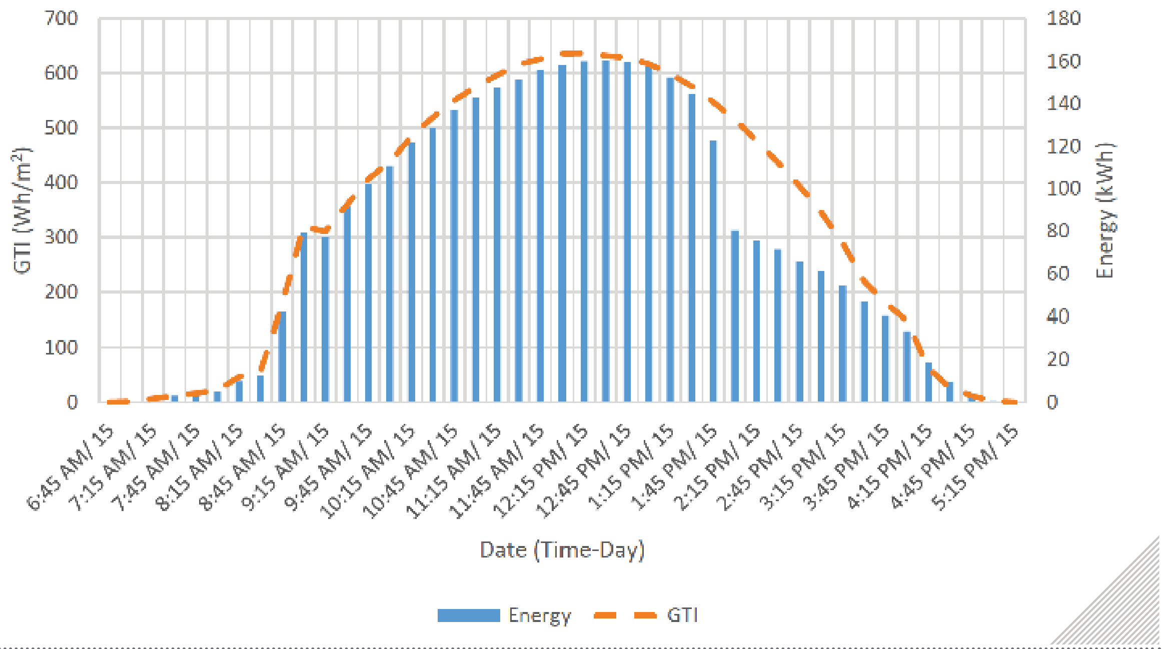

Figure 10. BRSS energy yield and global tilted irradiation - January 15, 2017

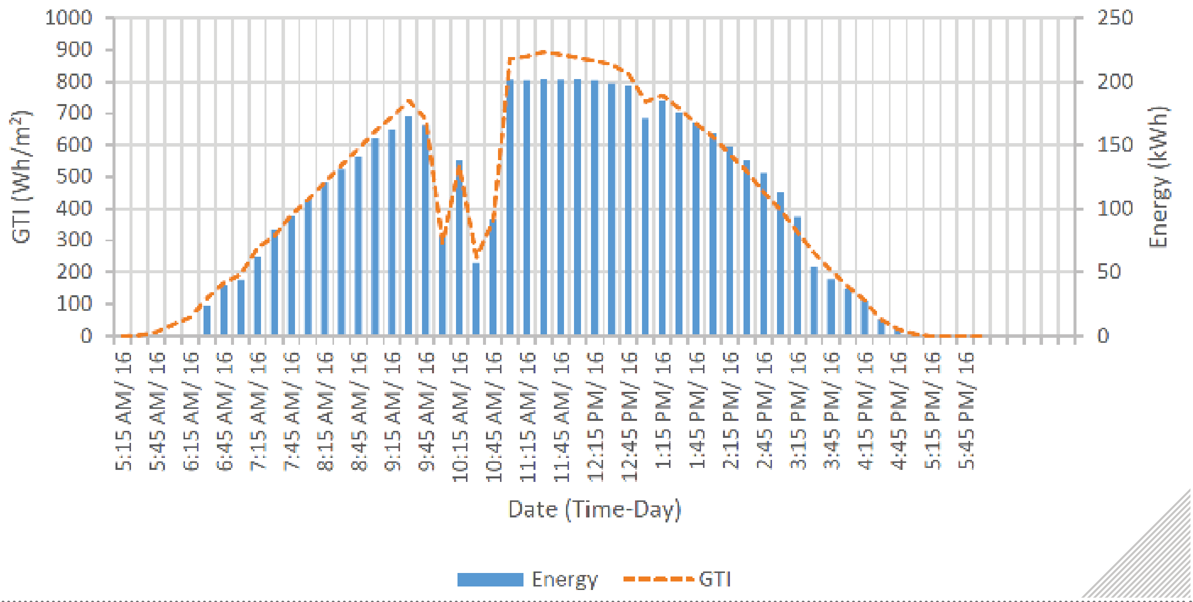

Figure 11. BRSS energy yield and global tilted irradiation - March 16 , 2017

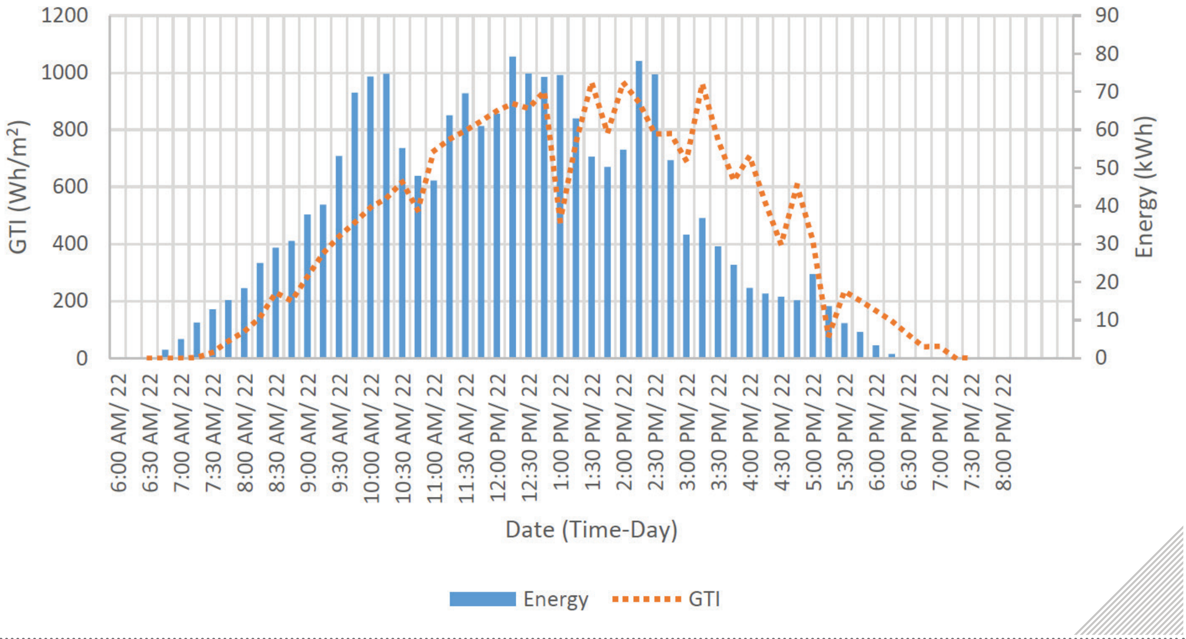

Figure 12. BRSS energy yield and global tilted irradiation - April 22, 2017

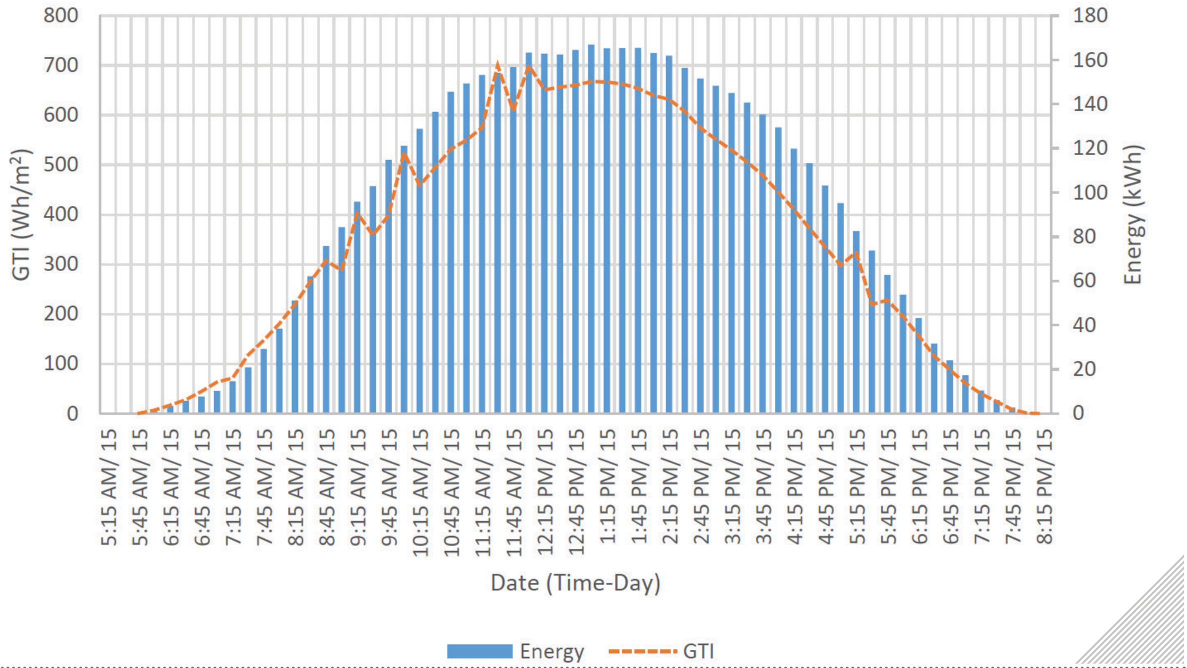

Figure 13. BRSS energy yield and global tilted irradiation - July 15, 2017

The seasonal effect on the energy production pattern of the PV plant was also observed when comparing the energy yield and GTI during different months in different seasons. High values of energy production were observed in summer as opposed to low energy production values in winter. Cloud coverage and deprivation from solar irradiation are major contributing factors to the low energy yield values, and to the distortion of the typical parabolic shape and pattern of the energy generation profile of the PV plant as shown in Figure 14 and Figure 15.

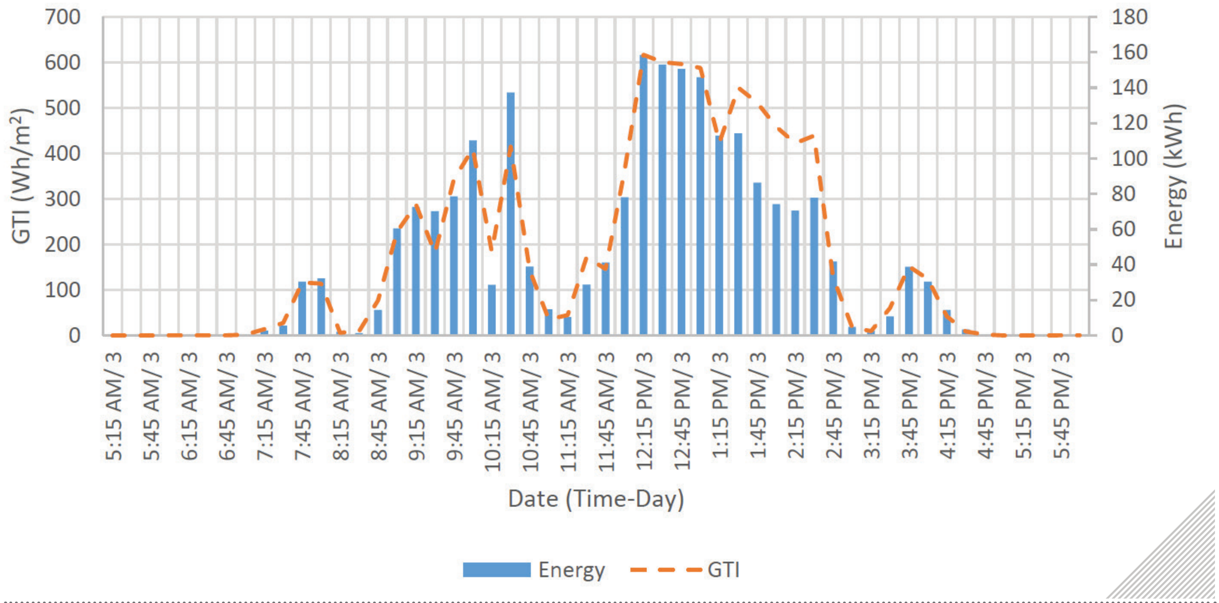

Figure 14. BRSS energy yield and global tilted irradiation - January 3, 2017

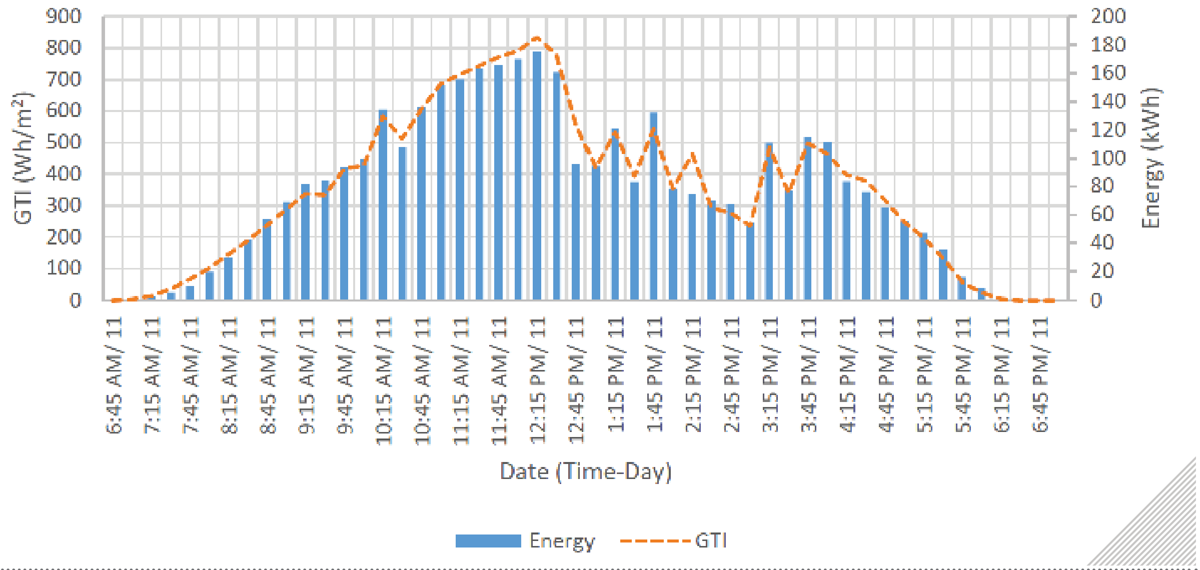

Figure 15. BRSS energy yield and global tilted irradiation - October 11, 2017

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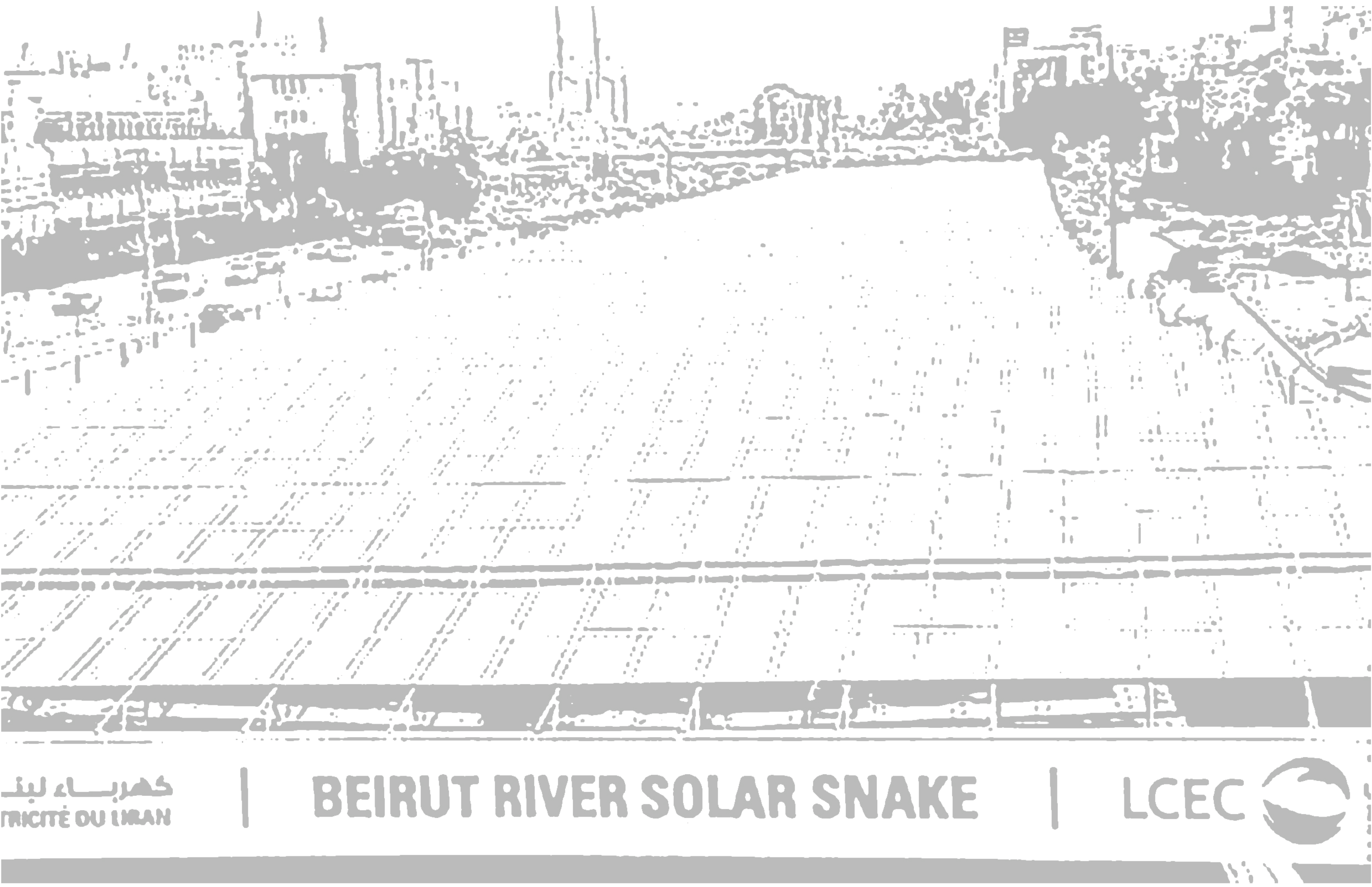

4 Grid support potential

It is true that renewable energy integration, including solar PV, adds complexity and imposes many challenges on the operation and management of power systems, but it is also true that it provides multiple supportive functions that have a highly substantial economic and technical value. In fact, many studies and efforts have been established at a national level to de-risk and promote renewables. One key document is Solar PV Grid Interconnection Code for Lebanon: Recommendations and Guidelines, which addresses large-scale PV plants in Lebanon (Idlbi, Jansen, & Rammal, 2016). In fact, large-scale solar PV projects could potentially support the national grid from both a technical and an energy generation point of view.

From a technical point of view, centralized solar PV plants can provide valuable steady state voltage and power support to the grid and improve the voltage profile across the various nodes of the system. They can also potentially provide valuable dynamic support to the grid during faults and during normal operation within specified voltage and frequency ranges, specific to the local grid on a case-by-case basis.

In fact, the voltage variations on the Lebanese MV grid during normal system operation fall in general within 10% of the nominal base value, which indicates compliance with international standards and confirms the potential feasibility of PV grid support features in Lebanon. The proposed frequency values in the inverter settings of BRSS indicate as well that it remains online for the complete frequency range specified in Solar PV Grid Interconnection Code for Lebanon: Recommendations and Guidelines (Idlbi et al., 2016), because its inverter time settings keep it online within the upper and lower maximum limits of frequency deviations set at 52 Hz and 47 Hz respectively as shown in Tables 3 to 6. It should be noted that additional analysis is needed in this context since there might be some cases where the voltage and frequency might show high deviations, specifically during faults and contingencies, which might jeopardize the ability of PV plants to provide grid support. Tables 3 through 6 summarize the inverter settings at BRSS and show the allocated tripping time for different values of voltage and frequency.

Table 3. BRSS general inverters settings

Settings Parameters	Assigned Value
Maximum duration of a short interruption	3 s
Maximum grid unbalance	10%
Maximum tripping time after unbalance detection	500 ms
Maximum frequency change per second	10 Hz
Tripping time for maximum frequency change	10 ms

Note: Hz = hertz; ms = millisecond; s = second

Table 4. BRSS inverters settings - frequency

Settings Parameters	Assigned Value
Median maximum threshold	52 Hz
Median maximum threshold tripping time	10 ms
Lower maximum threshold	51.5 Hz
Lower maximum threshold tripping time	90 ms
Upper minimum threshold	47.5 Hz
Upper minimum threshold tripping time	20 ms
Median minimum threshold	47 Hz
Median minimum threshold tripping time	500 ms

Note: Hz = hertz; ms = millisecond

Table 5. BRSS inverters settings - voltage and frequency reconnection limits

Settings Parameters	Assigned Value
Upper frequency limit for reconnection	65 Hz
Lower frequency limit for reconnection	44 Hz
Upper voltage limit for reconnection	280 V
Lower voltage limit for reconnection	45 V

Note: Hz = hertz; V = volt

Table 6. BRSS inverters settings - voltage

Settings Parameters	Assigned Value
Median max threshold	276 V
Median max threshold tripping time	500 ms
Lower max threshold	262.2 V
Lower max threshold tripping time	1 ms
Upper min threshold	200.1 V
Upper min threshold tripping time	2.5 ms
Median min threshold	184 V
Median min threshold tripping time	500 ms
Upper max threshold	400 V
Upper max threshold tripping time	0.312 ms

Note: ms = millisecond; V = volt

From an energy generation point of view, although a deeper analysis is needed to quantify the full potential of centralized solar PV to support the grid in Lebanon, it remains interesting to investigate how plants like BRSS contribute to the daily load demand curve in Lebanon, and check whether they can effectively contribute to electricity generation during peak time.

After inspecting the generation profiles of BRSS, it was noticed that it can contribute in general to electricity generation under normal day load conditions. In fact, BRSS can effectively generate energy between 8:00 and 16:00 in winter and between 7:00 and 17:00 in summer, which limits the potential of solar PV to support conventional generation during peak time if no storage is involved.

A more detailed study of the hourly load demand curves and the generation profile, including conventional and renewable plants, is needed to fully explore the potential of centralized solar PV plants in this context.

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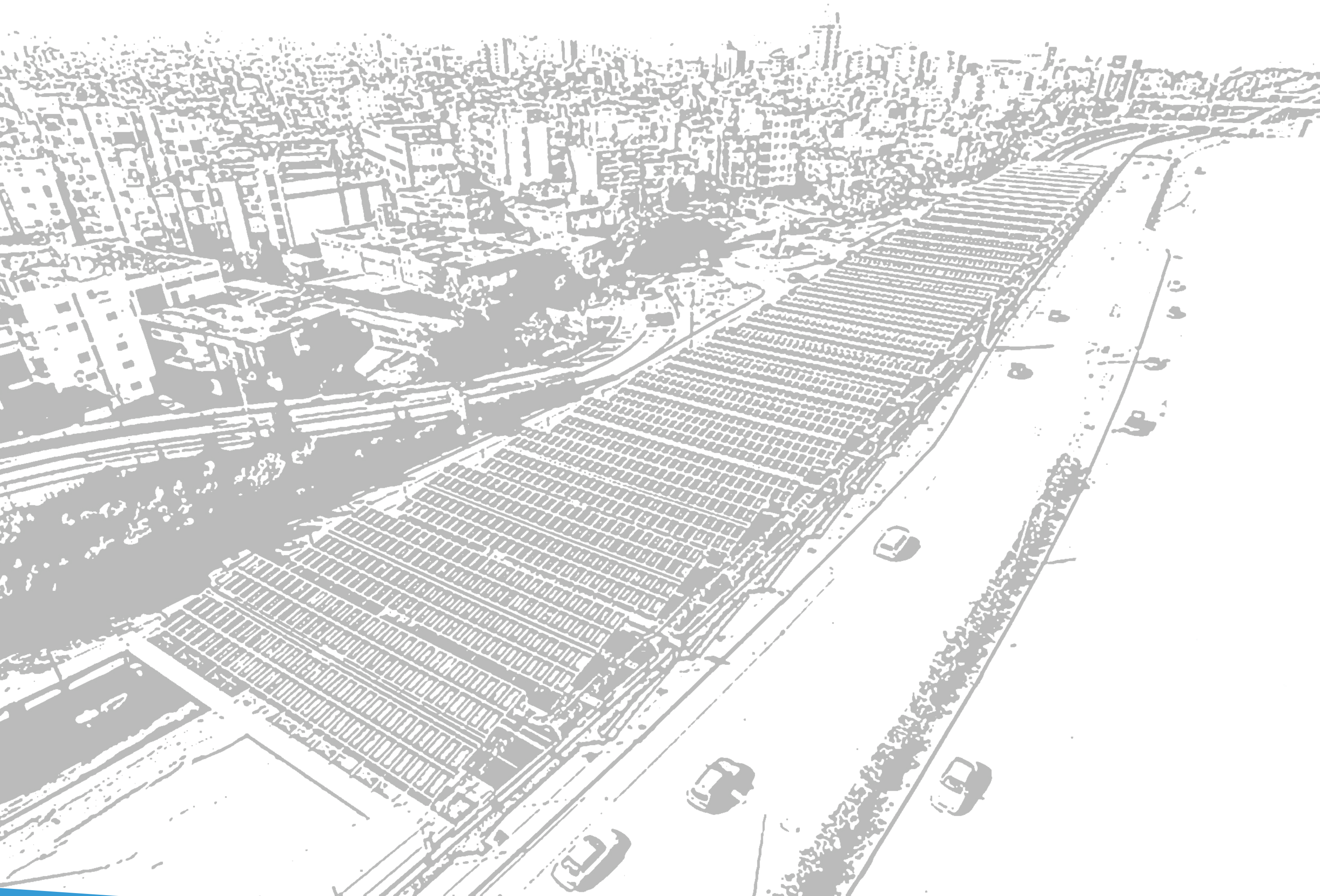

5 | Conclusions and recommendations

Based on the proposed analysis, it can be concluded that the performance of BRSS is satisfactory. Operating with an average PR of around 0.81, the iconic project proved that it is efficiently feeding EDL's MV grid with green energy, saving an average of 4.15 kt of CO_2 per year and promoting annual average savings estimated at USD 894,000 (SMA, July 2019).

Additional grid-integrated PV plants similar to BRSS, are expected to be executed and operational online by 2030, providing green energy to the EDL grid. BRSS assessment provides a reference benchmark document for the future assessment of pipelined grid-integrated, centralized PV plants. In addition to the monetary and CO_2 savings, BRSS can be potentially upgraded to provide grid support via active power-frequency and reactive power-voltage contribution.

PV integration is also expected to mitigate the severity of the load shedding problem and provide diversity to the energy resources in the country that currently relies heavily fossil fuels. However, further considerations and detailed grid-integration studies should be performed in parallel with the increase in the penetration level of centralized solar PV systems, since it poses many challenges that affect the stability, reliability, security, management, and continuity of the EDL grid. Other issues related to storage facilities, spinning reserves, and network expansion should be also investigated to mitigate the impact of large-scale solar PV grid integration.

ANNEX

A | Main grid integration considerations for renewables

Renewable energy systems are considered distributed generation sources that have numerous considerable impacts on classical centralized power systems, especially at high penetration ratios. Several major issues should be analyzed before their full-scale integration including system stability, voltage stability, frequency stability, and rotor angle stability.

A.1 System stability

The stability of a power system is reflected in its ability to regain normal balanced operation following a disturbance. A power system is stable when the generated power and the demanded power are balanced, a challenging task due to the constantly varying load and the intermittent renewable resource. Effects of system instability can be devastating as they can vary from a small load shedding to a complete system blackout. It is therefore fundamental to preserve the system's stability to ensure the grid's reliability and a smooth integration of renewables. Stability is classified according to the disturbance's nature, size, and time span. The main stability types - voltage, frequency, and rotor angle - are summarized in Figure 16 (A. Diaz, personal communication, March 2017).

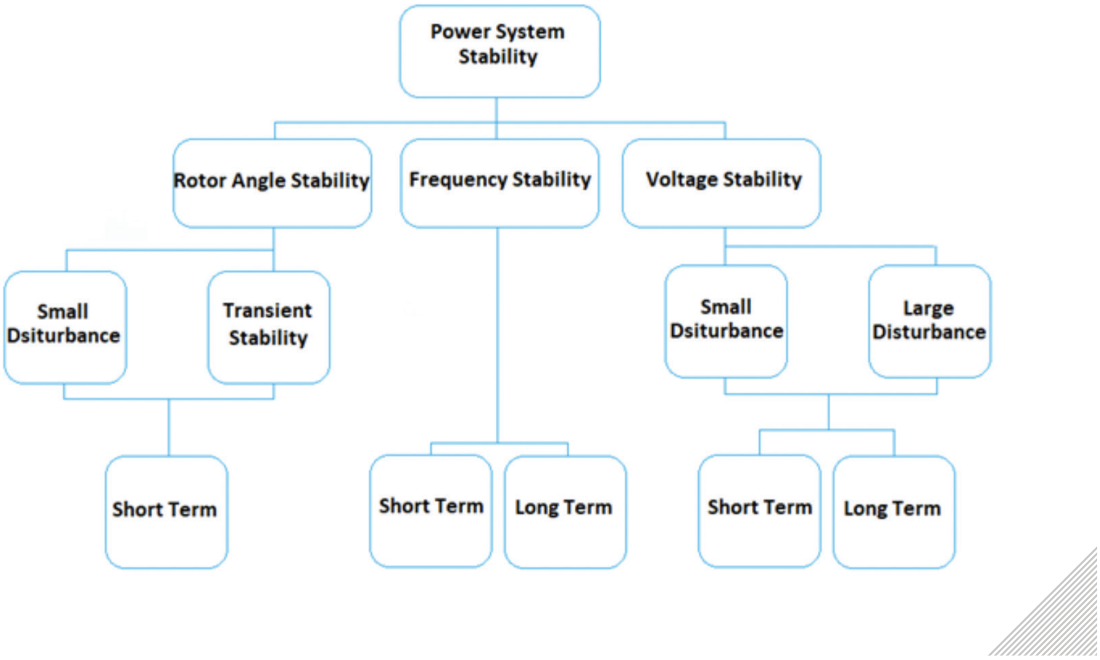

Figure 16. Classification of the types of stability issues in power systems

A.1a Voltage stability

Voltage stability is the system's ability to preserve stable voltage levels across all its buses following a disturbance and until normal operating conditions are re-established. Under stable conditions, when the voltage level increases, the reactive power level increases and vice versa, so progressive voltage variations can lead to variations in the load's reactive power requirements and cause voltage instability. The standard on electricity characteristics in public distribution systems European Norm (EN) 50160, specifies that no voltage variations should be greater than 10% at any node in the system to preserve voltage stability.

Small disturbance voltage stability results from small changes in voltage due to small incremental changes in system loads, while large disturbance voltage stability is due to large changes in the system's load or generation. Whether small or large, short term or long term, voltage stability is considered a local problem that has a system-wide global impact. In fact, reactive power evolution at the load is a good indicator of the system's voltage stability. The system can still be considered voltage stable if the reactive power at every bus increases with a voltage level increase. The following factors are one of the options that could help in the assessment of the system's voltage stability (A. Diaz, personal communication, March 2017):

1. The variation of the load bus voltage following a change in reactive power
2. The sensitivity of the receiving end voltage level with respect to changes in the sending end voltage levels
3. The total change in the generated reactive power due to variations in the load bus reactive power

A.1b Frequency stability

Frequency stability is the system's ability to preserve a steady frequency following a severe imbalance between demand and generation. As previously stated, the supplied power should always be equal to the generated power during steady-state operation, to preserve the average operating frequency around its rated value. In general, frequency stability issues are associated with insufficient generation reserves, poor equipment, inadequate protection coordination, and inconvenient equipment response.

Small-islanded or semi-islanded systems, like the Lebanese grid, are very susceptible to frequency stability issues, as it becomes hard to maintain stability in case of contingencies, faults, or similar events without a suitable backup provided in general through interconnections, storage facilities, or spinning reserves. EN 50160 restricts changes in frequency to no more than 1% from the rated nominal base value. Frequency instability can be a short-term instability due to sudden severe events such as loss of generation, line, or load, but it can also be a long-term instability caused by the slow change in load levels.

Being a global issue, the frequency is directly correlated with active power injection, and hence with the balance between demanded and generated active power. Two different strategies can be used to compensate active power imbalances; the first targets the demand side and the second focuses on the generation side. Demand-side compensation measures mainly focus on load shedding and time-of-use signals, while generation-side measures include the use of storage facilities, spinning reserves, and the modification of the power plant set point via automatic generation control (A. Diaz, personal communication, March 2017).

A.1c Rotor angle stability

Rotor angle stability can be thought of as the ability of the synchronous machines of the interconnected power system to remain in synchronism under normal operating conditions after being subjected to a disturbance. The mechanical torque input of the synchronous machine should always be compatible with its electrical output, which is translated in a constant speed under steady-state conditions. However, these machines tend to accelerate or decelerate when restoring forces act following a change in demand, which makes their speed proportional to the demanded power. When demand goes up, the machine will tend to accelerate, and when the demand goes down, the machine will tend to decelerate. These speed variations might increase the angular swings of one or more generators and lead to a loss of synchronism and a possible system collapse (A. Diaz, personal communication, March 2017).

As its name suggests, rotor angle small signal stability reflects the system's ability to maintain synchronism following small disturbances. Small signal stability depends on the system's initial operating state and usually corresponds in general to a 10–20 second time span after the disturbance. Conversely, transient stability is the system's ability to remain in synchronism when subjected to severe transient disturbances such as faults on transmission lines, loss of lines, loss of generators, loss of load, or loss of essential components such as transformers. The system's initial operating state and the severity of the disturbance determine the magnitude of the angle deviation. Transient rotor angle stability is in general examined up to 10 seconds after the disturbance. The post-disturbance system reactance as seen from the generator, the duration of the fault clearing time, the inertia of the generator, the generator internal voltage, the load level prior to disturbance, the generator's output during the fault, and the generator's internal reactance, are all factors that affect rotor angle transient stability (M. P. Comech, personal communication, March 2017).

A.2 System safety and security

Power systems containing distributed generation sources such as renewables might suffer from unintentional islanding, and therefore special care is usually taken by applying the relevant standards such as such as those developed by the Institute of Electrical and Electronics Engineers (IEEE) 1547 and the International Electrotechnical Commission (IEC) 62116 that address the obligation of distributed generation tripping to avoid inadvertent islanding. In fact, in electrical engineering the term island is used to describe an isolated electrical power system that has its own generation and can meet its active and reactive power demands. Based on this definition, islanding does not seem to impose serious safety threats. Unintentional islanding, however, is a big concern as it seriously jeopardizes the safety of personnel who might be performing maintenance work on seemingly de-energized parts of the network that are in fact energized. When it comes to security, N-1 system conditions are usually analyzed as a first step when testing the system's security and reliability. It is therefore essential to assess N-1 system security during post-renewable energy integration scenarios (M.P. Comech, personal communication, March 2017).

A.3 Relay coordination and protective equipment settings

Relay coordination becomes a critical task when dealing with renewable energy integration since it affects the system's stability, security, and reliability. The protective relays, essential for fault clearing and for preserving the system's safety and security, should be properly coordinated to avoid unwanted or delayed tripping.

A.4 Secure communication schemes

Evolving cyber threats jeopardize many important sectors including the vital power sector. Cyberattacks on power systems can lead to critical problems such as loss of load, line overloading, loss of generation, and loss of personnel safety, and can create serious permanent damage to the overall system infrastructure. Specific communication schemes and protocols such as IEC 61850 and generic object oriented substation events (GOOSE) messaging should be therefore adopted by the renewable energy plant operator for a secure and safe operation.

A.5 Technological challenges

Integrating renewable energy systems to a grid has many constraints and technological challenges which should be taken into consideration when performing grid access studies. Some of the major technological challenges in renewable energy systems integration include fault ride through (FRT), active power frequency control, reactive power-voltage control, and quality of supply (A. Diaz, personal communication, March 2017).

A.5a Fault ride-through

FRT is defined as the ability of a generator to remain online within a specific range from its rated output, when subjected to a fault. FRT is a key issue when integrating renewables especially at high penetration ratios, where the dispatch of a large amount of generation can have devastating consequences on the system's overall performance. In fact, unexpected loss of a big part of a generation, such as wind farms at low wind speeds and solar PV farms at low irradiation levels, can potentially trigger a cascading sequence of events, in case of high renewable penetration, that lead to a partial load shedding or even a total system blackout in severe cases. Generators are therefore required to remain connected during faults, according to specific grid codes, to prevent stability problems and support system recovery.

A.5b Active power-frequency control

Power systems cannot operate without real-time control due to the grid's dynamic nature and the required continuous demand-supply balance. The importance of these control methods increases when high amounts of renewables are integrated into the grid due to the resulting uncertainties and intermittencies that they add on the generation side. Power frequency control is one of these main control techniques as the grid's frequency is directly linked to the net power flow. Controlling the active power flow in the network would allow us to directly control the system's frequency, a necessary factor that contributes to the overall system stability and security.

In general, primary reserves are directly initiated after the event's occurrence. They are kept online up to 15 minutes if needed. Secondary reserves also provide support in that context, as they are triggered 30 seconds after the fault's occurrence. They are kept online as long as needed to restore the system's normal operating conditions. Similarly, tertiary reserves are also kept online as long as required but are triggered after a considerable time delay that can go as long as 15 minutes depending on the event's severity. Conventional and renewable generators are required to follow specific requirements, which vary between countries, and provide suitable frequency response under such events. In extreme cases, reserves cannot counter the effects of severe faults, and load shedding is performed by sacrificing part of the demand to avoid a complete blackout.

A.5c Reactive power-voltage control

Reactive power-voltage control is also fundamental to preserving the power system's stability and reliability. The voltage profile across the system's nodes could be controlled via reactive power injection. In fact, reactive power and voltage are directly correlated, so the voltage at each node can be controlled by controlling the same node's reactive power. Voltage control becomes more critical when the system operator is dealing with large amounts of integrated renewables due to the intermittent nature of renewable resources that adds uncertainties to the generation and imposes complexities on the system's operation (A. Diaz, personal communication, March 2017). Reactive power voltage control can be achieved in one way through flexible AC transmission system (FACTS) devices as detailed in Table 7 (M.P. Comech, personal communication, March 2017).

Table 7. Supportive functions of flexible alternating current transmission system devices

Subject	Problem	Corrective action	FACTS device
Voltage limits	Low voltage at heavy load	Supply Q or reduce X line	SVC, STATCOM, TCSC
	High voltage at low load	Absorb Q	SVC, STATCOM
	Post-outage high voltage	Absorb Q	SVC, STATCOM
	Post-outage low voltage	Supply Q	SVC, STATCOM
Thermal limits	Transmission circuit overload	Increase transmission capacity	TCSC, SSSC
Load flow	Power distribution on lines	Supply Q or adjust the voltage	SVC, STATCOM
	Reverse load flow	Adjust the phase angle	SSSC
Short circuit power	High short-circuit current	Limit short-circuit current	TCSC
Stability	Limited transmission power	Reduce X line	TCSC, SSSC

Note: FACTS = flexible alternating current transmission system; Q = reactive power; SSSC = series connected synchronous current source; STATCOM = static synchronous compensator; SVC = static reactive power compensator; TCSC = thyristor controlled series capacitor ; X = Reactance. M.P. Comech, personal communication, March 2017

A.5d Quality of supply

Large penetration of inverter-based, or nonsynchronous, wind and solar generation may substantially alter the system's stability, as they reduce the system's inertia which leads to variations in angle-speed swing behavior. The use of different voltage control systems influences the voltage swing behavior, while displacement of synchronous generation at key locations creates different power flow patterns. Distortion and fluctuation limits are outlined in IEC/TR3 61000-3-6/7 and European Committee for Electrotechnical Standardization (CENELEC) norm EN 50160.

A.6 Supportive functions

It is true that the integration of large-scale renewables imposes complexities and adds many challenges on the operation and management of power systems, but it it is also true that it provides multiple supportive functions that have highly important economic and technical values such as steady-state voltage support and dynamic grid support. In fact, dynamic support to the grid during faults is a very important feature that mitigates the impact of faults and improves the grid's reliability and continuity of supply.

B | Frequency conditions at the BRSS grid connection point

The international standard EN 50160 specifies, under normal operating conditions, the main characteristics of the electricity supplied by public electricity networks. The standard addresses many parameters related to the quality of power supply such as total harmonic distortion, flicker, voltage unbalances, and frequency variations. Due to its high importance in the local context, and since the other aforementioned parameters on EDL's MV grid are in general compatible with the international standards, the grid frequency was monitored at the BRSS point of interconnection from September 2015 to December 2017. The results were computed as a daily average for each month based on 15-minute time resolution measurements. It was concluded that the mode operating frequency was around 50.61 Hz. The lowest observed value was around 44.00 Hz, the highest recorded value was around 50.99 Hz, and the average computed value was around 49.23 Hz compared with a nominal base value of 50.00 Hz. It should be noted that these conditions only apply to the BRSS point of interconnection with EDL's MV grid, and other locations might have different values for these parameters.

It was noticed that the frequency at the point of interconnection was in general subject to variations that make it incompatible with international standards. However, the comparison of these local conditions with international standards, such as EN 50160, is not highly relevant at this stage due to the special nature of the Lebanese grid, and due to the ongoing infrastructure developments. These results were in fact expected since in general, the high frequency values are caused by a sudden loss of load, while low frequency values can be caused by a sudden increase in load or a sudden drop in generation. In fact, if a large load is suddenly dispatched or lost, the system's frequency overshoots and active power output is reduced to restore normal operating conditions. Similarly, under frequency events are usually caused by an excess demand and a lack of generation, which fits the Lebanese case specifically during transition from non-peak to peak times. Unstable grid conditions constitute considerable obstacles for the integration of solar PV and renewables; however, many technologies have been developed as previously described to mitigate these issues.

References

- Amine, J. & Rizk, S. (2018). *2017 Solar PV status report for Lebanon.* Lebanon: United Nations Development Programme Small Decentralized Renewable Energy Power Generation Project. Retrieved from http://www.lb.undp.org/content/lebanon/en/home/library/environment_energy/The-2017-Solar-PV-Status-Report-for-Lebanon.html

- Bassil, G. (2010). Policy Paper for the Electricity Sector. Lebanese Republic Ministry of Energy and Water. Retrieved from http://climatechange.moe.gov.lb/viewfile.aspx?id=121

- Idlbi, B., Jansen, A., & Rammal, Z. (2016). Solar PV grid interconnection code for Lebanon: Recommendations and guidelines. Lebanon: United Nations Development Programme Small Decentralized Renewable Energy Power Generation Project and Country Energy Efficiency and Renewable Energy Demonstration Project for the Recovery of Lebanon. Retrieved from http://www.cedro-undp.org/content/uploads/publication/170919123323430~CEDROSOLARPV.pdf

- Lebanese Center for Energy Conservation. (2012). The National Energy Efficiency Action Plan for the Republic of Lebanon-NEEAP 2011–2015. Beirut, Lebanon: Ministry of Energy and Water and Lebanese Center for Energy Conservation.

- Lebanese Center for Energy Conservation. (2016). The National Renewable Energy Action Plan for the Republic of Lebanon 2016-2020. Beirut, Lebanon: Ministry of Energy and Water and Lebanese Center for Energy Conservation.

- Lebanese Republic Ministry of Energy and Water. (2019). Updated policy paper for the electricity sector. Retrieved from https://www.energyandwater.gov.lb/mediafiles/articles/doc-100516-2019_05_21_04_50_46.pdf

- Marion et al. (2005). Performance parameters for grid-connected PV systems (NREL/CP-520-37358). Retrieved from National Renewable Energy Lab website: https://www.nrel.gov/docs/fy05osti/37358.pdf

- Renewable Energy Policy Network for the 21st Century. (2017). Renewables 2017 Global Status Report. Retrieved from https://www.ren21.net/gsr-2017/

- SMA Solar Technology AG (2018). Performance ratio: Quality factor for the PV plant. Retrieved from http://files.sma.de/dl/7680/Perfratio-TI-en-11.pdf

- SMA Solar Technology AG Sunny Portal (July 2019). Beirut River Solar Snake. Retrieved from https://www.sunnyportal.com