Czech Technical University in Prague

Faculty of Electrical Engineering

Bachelor Thesis

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Wind Energy; A Sustainable Support for Electricity Shortages in Lebanon

Bachelor Thesis

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Guidelines:

1. Introduction:
The importance of renewable energies has grown significantly and showed a stable reliance on its sources in 21st century. And as many countries still face power cut-offs due to shortages of electricity supply, it can benefit from its natural landscape to implement renewables which are capable to cover the deficit of energy supplies and even surpass it.
2. Chapter 1: Environmental impacts of thermal power plants
3. Chapter 2: Renewable energy overview
• Main sources of renewables
o Wind Energy
o Solar Energy
o Biomass Energy
o Hydropower
• Evolution of Wind Power Generation
4. Chapter 3: Case in Lebanon
• Energy shortages in Lebanon
• Causes of shortages
• Wind power as solution
5. Results & Conclusion

Bibliography / sources:

1. Gaeth Fandi; Zdenek Muller; Vladimir Krepl. Design of an Emergency Energy System for a City Assisted by Renewable Energy, Case Study: Latakia, Syria. 2018, 11, 3138 [from mdpi.com]
2. Gaeth Fandi. Intelligent Distribution Systems with Dispersed Electricity Generation. 2017 [from CTU]
3. Zoheir Hamedi; Reem Korban; Gürbüz Gönül; Ricardo Gorini; Rodrigo Leme; Elisa Asmelash; Joseph El Assad; Rawad Nasr. Renewable Energy Outlook Lebanon. 2020 [from irena.org]

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Declaration

I hereby declare that I worked on my thesis independently and that I have written using professional and trusted sources with quoting all the citations according to ethical writings of academic thesis.

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January 5, 2021

Acknowledgment

I would like to express my gratitude to my supervisor Ing. Ghaeth Fandi, Ph.D for his continuous assistance and advice during all stages while writing the thesis. As well to my family for continuous support to complete my bachelor's study.

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iii. Abbreviations

AUB	American University of Beirut
BLDC	Brushless DC electric motor
CCGT	Combined Cycle Gas Turbine
CEDRO	Country Energy Efficiency and Renewable Energy Demonstration Project for the Recovery of Lebanon
CSP	Concentrated Solar Power
DFIG	Doubly Fed Induction Generator
EDL	Electricité Du Liban
EDZ	Electricité De Zahle
EEZ	Exclusive Economic Zone
FESG	Field Excited Synchronous Generator
FSIG	Fixed Speed Induction Generator
GH	GL Garrad Hassan
GSC	Grid Side Converter
IEA	International Energy Agency
IFI	Issam Fares Institute for Public Policy and International Affairs
IRENA	International Renewable Energy Agency
MEW	Ministry of Energy and Water
ML	Météo Liban
PMSG	Permanent Magnet Synchronous Generator
PV	Photovoltaic
RMF	Rotating Magnetic Field
RPM	Revolutions Per Minute
RSC	Rotor Side Converter
SCIG	Squirrel Cage Induction Generator
UNDP	United Nations Development Programme
UNHCR	United Nations High Commissioner for Refugees
WPD	Wind Power Density
WT	Wind Turbine
WTG	Wind Turbine Generator

iv. Abstract

This paper presents the most viable renewable energy sources available today and precisely on the designs of wind turbines, describing its parts and functionality. It also compromises the electricity shortages in the Republic of Lebanon due to the influence of different factors. And by collecting data from different sources regarding the wind speeds in the Lebanese onshore land and offshore zone, the study shows the capability of the country to null these electricity deficits and simultaneously increase the renewable energy mix percentage in the total consumption to reach its targets. The main study is focused on specific regions in the country with higher wind speeds as well as available spaces to construct wind turbines with a minimum distance apart. It also reveals the estimated costs of the construction of new wind farms comparable with the annual resulting deficit in the budget due to the energy sector.

Keywords: Wind, turbines, generators, Lebanon, electricity, shortages

v. Abstrakt

Tento článek představuje nejživotaschopnější obnovitelné zdroje energie, jaké jsou dnes k dispozici, a přesně popisuje konstrukci větrných turbín, popisuje její součásti a funkčnost. Rovněž ohrožuje nedostatek elektřiny v Libanonské republice vlivem různých faktorů. A sběrem údajů z různých zdrojů týkajících se rychlosti větru v libanonské pevnině a pobřežní zóně studie ukazuje schopnost země tyto deficity elektřiny zrušit a současně zvýšit procento energie z obnovitelných zdrojů v celkové spotřebě k dosažení svých cílů. Hlavní studie je zaměřena na konkrétní regiony v zemi s vyšší rychlostí větru a také na dostupné prostory pro konstrukci větrných turbín s minimální vzdáleností od sebe. Rovněž odhaluje odhadované náklady na výstavbu nových větrných farem srovnatelné s ročním výsledným schodkem rozpočtu v důsledku energetického sektoru.

Klíčová slova: Vítr, turbíny, generátory, Libanon, elektřina, nedostatek

1. Introduction

With the increased demands over electricity consumptions paralleled with a growth in manufacturing have urged the needs for maintaining renewable energy sources instead of relying on limited fossil fuels amounts. Together with the increased greenhouse gases mainly from CO2 emissions, reaching threatening limits for life. Thermal power plants are one of the main contributors in the increased emissions since industrial revolutions. Taking into consideration that renewable energy is not only limited for electricity generation, but heating as well, many countries have set higher targets for usage of renewables, where some have already accomplished more than half of its needs. Renewable energy is compromised into different sources, primarily hydro, wind and solar, as well as geothermal and biomass energy. As renewable energy is directly derived from natural sources, it widely depends on geographic locations as it varies wide among opportunities in different countries. This sector is not just renewable, but also clean due to absence of emission of any greenhouse gases and contributes in reduction in usage of fossil fuels in electricity generations.

Wind Energy

Air flows naturally in the Earth's atmosphere. Wind turbine blades are designed to capture the kinetic energy in the wind to rotate, converting it into mechanical work. Then this mechanical energy is converted into electrical energy through the generator of the wind turbine connected to its rotor. This technique of using wind power has been known for centuries in windmills, where the latter converts kinetic energy only into mechanical energy, to grind or pump water or other work, without converting it further into an electrical power due to the absence of the generator. Wind energy has higher power on continental shelves, resulting in offshore wind farms being more productive than onshore wind farms. And this electrical energy produced is connected into the power grid, to be transmitted later to distribution lines. While some wind farms are placed nearby pumped-storage hydraulic stations so that in higher wind speeds, the energy is used to pump water to be later used during high demand or peak hours of electricity consumption. Wind energy is the second biggest source of renewable energies after hydro power, and it is one of the dominating installed capacities during the last century [1].

Hydropower

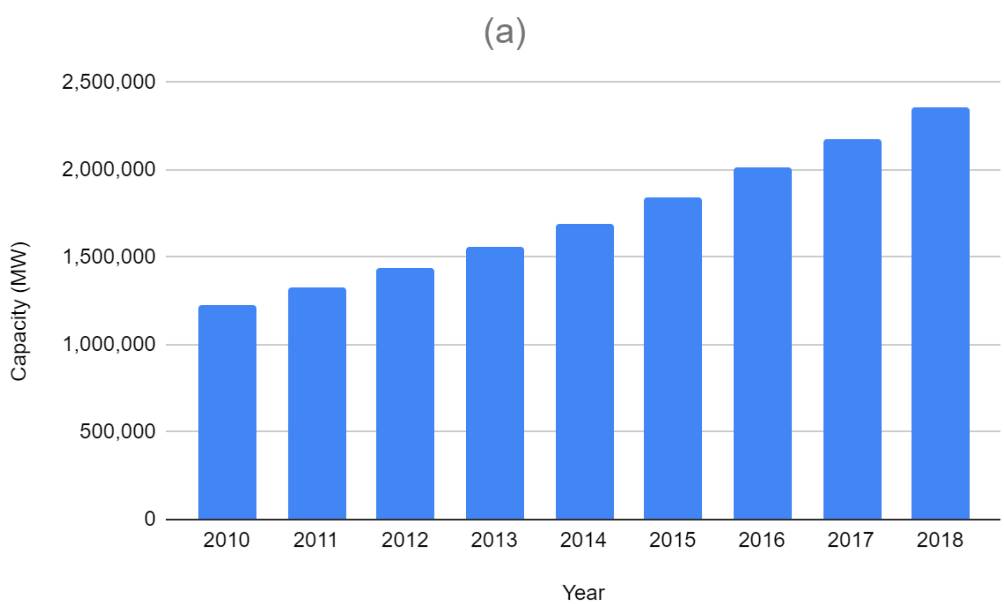
Hydropower from the energy of the river currents have been widely used for many centuries as well. Methods of creating mechanical work for variable usages like grains and mills were already operational long time ago, whereas the electricity generation from hydropower was first developed in the 19th century, to be one of the main sources of electricity generation. Today, hydropower contributes more than 15% of the world's total generation of electricity, making it the biggest source for renewable energy. While this process of electricity generation remains clean, effective and more controllable, it still has harmful effects on the rivers' ecosystems and the wildlife surrounding it. Hydropower can be used on running rivers or by building dams and conventional pumped storages.

Solar Energy

This is so far the cleanest renewable energy by converting the incident radiant light which is not reflected from the sun and its heat into electrical energy through various technologies like photovoltaics, solar heating systems, concentrated solar power and others. This is a more flexible source of energy where it can be used in wider scales like in power plants or smaller scales for self-consumption for buildings and houses. It is trending nowadays to have solar panels on the rooftops of buildings for heating purposes. The efficiency of PV and CSP systems is in the range of 15 - 25%. There is high potential of solar energy on Earth which is a promising source if efficiencies of the materials are to be improved in advanced technologies.

Biomass Energy

Ancient process of burning material for heat is today renowned as biomass energy. It is classified organic as it comes from burning plants and materials of animals to be used as biofuel, which can be converted directly into electricity when used in electrical generators. The renewable idea behind this method is controversial. However, the UN and EU recognize biomass as a renewable source of energy. This source of energy could be also used for other purposes as well, like heating. While this source is renewable, it still has carbon emissions when being burnt, resulting from carbon absorption. Some coal power plants use co-firing by using biomass which produces less Carbon emissions, simultaneous benefit of savings without the need of building new power plants [2].



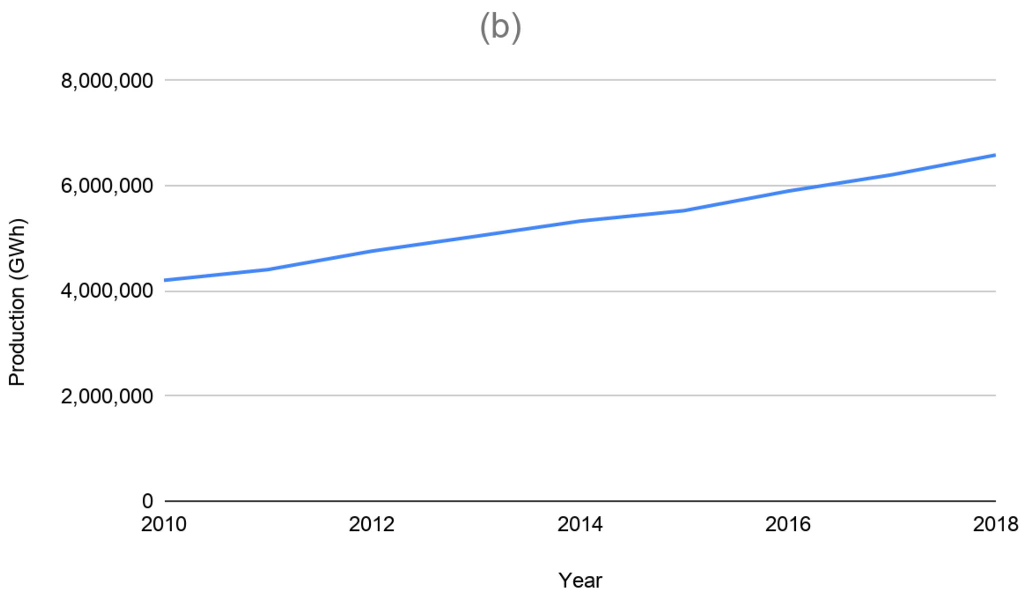


Figure 1 Increased Capacity (a) and Production (b) of renewable energies in the world [3]

2. Methodology

The data of wind speeds in Lebanon were not fully calculated in all parts of Lebanon except of being analyzed and published on a map model. Therefore, my case of study is based on collecting data from different meteorological stations surrounding the region affected by highest wind speeds in Lebanon and calculating the annual output generation of a small-scale wind farm to obtain its efficiency. This yearly production is estimated to reduce the electricity deficit in some regions in Lebanon, like those with higher wind speeds and rural areas with spacious lands available for wind turbines installations.

3. Wind Turbine Module

3.1. Types of Wind Turbines

Primary there are two types of wind engines: Draft-based engine and lift-based engine. Additionally, there are two more types according to the position of rotation axis: Horizontal axis and vertical axis.

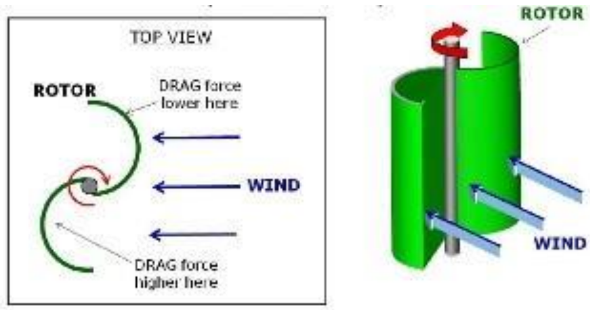


Figure 2 Drag-based Wind Turbine

The drag-based engines are considered to be the oldest type of wind engines. Its rotary motion is based on aerodynamic resistance where the downwind part of the motion must always exhibit higher aerodynamic resistance than the upwind part. It tends to have a simpler structure and independent of direction of wind, but it has lower RPM and thus lower efficiency.

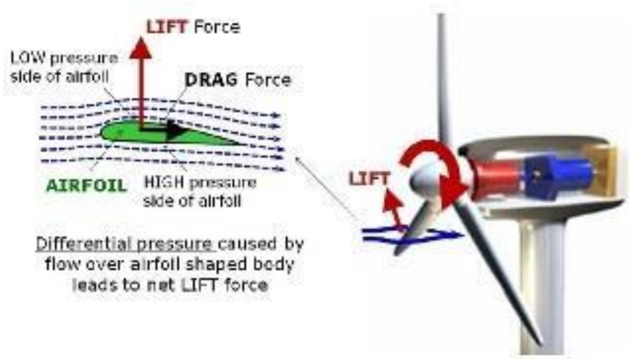


Figure 3 Lift-based Wind Turbine

The lift-based engine has a majority of horizontal axis and is the most viable type of wind engine for electricity generation. Its rotor is constructed of 2 or 3 blades in most cases. It requires a wind speed of 5 $m.s^{-1}$ for startup, but it has higher efficiency exceeding 40%. The continuum equation of such turbine is given through:

$$A_1 * V_1 = A_2 * V_2$$

Where A_1 is an area of wind flowing with speed V_1 in front of blades and A_2 and V_2 of those behind the rotor. Shown as below:

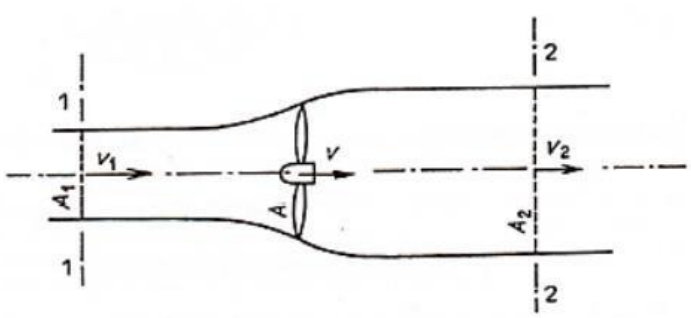


Figure 4 Wind speed flowing through Turbine

The maximum theoretical conversion efficiency due to wind deflection is given by Betz's law when $V_2/V_1 = 1/3$ which is 59.26%.

3.2. Components of HAWT and its main degrees of freedom

Rotor

It generates aerodynamic torque from the wind due to mechanical mechanism when the blades that it holds rotate, in which the rotation of the rotor about its shaft, the azimuth, is normally calculated as from vertical distance. The turbine's control system maintains operating limits due to variable wind speed changes with a blade pitch control feature for rotation of blades about their lengthwise axis. It consists of a hub which contains the spinner and connects the blades to the main shaft through pitch bearing and to the rest of the drivetrain. While the pitch bearing is the assembly for the required load and power of the wind turbine by changing the desired angle of attack and lift of the blades [4]. It is also used in the emergency brakes of turbine systems in case of failure.

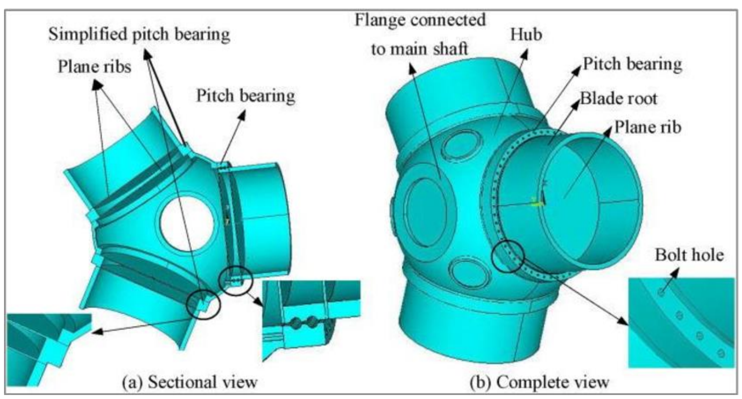


Figure 5 Four-point contact pitch blade bearing [5]

Nacelle

It converts the aerodynamic torque that goes into the hub through the low-speed main shaft into electrical power and is held by the main bearing. It consists also of a gearbox which translates the low-speed shaft coming from the torque of the rotor into a high-speed shaft capable of rotating the generator, with a brake connected to the end of high-speed shaft. It converts the low-speed motion of rotor from 12 - 30 revolutions per minute via two or three stages set of gears into 1200 – 1800 RPM which is the speed required to economically generate electricity. All those components in Figure 6 are placed on a bedplate whose orientation is adjusted through a yaw system to keep the turbine rotor towards the wind.

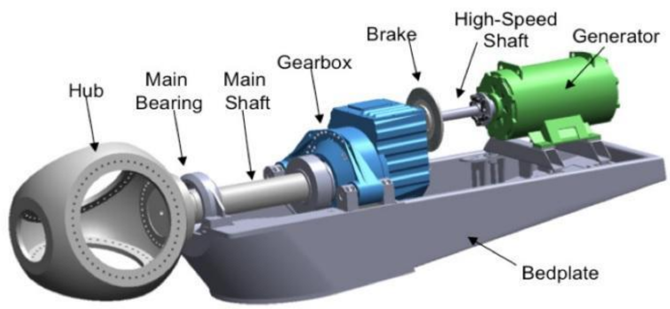


Figure 6 Nacelle with drivetrain and power electronics [6]

Tower

It holds the nacelle and the rotor with blades up in the wind and provides access into the nacelle for maintenance. It could be a typical tubular tower made of steel (or concrete) and being used in most large wind turbines. It has conical shape to improve strength and economical use of materials. Or a lattice tower using welded steel profile and has lower costs due to less materials than the tubular. Also, hybrid tower which is a combination of previous techniques like a three-legged tower or guy-wire pole tower [7] as shown in Figure 7.

Figure 7 Wind turbines tower types [8]

Foundation

It holds the turbine in its place which ensures its stability. It could be an onshore concrete gravitation foundation where the gravity is holding the whole thing and it is made up concrete as we see in Figure 8 where the tower is to be installed on the top of it later.

Figure 8 Onshore wind turbine foundation [9]

Or an offshore foundation which has different types as in Figure 9. We have a monopile which is similar to a tubular steel turbine that is hammered into the ground, the tripod which can also have suction bucket foundation, jacket, semi-submersible and spar buoy with wiring lines which are floating platforms.

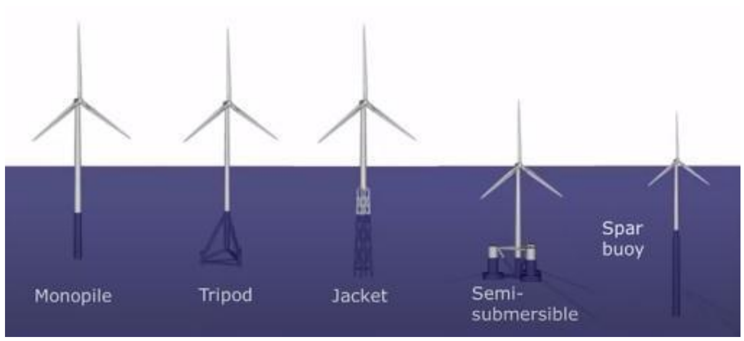


Figure 9 Offshore foundations and floating platforms [10]

3.3. Onshore Power Plant

Wind farms tend to be located more in rural areas and country sides, where there are higher wind speeds and less homes around to avoid high noises. The world's biggest farms are located in China with more than 23 GW in 2020, followed by the United States. Wind power plants are much more efficient than any type of other power plants due to its zero emissions of any gases as well as the ability to use the land for agriculture or other purposes. Though, some environmentalists still criticize the negative impact it has on natural landscapes as well as some claims to be the cause of death for some birds. Yet, such impact is considered negligible in relation to other power plants regarding safety and environmental concerns. One main problem is the noise of the wind spinning the blades which affects the residents living nearby those turbines. It is said that some manufacturers are paying the surrounding residents as compensation to such noises. Maintenance of onshore plants are less complicated and cheaper than that of offshore which can still permit the use of geared and brushed turbine generators in some cases.

Figure 10 World's largest onshore wind farm in Gansu, China [11]]

3.4. Offshore Power Plant

Offshore wind turbines have feasible advantages in terms of power generation, in which an offshore wind farm can produce the same power of an onshore wind farm with less turbines. The power capacity of such turbines is higher than onshore ones, reaching a nominal power of 14 MW in 2020. Coastal areas have higher average wind speeds as well as consistent wind direction, which increases the efficiency of wind turbines with less rotations of their yaw. Moreover, it can be located within kilometers away from the land which eliminates its noise pollution factor. But offshore wind turbines are much more costly than regular onshore ones in terms of installation and maintenance. The installation process of foundation is more complex, alongside the transportation of its parts and equipment to kilometers in the waters and the complicated process of connections to the grid. To reduce maintenance costs, direct drive technology is highly applicable with gearless permanent magnet motors to ensure lower-maintenance needs and less faults, as well as having higher efficiency with the lack of need of excitations. Such designs keep the weight and dimensions lower which reduces the transportation costs. The UK has the biggest cumulative offshore installed capacity with over 10 GW in 2020, followed by Germany and China respectively, with Europe as the world's leader in offshore wind electricity generation.

Figure 11 Offshore wind farm in the United Kingdom [12]

4. Wind Turbine Generators

In modern days, there are mainly 3 types of wind turbine generators (WTGs): DC motors, AC Synchronous generators and AC Asynchronous generators. Of which, their principle could operate at fixed or variable wind speeds. In modern wind turbines, there are preferred candidates, the Permanent Magnet Synchronous generator (PMSG), Field Excited Synchronous generator (FESG) and Doubly-Fed Induction generator (DFIG). Each could differ with production cost relatively to electrical generation and efficiency. In addition, most industries seek for a lower maintenance possibility to ensure better operations in different locations and simultaneously reduce failures.

4.1. AC Synchronous Generators

The permanent magnet synchronous generator is a favorable case due to its high liability in wind energy utilization. WT manufacturers use more direct driven type systems, as the elimination of gearbox contributes to less maintenance and simultaneously to a higher efficiency. The gearbox itself is specifically designed for WTGs and requires regular maintenance. As most of today's WTs are located in unreachable areas like offshore, such complicated repairs, high replacement costs and downtimes causes serious revenue losses for utility authorities. More to mention, torque from the rotor produces power but it is simultaneously in big moments and forces the turbine drivetrain. The drivetrain must separate from the gearbox or the internal gearbox must be designed for sustain loads, otherwise transmission failures can occur which in brief causes serious damages to the wind turbine. Some of causes of failures of wind turbine gearboxes can include harsh environmental conditions, insufficient oil drains, torque reversals due to disconnection and reconnection of generator, additional axial and radial forced by rotor, abnormal vibrations and rapid load changes [13]. Some failure in WTs can be seen in Figure 12.

Figure 12 Geared Turbine Failure [14]

Most gearless motors tend to be permanent magnetic generators which are lighter and more convenient for offshore applications [14]. Perhaps the permanent magnets generators are a competitive technology due to having extra number of poles than conventional synchronous motors, for low-speed direct drive generators. The excitation field of PMSG is done with the use of a permanent magnet rotor. The rotor could be placed internally in the stator or out-runner surrounding it, while the air gap between rotor and stable shall be minimized to reduce losses and simultaneously maximize the efficiency [14]. PMSG has higher material costs but could be compensated with higher energy produced. The generated AC power with variable frequency and magnitude to be rectified into DC power then converted again into AC with fixed frequency and magnitude. For such a process, an AC-DC-AC power converter should be connected to PMSGs as it cannot produce fixed frequency due to variable wind speeds.

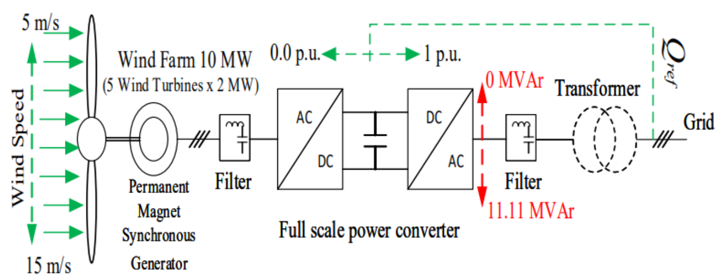


Figure 13 Full Scale Power Converter in a gearless PMSG [14]

For fixed-speed synchronous generators, the rotor must be kept at same synchronous speed to avoid losing synchronism. Furthermore, synchronous generators tend to have low damping effects so that it doesn't allow drive train transients to be electrically absorbed as the random wind speed fluctuations and periodic disturbances could be passed to the power grid.

4.2. Induction Generator

Such generators are applied to bigger scales in wind farms and are extensively used in modern WTs. It works on the principle of the slip created while the rotor rotates at a speed different to synchronous speed of RMF between air gaps. It is well developed, inexpensive and liable. It can be two types: Doubly fed induction generator with wound rotors (DFIG) and Fixed-speed induction generator with squirrel cage rotors (FSIG or SCIG).

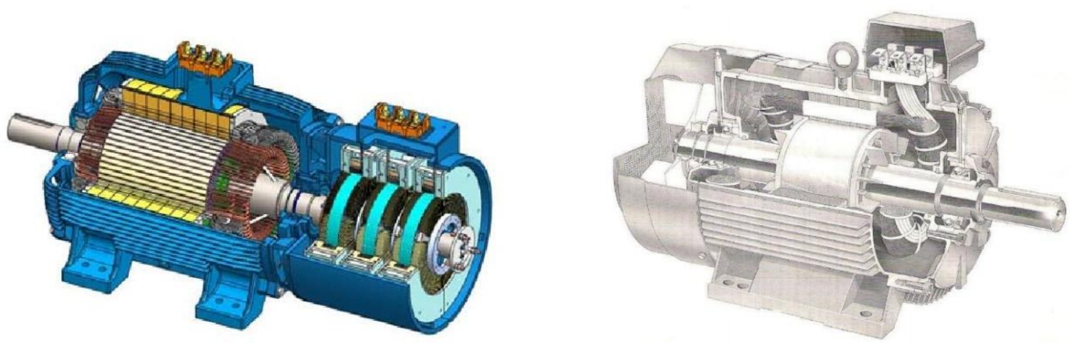


Figure 14 DFIG to the left [15] vs SCIG to the right [16]

The latter has proven prominent service failure with high-maintenance, noisiness, size, lower efficiency and reliability. Today most modern turbines adopted the use of DFIGs as it is capable of capturing maximum energy at variable wind speeds. Thus, it has tremendous advantages over speed control and reduced power losses. Its stator is connected to the grid via transformer which requires a full-scale power converter for AC/DC/AC converter as shown in Figure 13. Such generators have high degree of damping which can absorb drive train transients due to variable wind speed fluctuations which results in less failures. It needs capacitors or converters as compensation for drawback reactive power from the grid, but there is still a risk of causing self-excitation. The rotor side converter (RSC) regulates the torque of DFIG. The rotor can handle power in both directions while the stator always transfers power into the grid. Due to this fact, DFIG can operate in both sub-synchronous and super-synchronous operations. In case of the first, the RSC acts as an inverter and the grid-side converter (GSC) would be a rectifier. While in the super-synchronous case, the opposite applies where the RSC acts as rectifier and GSC as inverter [17]. These are connected via DC-link capacitors. Therefore, the main task of RSC is to control the rotating speed of the rotor by controlling the DFIG torque, in addition to the active power coming from the grid through the DFIG's stator windings. The electrical disturbances due to aerodynamic torque driven by variable wind speeds spinning the blades of the rotor causing fluctuations on its rotational speed, can be damped out by the torsional characteristics of the drivetrain. With the use of a specific ratio gearbox, it increases the main hub's rotational speed to the machine's rotor shaft. Bearings' frictions result in power losses [17].

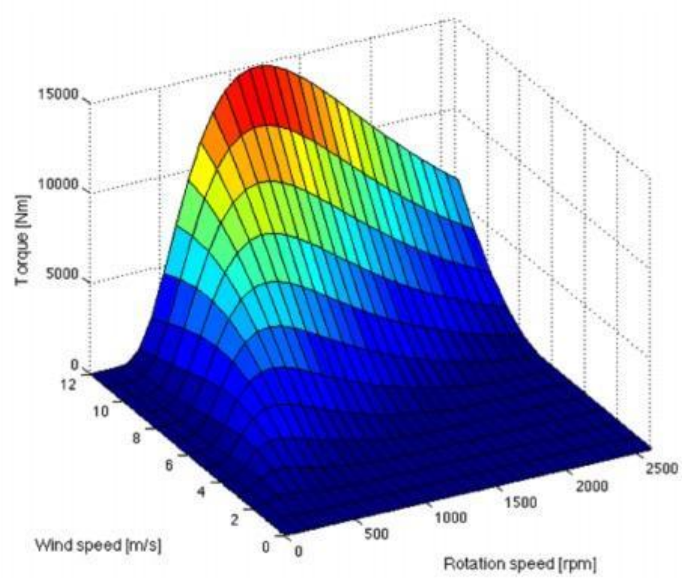


Figure 15 Wind speed vs Torque and rotor's rotational speed

4.3. DC Generators

DC generators in wind turbines could be both a conventional brushed electromagnetically excited stator or a brushless permanent magnet generator (BLDC) with Out-runner or In-runner rotor. The field current increases with operational speed which is determined by the balancing of wind turbine's drive torque and load torque in shunt-wound DC applications [13]. It is very uncommon to use such generators in modern wind turbines as it is heavy, requires high maintenance and expensive as well, such it decreases the reliability.

5. Contribution to the Electricity Sector in Lebanon

5.1. Energy Shortages in Lebanon

Ever since the 1990s, Lebanon has been witnessing significant electricity shortages across all over its territory where the supply is lower than the demand. And despite the rehabilitation plan that occurred between 1992 and 2002 under the Power Sector Master Plan, which involved expansion of generation capacity and the rehabilitation of the transmission lines and distribution networks , the plan was insufficient to meet the demands of electricity consumption, leading to many hours of daily power cut-offs among all cities in the country. Currently, Electricité Du Liban (EDL) is the main institution for electricity generation, transmission and distribution of the electrical energy in Lebanon since 1964, assigned by Ministry of Energy and Water (MEW), controlling over 90% of the territory alongside another private electric utility, Electricité de Zahlé (EDZ), operating under a concession agreement with the Lebanese authority and providing electric services in the Bekaa region. There are mainly 2 sources of electricity generation in Lebanon, thermal and hydraulic. While most of the thermal power plants were originally designed for the usage of natural gas, those power plants are operating using gas oil/diesel instead, which includes the two combined cycle gas turbine plants (CCGT) in Zahrani and Deir Ammar, and two open cycle gas turbine plants in Baalbek and Tyre.

Power Plant	Capacity (MW)	Effective Capacity 2018 (MW)	Operator
Zouk	805	597	EDL
Jieh	421	243	EDL
Deir-Ammar	464	430	EDL
Zahrani	469	420	EDL
Tyr	72	56	EDL
Baalbek	64	57	EDL
Hraiche	35	46	EDZ

Table 1 Operational thermal power plants in Lebanon [18]

River hydropower	Capacity (MW)	Effective Capacity 2018 (MW)
Litani	199	47
Nahr Ibrahim	32	17
Kadisha	21	15
Bared	17	6

Table 2 Hydraulic stations across rivers in Lebanon [18]

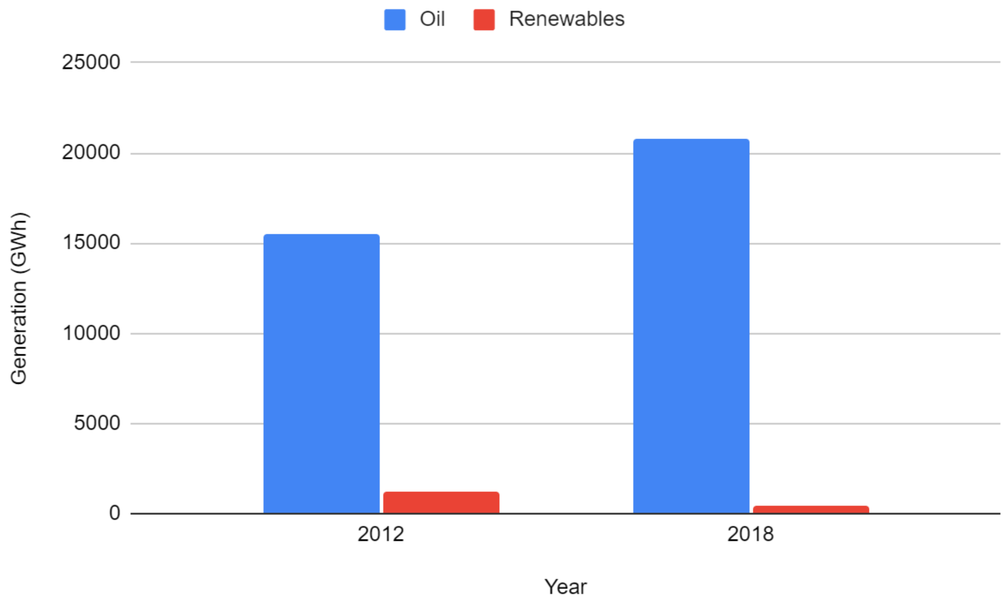


Figure 16 Generation of electricity in Lebanon [19]

The share of renewable energy electricity generation in 2012 was limited only to hydropower plants across the river, whereas due to the decreased efficiency of these hydraulic stations consecutively with less annual rainfalls, resulted in significant decrease of renewables share in the total generation, despite the installations of new solar PV plants.

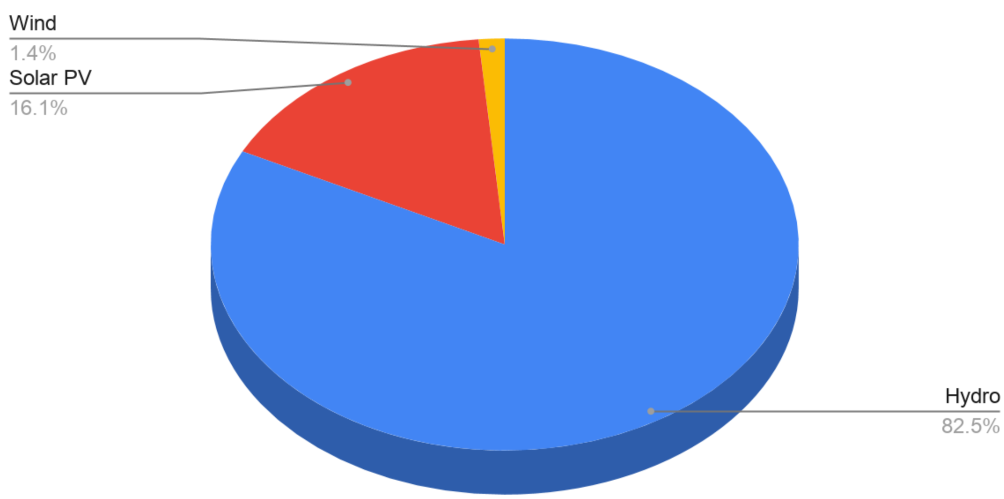


Figure 17 Renewable energy mix in Lebanon in 2018 [19]

Additionally, two Turkish Karadeniz powerships were deployed in Jiyeh and Zouk since 2013 after the Karpowership signed a contract with EDL in June 2012. Having a capacity of 202 MW each, these two powerships with 404 MW total capacity have been providing 25% of Lebanon's electricity needs. Electrical shortages in Lebanon is a main reason for the country's long-term deficit and increased debts, with losses of 1.5$ billion to 2$ billion annually.

Figure 18 Turkish Karadeniz Powership Fatmagul Sultan in Lebanon [20]

5.2. Causes of shortages

There exist several causes behind the electrical shortages in Lebanon that includes technical, political, demographic and geographical changes. First, the aging of the thermal power plants where most have already reached their lifespans and decreasing their operational availability. However, hydropower plants in Lebanon require rehabilitation and maintenance to improve its decreased efficiencies, whereas the geological factors played a role as well due to the change of the amounts of annual rainfalls in the country. Also, many of these power plants are operational with different fuel products as mentioned previously. While there are also technical losses amounting to around 15% after decreasing from previous years, non-technical losses stand as a major contributor in electricity shortages as well (Figure 19). Non-technical losses include illegal consumption of electricity from connections from the smaller distribution networks or power lines, as well as poor metering and lack of collections of bills from many consumers.

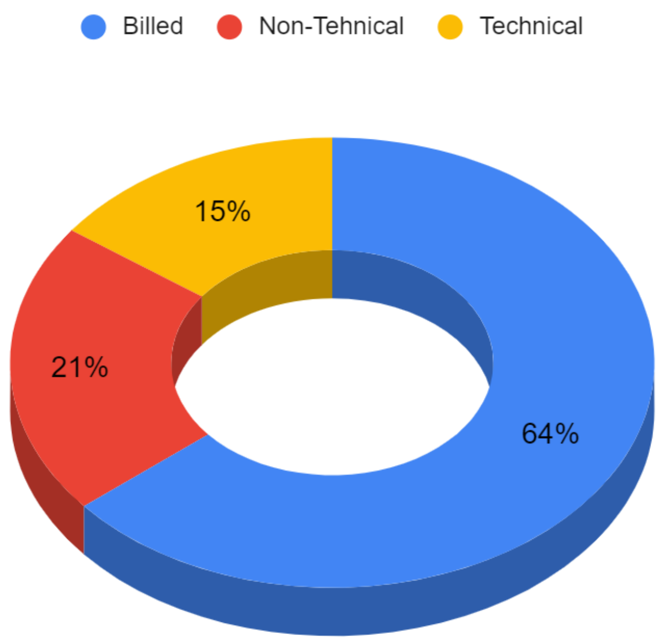


Figure 19 EDL network losses in 2017 [21]

EDL retail tariffs have not changed since the 1990s despite the increase of oil prices in the global market, standing at an average bill of 127 LBP/kWh, while the average production of EDL costs 255 LBP/kWh, nearly double the tariff. This tariff is low for EDL's production, but it remains higher than the average standards in the region, while the Lebanese still receive the least energy services. Moreover, self-generation is a dominant factor in the country during public electric power cut-offs and its tariffs are higher than the ELD's. Thus, making the Lebanese people pay double bills, one for EDL and another for private generators.

Administratively, the human factor is also playing a role, with a low number of employed staff compared to the needed number [22] due to political reasons.

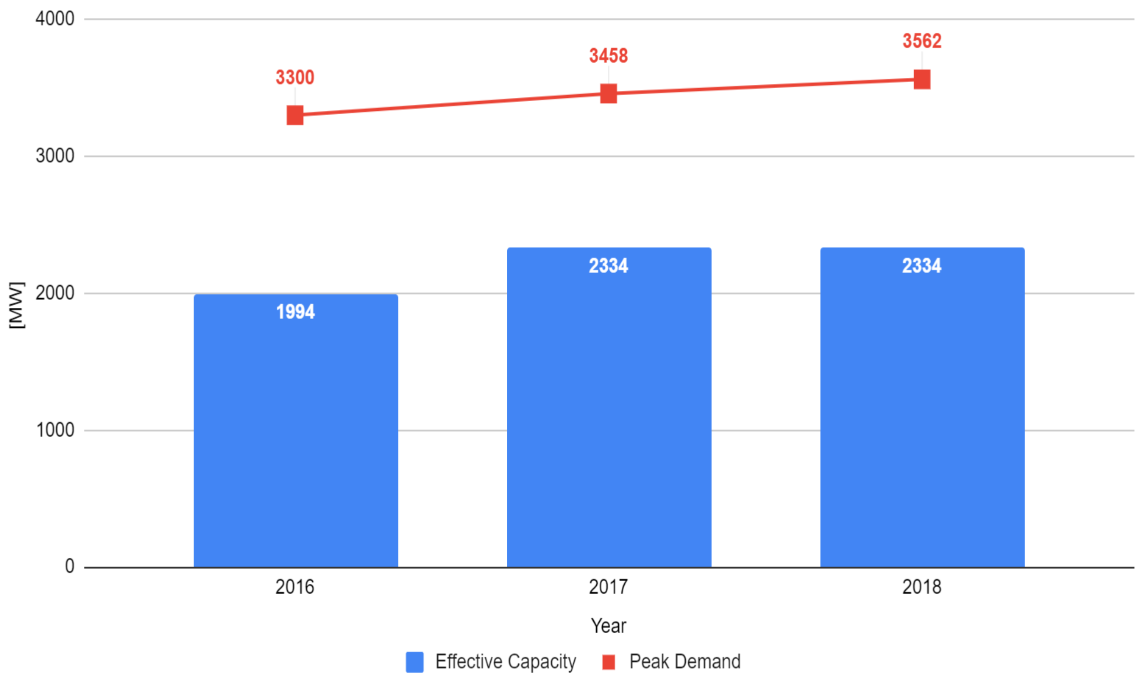


Figure 20 Effective capacity vs peak demand in Lebanon [23]

Additionally, the influx of immigrants and refugees in Lebanon with more than 1.5 million registered in the country, has caused a significant increase in the population in Lebanon to jump from around 5 million inhabitant to nearly 7 million, resulting in higher demands and higher peak hours, while coupled with decrease of electrical generation simultaneously.

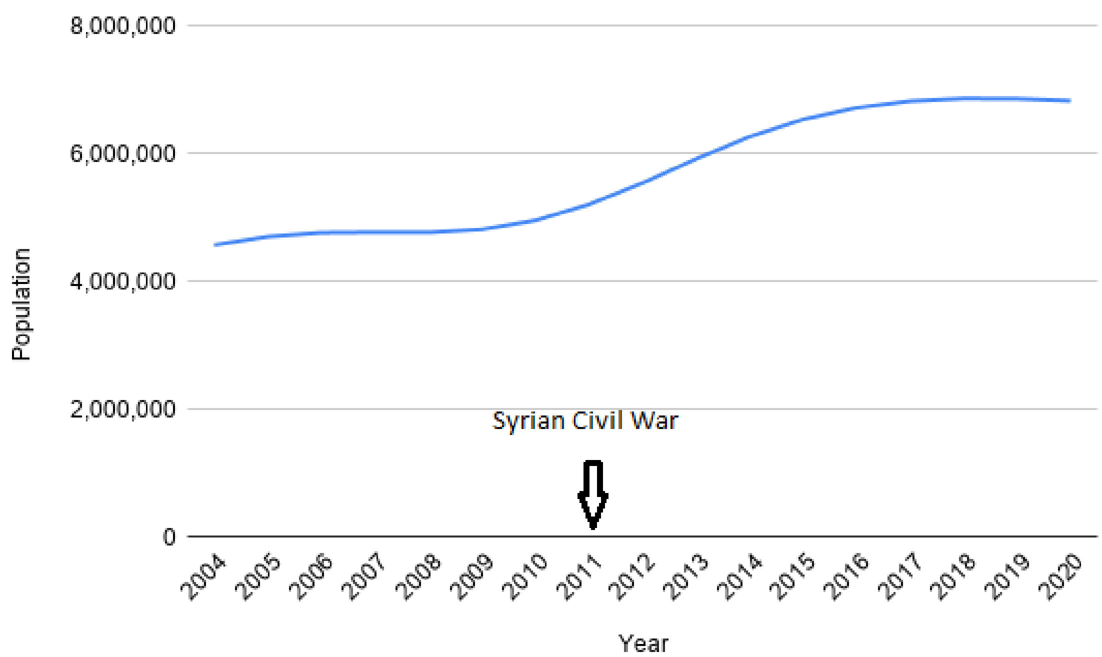


Figure 21 Annual growth of Lebanon's population [24]

5.3. Wind Power in Lebanon

Geography of Lebanon

Several researches were conducted in the past 20 years to collect data regarding wind speeds and density onshore and offshore in the country. Talking about a small Mediterranean country stretched across the coastline with an average width of 56 km of land and elongation of 225 km of shoreline, with a total area of 10,452 km2 divided into 5 topographic units (Figure 23) and an Economic Exclusive Zone of 19,516 km2, Lebanon shows to have a big potential for wind speeds in the region. And thanks to its geographical semi-rectangular shape, the country is capable of operating both onshore and offshore wind farms.

Figure 22 Lebanon in light blue color on the Mediterranean sea

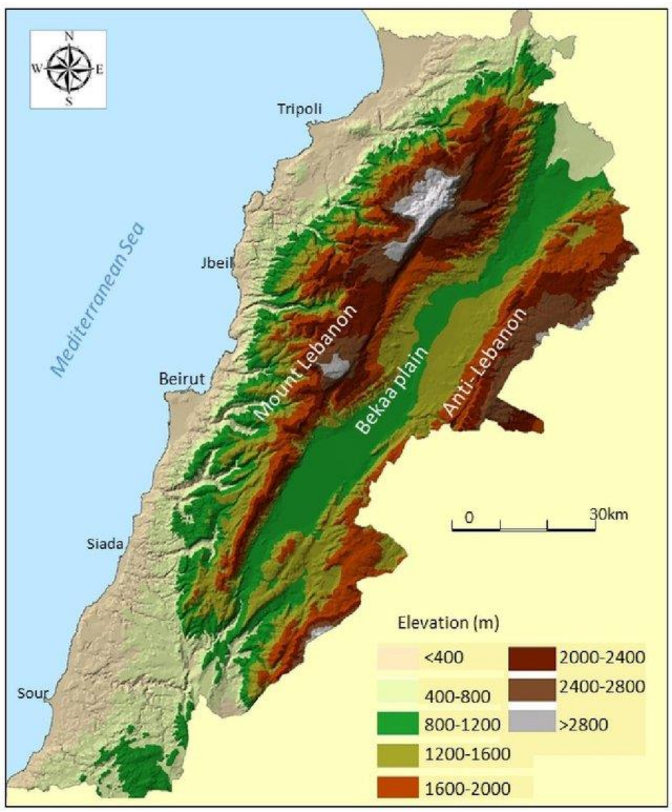


Figure 23 Major topographic units in Lebanon [25]

Wind speeds

Data has been collected between the years of 2000 - 2017 for wind power speed (WPS) and wind power density (WPD). According to a study conducted by different universities in Spain and Switzerland for the years 2010 - 2017 regarding offshore wind power in Lebanon, ERA5 meteorological hourly data were downloaded from the Copernicus Climate Data Store [26]. The data were collected on several points (Figure 24) in the EEZ on a height h of 178 meters corresponding to the hub of Siemens' 6 MW offshore wind turbine hub SWT-6.0-154. Lebanese waters have 3 km of buffer zone where depth rapidly increases more than 1 km which suggests floating type wind turbines, and its EEZ extends 200 nautical miles.

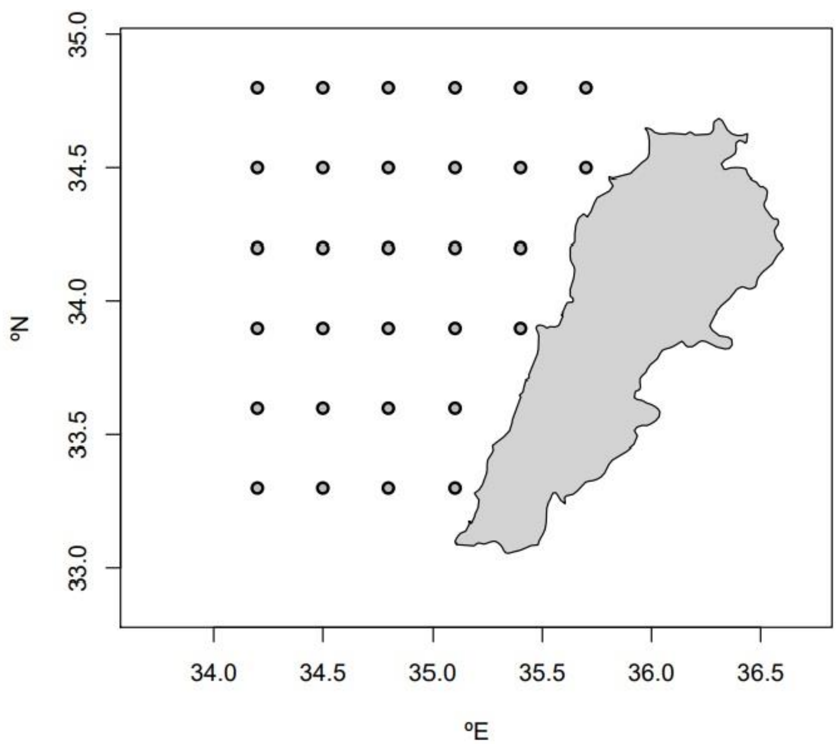


Figure 24 ERA5 grid points in the Lebanese EEZ [26]

Wind-speed values were calculated at 10 and 100 meters above the mean sea level corresponding to ERA5 zonal and meridional wind components at each grid point. Thus, by this logarithmic formula, it is possible to calculate the surface roughness $z_0$using equation:

$$\frac{U_{100}}{U_{10}} = \frac{log(100/z_0)}{log(10/z_0)}$$

were U corresponding to the wind velocity at a certain height. And then substituting the height h in the equation to calculate its wind speed. WPD can be calculated with the equation:

$$WPD = \frac{1}{2}\rho U^3$$

where ρ corresponds to the density of the dry air. And if we integrate the density over the surface area of the circle of the rotor, we will be able to obtain the wind power (P) passing perpendicularly through a closed circle by equation:

$$P = \frac{1}{2}\rho U^3 \pi r^2$$

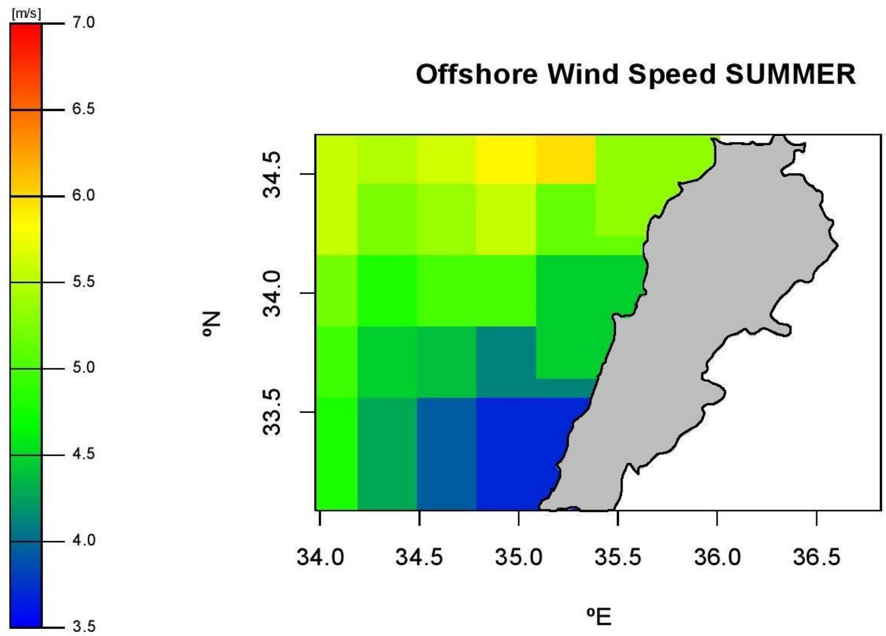
where r is the radius of the rotor of the wind turbine. The study does not specify the radius of the rotor, therefore only power density will be used to neglect the area of the rotor.

The average value of air density $\rho_0 = 1.19\ kg/m^3$would create significant errors if it has to be used as a constant value for all seasons. The country has four seasons:

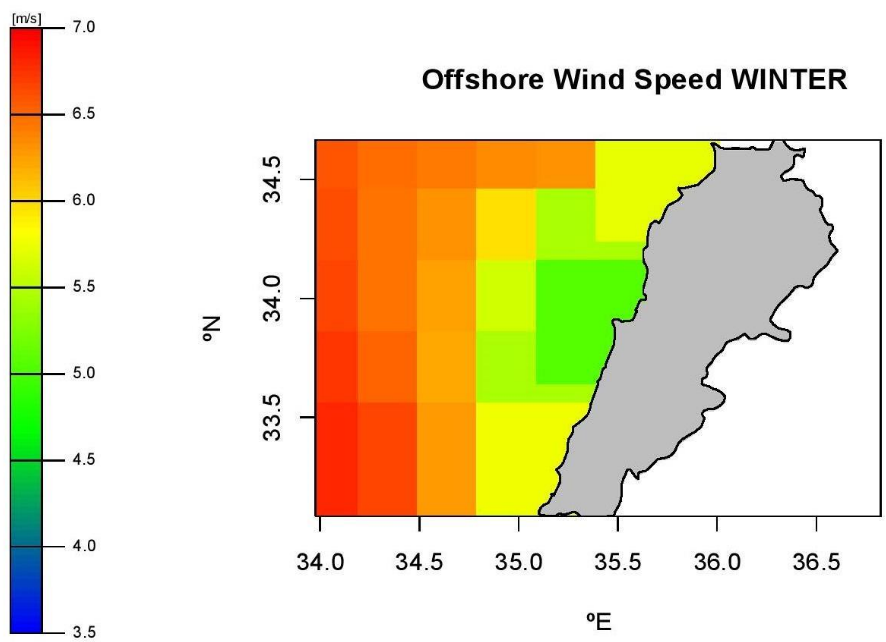
- Summer period: June to August
- Winter period: December to February
- Spring period: March to May
- Autumn period: September to November

The difference of air density between the summer and winter considerably results in $\pm$3% of the average value. Therefore, seasonal averages of hourly values were used instead. This results in more accurate data regarding seasonal wind speeds offshore which can be shown in Figure 25.

While the average WPD of the all four seasons through the whole period of 2010 - 2017 is illustrated in Figure 26.



(a)



(b)

Figure 25 Lebanon average offshore wind-speed [m/s] at altitude 178 m in summer (a) and winter (b) seasons [26]

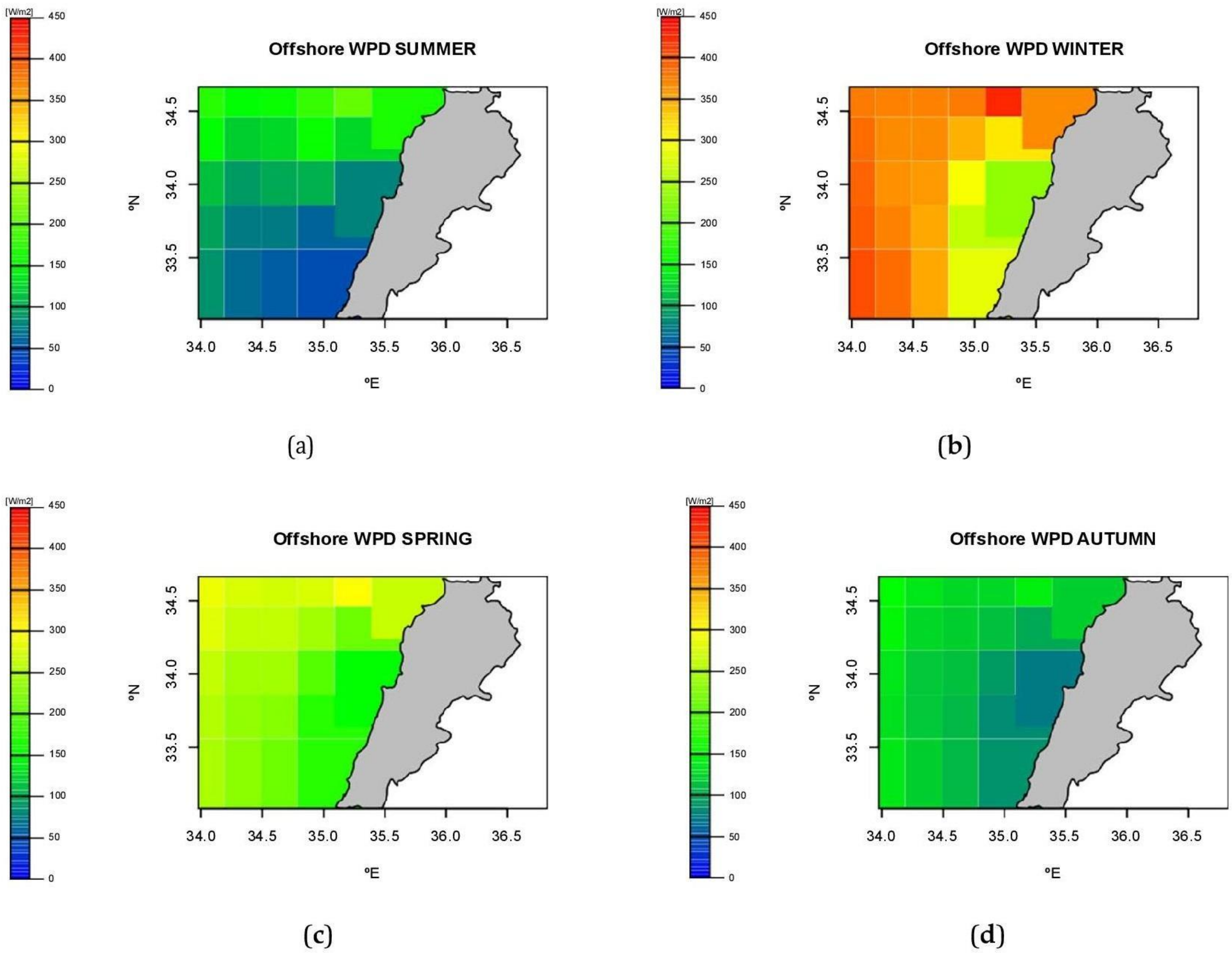


Figure 26 Average WPD [W/m2] at height 178m offshore in Lebanon through different seasons [26]

Retrieving all the data above, the northern part of Lebanese offshore shows a higher potential of wind speeds and densities, with the area around the grid point of North Latitudes 34.5° and East Longitude 35.25° having the maximum average of WPDs in the whole year. While the southern part is less windy during summer times. The middle part surrounding the capital Beirut has a more constant wind speed average around 5 m/s in all seasons which is close to the cut-in speed of a modern WT, thus rarely reaching its rated capacity, which reflects a lower generation of electricity throughout the year.

Different wind maps were developed in 2011 by GL Garrad Hassan under the United Nations Development Program (UNDP) and funded by Spanish government as part of the Country Energy Efficiency and Renewable Energy Demonstration Project for the Recovery of Lebanon (CEDRO). Unfortunately, these data had high uncertainties due to the measuring circumstances. Lebanon has a network of meteorological stations operated by Météo Liban (ML). While most these stations had anemometers placed at 10 m altitude which is considered relatively low and highly affected by surrounding objects, like high trees and buildings [27].

Figure 27 Beirut Golf Meteorological Station [27]

GH also used data recorded by 5 Syrian meteorological stations near the Lebanese border. But GH did not visit those stations and has no detailed information regarding the resolution and accuracy of the measurements recorded by the Syrian side which had anemometers at heights of 40 m and 10 m, thus it is considered to have extremely high uncertainties [27]. These data were used to estimate wind speeds onshore at altitudes 50 m and 80 m respectively. Most meteorological stations used French Auria E type systems, which GH has wide experience with, while Beirut International Airport and Tripoli meteorological stations used Milos technology, which GH was not experienced with. Anyway, these systems used anemometers widely known, which is acceptable by GH. Still, GH reported high uncertainties and low resolution in their data, which made them create another wind map with 10% upwards and downwards estimations. Similar method was used to detect average wind speeds 20 km offshore at heights 50 m and 80 m, while the latter was recalculated by the Spanish and Swiss group and showed that it had high uncertainties.

These maps again confirm with previous results of the studies that the northern part of the country is more windy, having more wind speeds and higher densities than the other parts, while again the central region surrounding the capital Beirut, the middle part of the country, shows low wind speeds and WPD, which is not very suitable for establishing wind farms neither onshore nor offshore.

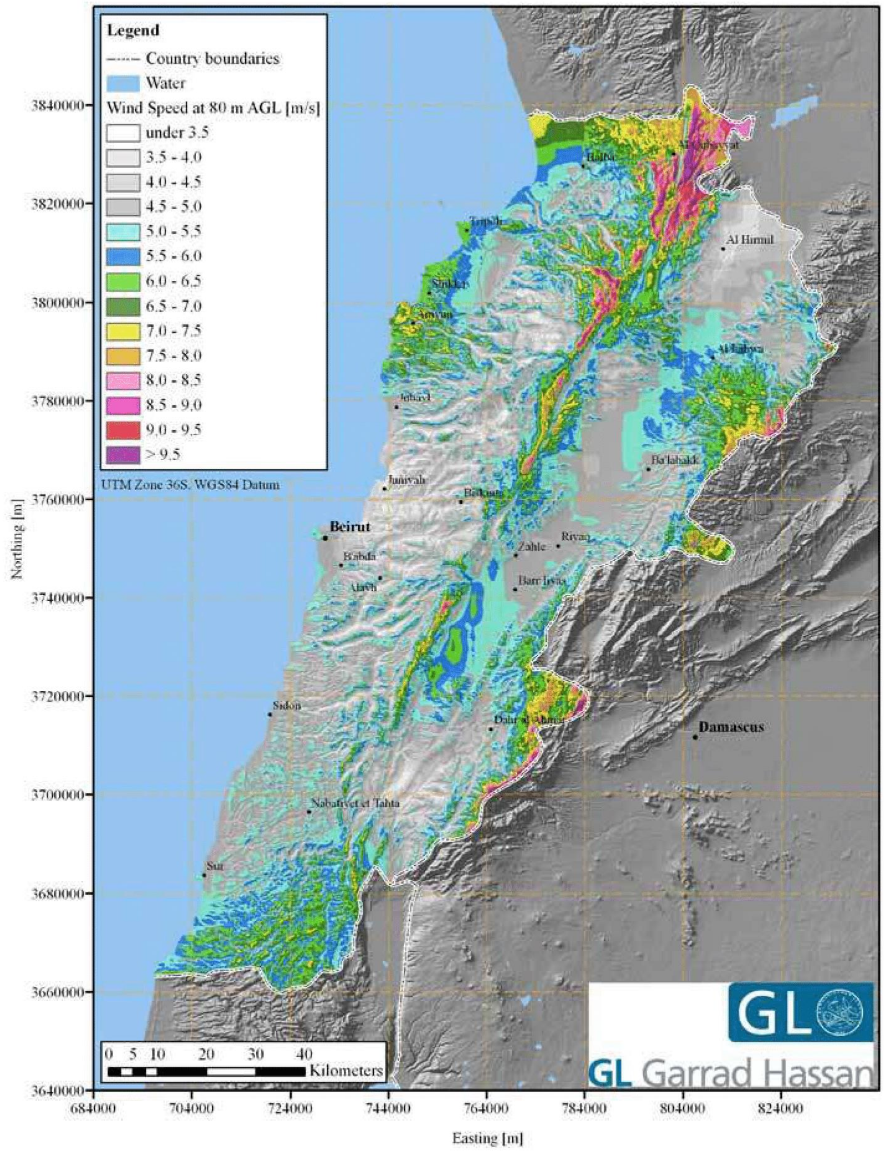


Figure 28 GH central estimate of wind speed in Lebanon at 80 m above the ground

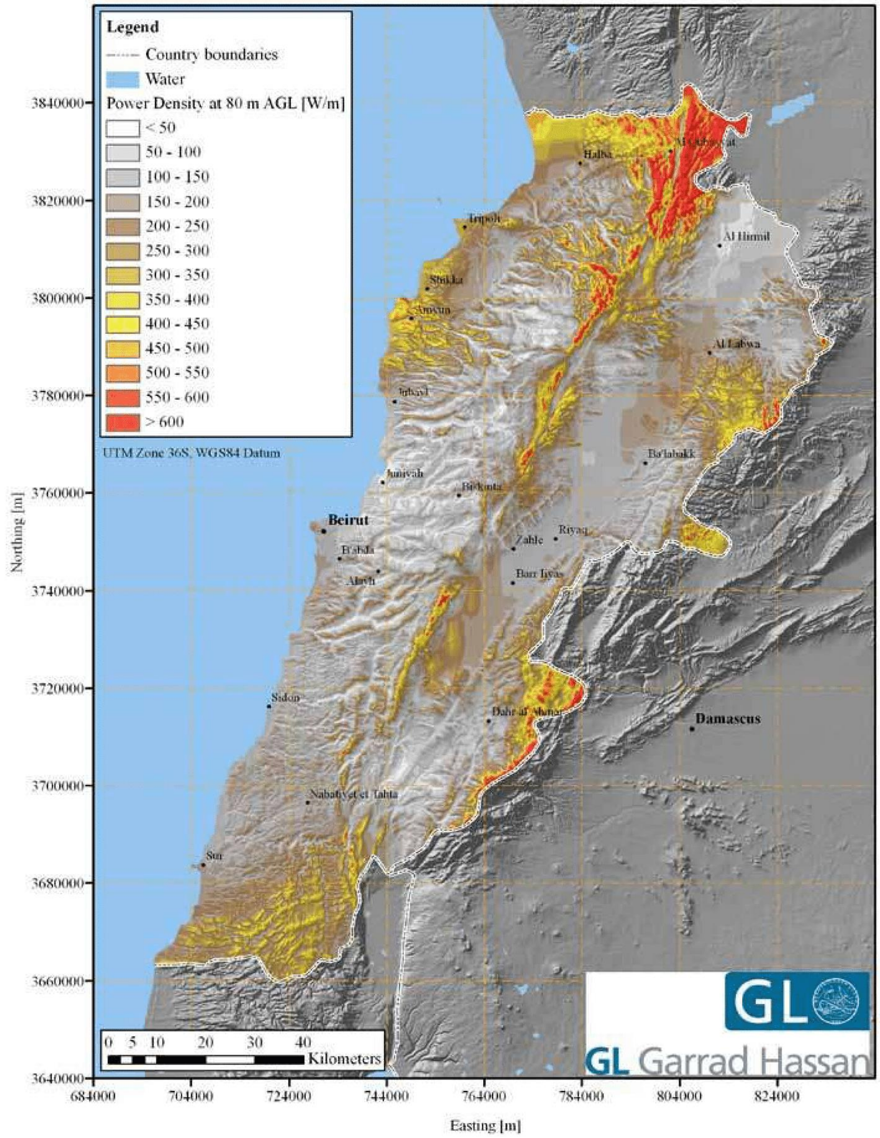


Figure 29 GH central estimate of WPD in Lebanon at 80 m above the ground

In February 2018, Power Purchase Agreement was signed with Lebanese government for the first large scale of wind farms in Lebanon. While there were 42 offers from 72 companies representing 21 countries with estimated capacity of 4000 MW, only 200 to 400 MW were required [23]. All the 3 wind farms are situated in Akkar region, north of the republic. Sustainable Akkar, one of the three who signed, has started collecting data since 2013 with 2 masts installed. It is very interesting to mention that the company reported a wind speed average of 15.6 m/s in July 2018 [28], which makes this region the one of the windiest not only in Lebanon, but in the Middle East as well.

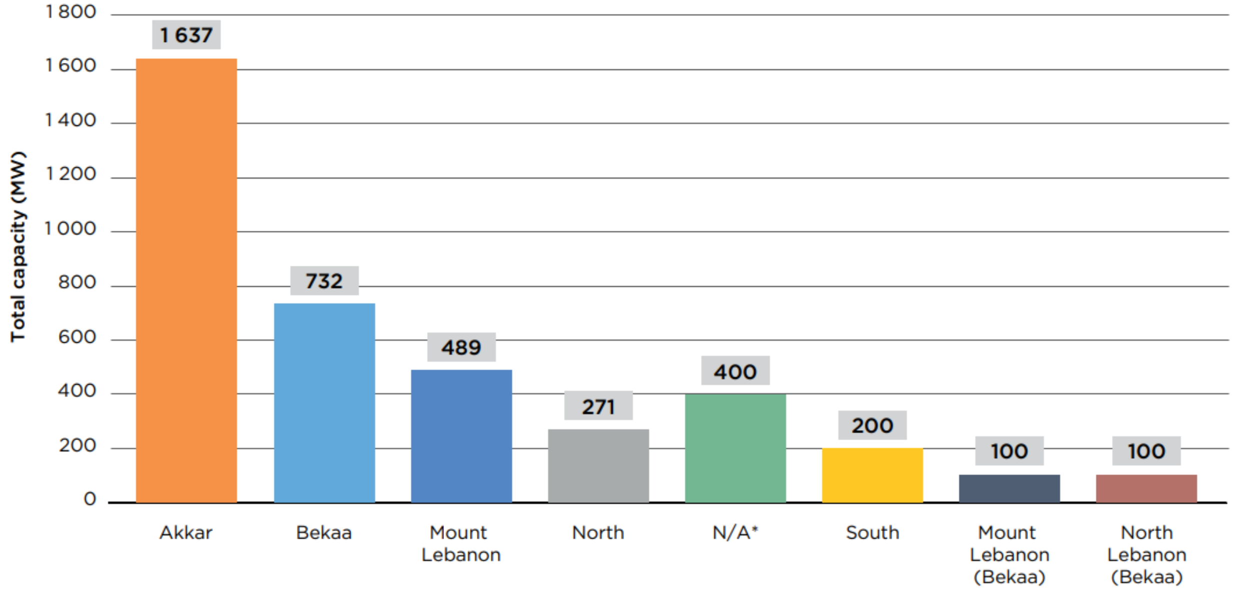


Figure 30 Total capacity per region in response to wind auctions in Lebanon [23]

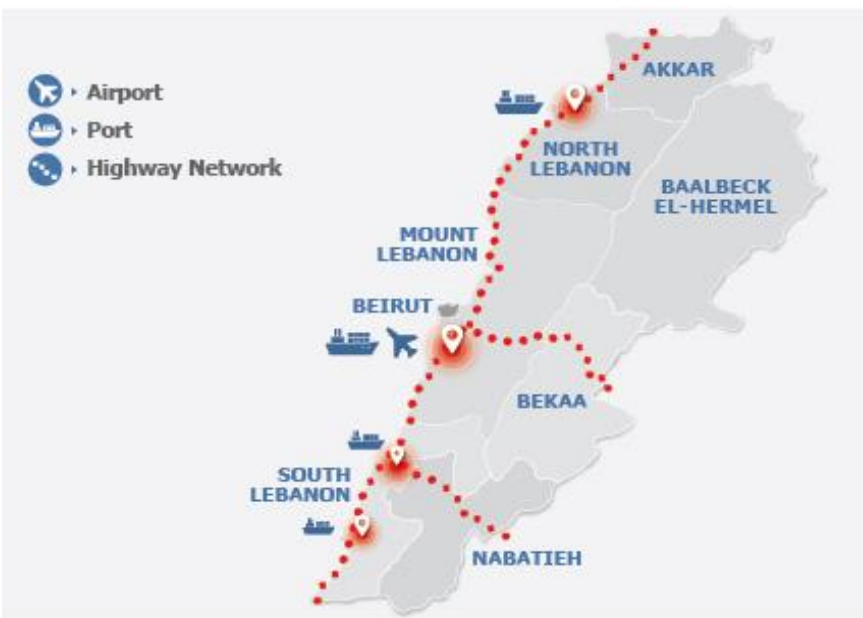


Figure 31 Map showing the governorates and major ports and connections of Lebanon [29]

Challenges & Recommendations

Akkar's region has the biggest potential among all the governorates of Lebanon, having higher wind speeds as well as more spaces for the constructions of wind farms at least 1 km distance from residential homes. The district has an area of 788 km2 and population around 400,000 inhabitants, including more than quarter of it as registered refugees [30]. Port of Tripoli, north of the country, is the second major port after Beirut port, and is located close to Akkar. However, according to the Wind Atlas onshore map shown previously, the eastern part of Akkar near the borders and stretching among high mountains have the higher WPDs. But since the agreement of construction of the first 3 wind farms in Akkar which should be operational in the beginning of 2021, part of the projects includes to establish and construct new roads for the transportation of WT parts and access to its location. Since the eastern part of Akkar is located on hills and mountains with a peak reaching almost 2 km in altitude, the challenging transportation of main WT parts like the tower and blades would require more constructions in infrastructure for the easing of such a process. The medium cost of a 1000 MW installed capacity wind farm accounts to 1.8$ billion, with an upper estimate of 2.1$ billion and lower estimate of 1.5$ billion, according to the International Renewable Energy Agency (IRENA) [23]. These estimates almost have the same values of the annual EDL's deficit. While the purchase of wind turbines can be also purchased from international factories in close countries, like Siemens Gamesa in Turkey, which would save more on transportation costs. Other parts of the country suitable for onshore wind farms can be also accessed through several ports for construction, as the republic has ports all over its coastline.

Thus, it is recommended to:

- Tariffs reformation compatible with production and transmission costs.
- Construction of needed infrastructure giving access to the surroundings of planned wind farms.
- Investing in wind farms as a major renewable energy due to high efficiency and negligible environmental impact.
- Building new wind farms with higher capacity instead of rehabilitating existing old power plants like in Tyre, Baalbek and Hraiche.
- Installing single WT instead of operating a self-generator in rural areas in mountains.
- Issuing more licenses to private investors, and encouraging the private sector to invest, like owners of private generators and distributors.
- Lebanon is currently witnessing its harshest economic crisis with foreign currency shortages, which is another obstacle for importing oil products for energy production. Thus, it is more beneficial to build larger scale hydraulic and wind farm projects rather than accepting international offers for constructing new thermal power plants.
- Extending the contracts with Turkish powerships until the operations of new wind farms and successful connections into the power grid.

Case of Study: Wind Farm in Akkar

In order to study the operation of a small-scale wind farm in Akkar region with coordinates 34°32'34"N 36°21'20"E and altitude approximately 1000 m, data have been collected from The National Wind Atlas of Lebanon regarding the average wind speeds at a 10 m height from two meteorological stations in Lebanon: Qlayaat and El Hermel. These data had monthly averages, while the meteorological station Sindiana in the Syrian part near the Lebanese borders of Akkar had only a year average wind speed. Therefore, it is possible to calculate the ratio of average wind speeds of Qlayaat and Sindiana and multiply it proportionally with the monthly averages of Qlayaat to obtain an estimation of monthly average wind speeds in Sindiana. By doing so, average wind speeds of three locations surrounding Akkar mountains in Lebanon become available, where Sindiana station is the closest and more geographically similar region. Therefore, to estimate the monthly average wind speeds in Akkar mountains, the average of the two Lebanese meteorological stations in Qlayaat and El Hermel have been taken, and this resulting value is taken with the average speeds in Sindiana to obtain the total average. The final average value is increased by 25% taking into consideration that the region is above 1000 m of altitude. That is having a ratio of 1:1:2 for Qlayaat, El Hermel and Sindiana respectively. To calculate the wind speed at a higher altitude of 100 m corresponding to the hub height of a Siemens Gamesa 5 MW wind turbine, defined equation is used to calculate wind speeds at a specific height from a reference height of 10 m for WT:

$$v_h = v_{10} * \left(\frac{h}{h_{10}}\right)^a$$

Where v_h corresponding to wind speed at a specified height h, and a is Hellmann exponent which is set it up to a value of 0.27 depending on the proposed geographical location.

The proposed wind farm consists of 4 x 5MW DFIG wind turbines with a total capacity of 20 MW. While taking into consideration the frequency of monthly operational hours of the turbines, hypothetically 0.7 for winter season due to possible windstorms where turbines have to break, 0.75 for spring season, 0.7 for summer season and 0.8 for autumn season due to a more stable windy weather. To calculate the mean active power output for each wind speed, DFIG wind farm simulation has been applied in Matlab/Simulink. The results are shown as on Figure 32. It shows that the wind turbines are effectively generative during the year except for some fluctional wind changes during the transition of seasons from summer to autumn, where October is the least windy month of the year.

	Qlayaat	El Hermel	Sindiana
Easting [m]1	776448	740292	846431
Northing [m]1	3750672	3693657	3821094
Altitude [m]	40	10	515

Table 3 Meteorological stations with UTM Zone 36S, WGS84 datum System [27]

	Qlayaat	El Hermel	Sindiana	Akkar Mountains
January	7.2	3.2	11.5	10.5
February	6.1	3.2	9.8	9.0
March	5.1	3.5	8.2	7.8
April	4.5	3.4	7.2	7.0
May	3.5	3.3	5.6	5.6
June	3.3	3.1	5.3	5.3
July	4.2	3.8	6.7	6.7
August	2.5	2.8	4.0	4.2
September	2.8	2.8	4.5	4.6
October	1.8	2.5	2.9	3.1
November	3.9	2.1	6.2	5.8
December	5.4	2.9	8.6	8.0
Average	4.2	3.1	6.7	6.5

Table 4 Average estimated monthly wind speeds [m/s] in and around Akkar mountains at 10 m height

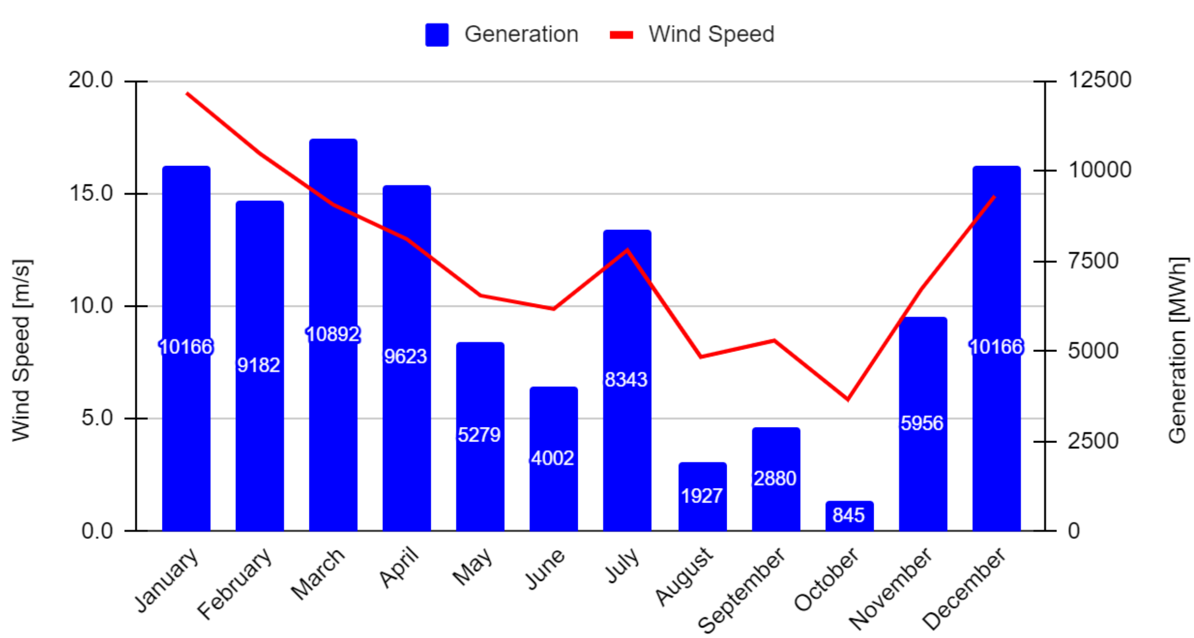


Figure 32 Average monthly speeds at a height of 100 m in Akkar mountains and the estimated generation output of a 20 MW wind farm

6. Results & Conclusion

Hypothetical results for average wind speeds in Akkar mountains confirm with The National Atlas of Lebanon map showing a wind speed higher than 9.5 m/s in that region with height above 50 m. Even though the collected data of wind speeds are subject to high uncertainties, yet the obtained annual efficiency of generation is 45% which is considered to be a promising environment for installing wider scales of wind farms with higher capacity to reduce the electricity shortages in the country.

Lebanon has already set a target of 30% of renewable energy in the energy mix for the year 2030 during the Copenhagen summit. While it has a high wind potential, it is more beneficial to construct onshore wind farms to compensate for the electricity deficit during the demand hours, for better prices. And after that, developing offshore wind farms to increase the renewable energy mix and reach its target in 2030 with sufficient production of electricity capable of covering all the shortages.

As the country is considered relatively small with high population density, the employment of PV systems to significantly reduce the national electric deficit would require massive installations with over 1000 MW of capacity which requires a huge land, turning the case favorable for wind farms that can be installed in agricultural places as well as on the offshore, with higher efficiency and effective capacities. While the solar systems would be more efficient to be used for heating purposes when being installed on rooftops of buildings or equipped with batteries to be used in private generation.

Unfortunately, political corruption remains the most challenging factor to overcome electricity shortage obstacles, as many of the Lebanese parliament politicians are affiliated with the import and trade of private small-scale generators, and distributors, to increase their own capital on the expense of public GDP growth.

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