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Adi Mohamad
Jamal

Design of Micro-Grids for Critical Loads

1-43 80 01 "Electrical Power Industry and Electrical Engineering"

Master′s thesis

Master's student's signature

Research advisor _Viktar Yanushkevich, Technical Sciences Associate Professor

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Content

ABBREVIATONS.

AC	Alternating current
AGC	Automatic gain control
AGL	Above ground level
BESS	Battery energy storage system
BRSS	Beirut River Solar Snake
BTM	Behind the Meter or BTM
CDR	Council for Development and Reconstruction
CEDRO	Country Demonstration Project on Energy Efficiency and Renewable Energy to Rebuild Lebanon
CERTS	Consortium of technological solutions to ensure the reliability of electrical equipment
CHP	Combined heat and power plant
DER	Distributed energy resource
DC	Direct current
EDL	Électricité Du Liban
EU	European Union
HPS	Hydroelectric power station
IRENA	International Renewable Energy Agency
MG	Microgrid
MEW	Ministry of Energy and Water
MPPT	Maximum Power Point Tracking
PVS	Photovoltaic Station
PWM	Pulse Width Modulation
RES	Renewable Energy Source
UNDP	United Nations Development Programme
USA	United States of America
WPP	Wind power plant

INTRODUCTION

The Lebanese Republic is currently experiencing an energy crisis, which the World Bank experts consider to be one of the largest since 1850 in the world [1, 2]

In early October 2021, two of Lebanon's largest power plants closed and the country was virtually plunged into darkness. In January 2022, a conflict between residents of the village of Aramoun near Beirut, where the Électricité Du Liban (EDL) power plant is located, and the plant's staff resulted in the entire grid failing and the company cutting off electricity to the entire country.

The country's energy infrastructure is virtually destroyed and requires substantial modernisation, which is time-consuming and financially demanding. According to Lauri Khaitayan, a Lebanese oil and gas expert in the Middle East and North Africa, technical and non-technical losses of electricity produced and supplied to the country account for more than 40 per cent. Non-technical losses refer to an inefficient collection system and theft of electricity by consumers [3].

The problem is partly solved by private companies, but their capacity is not sufficient to fully meet the demand for electricity. In addition, the electricity supplied by private companies is very expensive, as it comes from private generators that are not designed to operate for long periods of time and use the same imported fuel.

The situation is aggravated by the fact that legal energy imports into the country are extremely difficult, also due to the country's low solvency.

According to Lauri Haitayan, the country has now reached an agreement with the Iraqi government to buy Iraqi fuel, is negotiating with the Egyptian government to supply gas through the Arab Gas Pipeline (which runs from Egypt to Jordan, Syria and then north Lebanon to the Deir Ammar power station), and with Jordan to buy electricity, which will also come from Syria [3].

However, even the successful implementation of these projects will not cover all of the country's electricity needs. In addition, the funding for these projects is provided by the World Bank [3] and not by the Lebanese Republic itself. Therefore, it is not known when and how the funds and the electricity they pay for will arrive.

As a consequence, there is a sharp restriction of electricity supply to the consumer, strict rationing of electricity, blackouts reaching up to 22 hours a day [1, 2].

However, there are a number of consumers whose disconnection is impossible or ethically unacceptable - intensive care wards with life support systems, surgical, maternity and neonatal wards in hospitals, emergency lighting systems, fire alarm systems, etc. These categories of consumers are called critical loads.

To ensure uninterrupted supply of critical loads, it is necessary to provide an extensive system of power generation and supply that will remain operational even in the event of failure of some of its elements.

In such a situation, it may be appropriate to use electricity from the central grid and supplement it with electricity supply from a microgrid consisting of several alternative sources and standby generators of lower capacity, and therefore cost, compared to generators used by private power companies.

The operation of such microgrid elements is based on the principle of "hot" redundancy - with simultaneous operation and serviceability of all components it is possible to provide full power supply to the object, in case of failure of some elements - only supply of critical loads.

A microgrid can supply electricity to a part of a building or a residential complex, or even to a whole building or complex. In addition, such a structure can be scaled up through redundancy and backup to serve as the electricity supplier for an entire neighbourhood, allowing for energy autonomy and, in some situations, also supplying surplus electricity to the central grid.

Increasing the share of renewable energy sources (RES) in the energy structure will reduce damage to the environment and prevent the deterioration of the ecological situation in the country.

This master thesis investigates the feasibility and possibility of designing a microgrid for critical loads with the inclusion of several RES and backup generators in the microgrid. The system variants and the calculation of its parameters are carried out for application in the Republic of Lebanon.

Relevant issues are discussed in subsequent chapters.

GENERAL CHARACTERISTIC OF WORK

Relation of work to scientific programmes, themes

The topic of the thesis corresponds to the priority directions of fundamental and applied research of the Republic of Belarus - Energy, construction, ecology and rational nature management: energy efficiency, energy saving.

Aim and objectives of the study

The aim of this master thesis is to investigate the feasibility and propose a variant of microgrid structure for critical loads using an application example in the Lebanese Republic context.

In order to achieve the objective, the following *tasks* need to be accomplished:

- Analysing the status and prospects of alternative energy development in the Republic of Lebanon;
- analysing the experience of similar developments;
- Defining hypotheses, simplifications and assumptions in the course of the study
- selection of methods used in the work;
- defining the structure and calculating the parameters of the designed microgrid.

Scientific novelty and practical significance

1. A method for establishing a microgrid with operation in the conditions of the Republic of Lebanon based on the use of a hybrid microgrid in a hybrid mode of operation with energy availability under critical load conditions and the ability to redistribute surplus energy to the centralised power grid .
2. Optimisation of power supply for critical loads on the basis of justification of minimum required parameters of the designed microgrid.

Provisions for defence

1. A method of creating a microgrid under critical load conditions using a hybrid mode of operation due to the use of an intelligent hybrid inverter with the function of energy swept into the centralised grid.
2. Results of calculation of the minimum required parameters of the designed microgrid for critical loads.

Personal contribution of the Master's student

The master's student personally collected and analysed data from literature sources, proposed structural elements of microgrid for critical loads and connections between them, carried out necessary calculations of microgrid characteristics, selected specific brands and models of microgrid elements.

Approbation of Master's thesis and information on the use of its results

The results of the master's thesis were reported at the International Scientific and Practical Conference "Actual issues of modern science and innovation". Ufa, 5 December 2023.

Publication of Master's thesis results

1 article in the conference proceedings:

1. Stavniychuk D.I., Adi Mohamed Jamal. Factors influencing the choice of solar power plant capacity for power supply of a residential house. / D.I. Stavniychuk, Adi Mohamed Jamal. // Actual issues of modern science and innovation / Collection of scientific articles on the materials of the III International scientific-practical conference (5 December 2023, Ufa). In 2 parts. Ch.1 / - Ufa: Izd. SIC Vestnik nauki, 2023. - c. 51-58.

Structure and scope of the Master's thesis

The master's thesis consists of a list of conventions used, introduction, 3 chapters of the main part, conclusion, list of literature sources used and appendix A. It is executed on 58 pages, includes 9 tables, 9 figures, 16 formulas.

CHAPTER 1 - LITERATURE REVIEW. STUDYING THE STATE OF DEVELOPMENT MIROGRIDS FOR CRITICAL LOADS

1.1 Status and Prospects of Alternative Energy Development in the Lebanese Republic

According to the literature, the share of RES in the fuel and energy complex in Lebanon does not exceed 5%. In 2016, Lebanon adopted an energy action plan "National Renewable Energy" for 2016-2020 [4]. According to this plan, Beirut was to double its green energy capacity to 12% of its total electricity consumption by 2020. [5]. However, relative to the whole state, in 2019, the same 5% of electricity was still produced by RES, 96% was produced by using petroleum products [6].

A review by the International Renewable Energy Agency [4] notes that following the COVID-19 pandemic in 2020, the use of renewable energy and energy efficiency have become key aspects of the country's recovery plan.

In 2020, nationwide installed RES capacity totalled 350MW, of which 286 MW came from hydropower installations, 56.37 MW from PVS and 7 MW from waste treatment [4].

By 2030, the country plans to increase the volume of "green" energy to cover 30% of electricity demand [4]. It is planned to generate 1000 MW from wind, 601 MW from hydropower, 2500 MW from centralised PVS, 500MW from decentralised PVS, and 13 MW from biogas production [4].

Solar energy, wind and water energy (hydroelectric power plants, tidal and wind wave energy, geothermal energy), biomass energy, and nuclear power plant energy are among the world's widespread and popular RES [7].

Hydrogen power engineering is also considered as a potentially promising industry [8], but most of the implemented projects are experimental in nature and are associated with organisational and technical difficulties, which does not allow their use on an industrial scale.

Emphasis in the development of Lebanon's electricity sector should be placed on the construction of local power plants using mainly renewable energy sources [9].

It is reported in [10, 9, 4] that it is feasible and promising to turn to the use of RES such as solar electric energy, wind energy, small hydropower on local rivers throughout the Lebanese Republic.

As for solar water heaters, the information is contradictory: until 2010, they were not very popular in Lebanon and their share in the country's energy mix did not exceed 1%. To heat water, 70% of residents used electricity, 10% used gas heaters, 10% used liquid (oil products) heaters, and 5% used solid (wood) fuel [10]. However, authors [11] state that since 2012, Lebanese residents started to experience significant interest in such systems at the household level, and the number of firms working with solar water heaters increased from 37 in 2008 to 110 in 2012 [6]. In 2018, the installed areas of solar collectors totalled 669.291 m^2 [4].

Hydroelectric power plants are the only source of electricity that can ensure the stability of the electric power system according to [9].

While the share of capacity generated by hydraulic energy from rivers reached only 2.8 per cent of the total energy produced or more than 50 per cent of the total energy produced by RES in 2005 [7, 9].

Taking into account technical feasibility, the hydroelectric potential of Lebanon's rivers can be estimated as 4.4-106 MWh/year [9].

Offshore wind wave, geothermal, wind and biomass energy can be successfully utilised in relevant geographical (agricultural) areas of Lebanon, but not throughout the country.

According to the author [9], the tidal height on the Lebanese coast does not exceed a few centimetres, and for this reason there is no industrial conversion of tidal energy [9].

Considering that the Lebanese coastline is 200 km long, the annual wind wave energy along the entire coast is estimated at 41.6 million MWh/year. Due to the fact that current technology allows only 5% to 30% of the potential wave energy resources to be extracted, the technical resources of wave energy would be 2.1-12.5 million MWh/year [9].

Ocean (marine) thermal power plants in the maritime boundaries of the Lebanese territory have little prospect at the moment [9], but may be of interest in the future.

From a bioenergy perspective, the production of biogas from plant and animal by-products in Lebanon's agricultural areas and the conversion of domestic waste [10] into fuel are of interest.

Geothermal energy in Lebanon has no special prospects, as special expensive prospecting and exploration works are required to accurately assess its potential, and the depth of occurrence of such sources should be at least 3km [9].

However, these types of RES can be incorporated as additional local elements into distributed power sources to reduce the load on EDL's existing grid.

Solar power plants in Lebanon.

The utilisation of solar energy is the most preferred direction for the development of Lebanon's electricity sector in all its areas [10, 9, 12, 11].

The IRENA Global Renewable Energy Atlas (see Figure 20) indicates that the average annual solar radiation in Lebanon ranges from 1,520 kWh/m^2 /year and 2,148 kWh/m^2 /year, with a large majority of areas exceeding 1,900 kWh/m^2 /year [4, 9].

The distribution of solar radiation over Lebanon is shown in Figure 1 [4].

Based on these data, IRENA believes that the potential of solar photovoltaic energy for physical consumers can reach 182 GW. The specific figures of the estimate depend on the characteristics of the area for panel installation - quality and proximity of centralised electricity supply, density of buildings and population, presence of protected areas, etc [4]. The results of this assessment indicate that more than 5,558 km2 of land in Lebanon is suitable for PV panel installation. Considering a PV land use area of 33 MW/km2, this amounts to about 182,615 MW of solar PV capacity. [4].

This value is three times the current electricity generation in the country and is significantly larger than the resources of all other primary energy sources, both renewable and non-renewable [9].

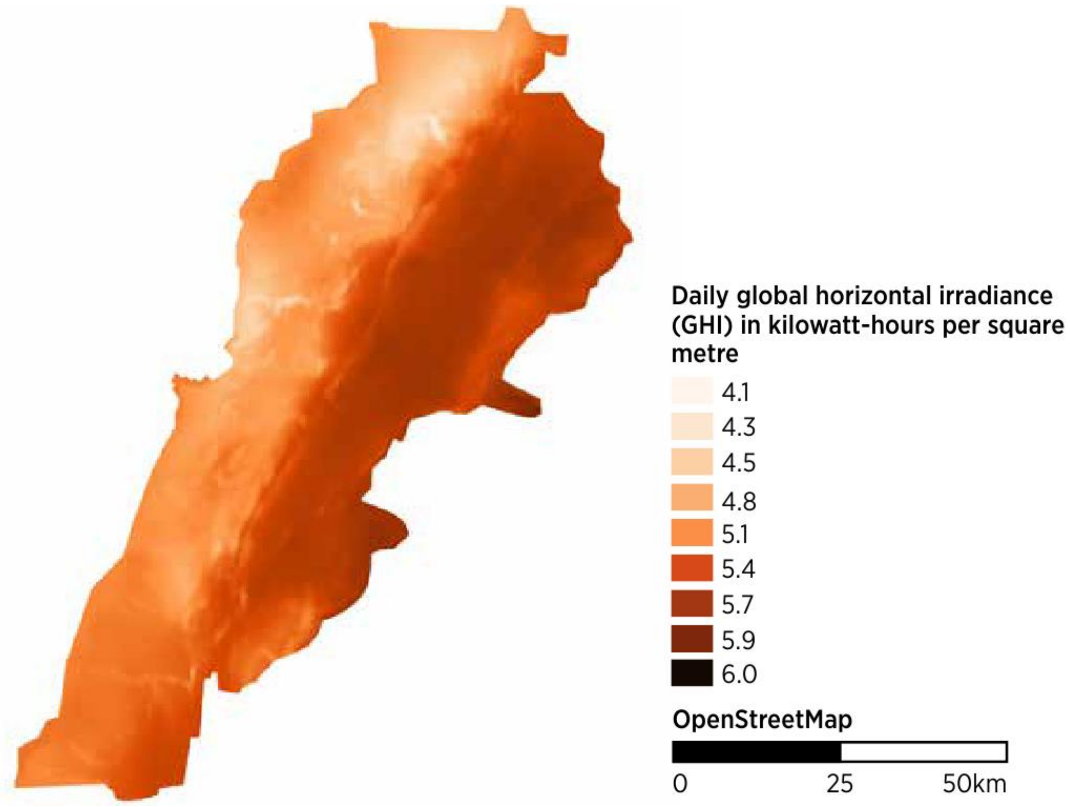

Figure 1 - Distribution of incident solar radiation over the territory of Lebanon

As you can see, the World Bank's estimate is more modest, but still very promising.

The total installed capacity of solar PV systems in Lebanon totalled 56.37 MW at the end of 2018 (LCEC 2019d), including large-scale projects and distributed installations.

Today, most of the newly installed PVSs are decentralised (off-grid) single-grid PVSs located on rooftops [4]. The annual output of such PVSs in 2018 was 83.5 GWh [4].

Distributed solar power plants, as defined by NREAP, refer to photovoltaic systems installed to meet the local demand of a specific customer or group of customers [4].

The potential of distributed PVS is difficult to assess due to the complexity of the procedure for estimating the capacity of rooftop PVS. The National Council for Scientific Research estimates that between 30% and 80% of the total roof area of Beirut is suitable for the installation of PV plants. This is sufficient to cover 13% and 34% of the capital city's energy consumption, respectively [4].

The highest concentration of projects and capacity were in the Bekaa and Hermel regions due to their higher light coverage (approximately 20% or more) and lower land prices [4].

The first large-scale PVS installation project was the Beirut River Solar Snake (BRSS), deployed in 2013 to install photovoltaic farms with a peak capacity of 1.08MW in the Beirut River bed.

The demonstration of the 1.08 MW project was important because it proved the feasibility of large-scale solar PV installation in Lebanon and thus contributed to risk mitigation in the sector [4].

In 2016, BRSS was handed over to EDL with a two-year utilisation contract. In 2018, EDL announced a tender for the second phase of the 7 MW BRSS project [4]. Data on the status of the BRSS project to date, however, could not be found.

MEW (Ministry of Energy and Water) has also installed about 4,000 PV street lighting systems with an installed total capacity of about 1.2 MW. In addition, the Ministry of Education and Higher Education is also involved in the development of distributed PV systems by installing 113 battery-operated PV plants [4].

Another example of a distributed PV system in the private sector is a project implemented by the Council for Development and Reconstruction (CDR), which installed 800 PV street lighting towers with a capacity of about 24 kW peak combined with 11 PV pumping stations in the Baalbek area with a total capacity of 1.4 MW peak [4].

Until 2020, the total capacity of Lebanon's solar PV systems was 100 MW. In 2021, another 100 MW were added. In 2022, 250 MW was added to bring the total capacity of solar PV systems to 450 MW. All this capacity was added by citizens and companies investing in off-grid solar PV systems [14].

In the municipality of Zahle, 8 MW solar power plants have been installed by 2020, capable of covering up to 10% of the electricity demand from the municipality's population [6].

More than 80% of the installed solar systems are locally produced by about 10 Lebanese industrialists who are mainly members of the "Lebanese Association of Solar Energy Industries (ALIS)" [10].

According to the Lebanese company Smart Power, which supplies and installs solar panels for the Lebanese population, it receives up to 500 requests per week for the installation of solar panels in residential houses. At the same time, the American and Chinese solar power plants they supply are capable of providing power for one small house for 8-10 hours at a system cost of about 6000 USD, which is unaffordable for the majority of the country's population.

Small photovoltaic (PV) initiatives have been implemented by CEDRO (State Demonstration Project for Energy Efficiency and Renewable Energy for Lebanon's Reconstruction) as pilot projects in different locations. A street lighting system in Chekka (North Lebanon), a tunnel lighting system, and a PV driven wind turbine project in Akkar (North Lebanon) were successfully launched [15].

The driving force behind all these initiatives has been the falling cost of the technology. IRENA estimates that the price of solar PV modules has fallen by about 90 per cent since the end of 2009 (IRENA, 2019b).

An important support for the expansion of solar energy in Lebanon is the net metering policy that has been adopted and endorsed by Electricity of Lebanon (EDL). Its benefits include legal and technical simplicity, in addition to the free installation of EDL meters [16].

The main obstacle is the lack of institutional incentives for both consumers and local producers, as well as a lack of public awareness and financial resources [10].

Wind energy in Lebanon.

Lebanon's wind energy development started with the publication of a national wind atlas in 2011. The potential wind power capacity based on its data was 6100 MW. Taking into account technical, technological and organisational constraints, it would be 5400 MW with an annual output of 12.139 GWh, and the real achievable capacity is 1500 MW [4, 9, 6].

A distinctive feature of wind energy is that wind speed depends on the height above ground level. For Lebanon, in most of the country at an altitude of 50m from the ground level the average annual wind speed is 3.5-4 m/s, while at an altitude of 80m from the ground level about half of the country is characterised by winds of 5.5-6 m/s [13, 17]. And this is already a commercially justified wind speed.

The wind map for Lebanon for an altitude of 80m above ground level is shown in Figure 2.

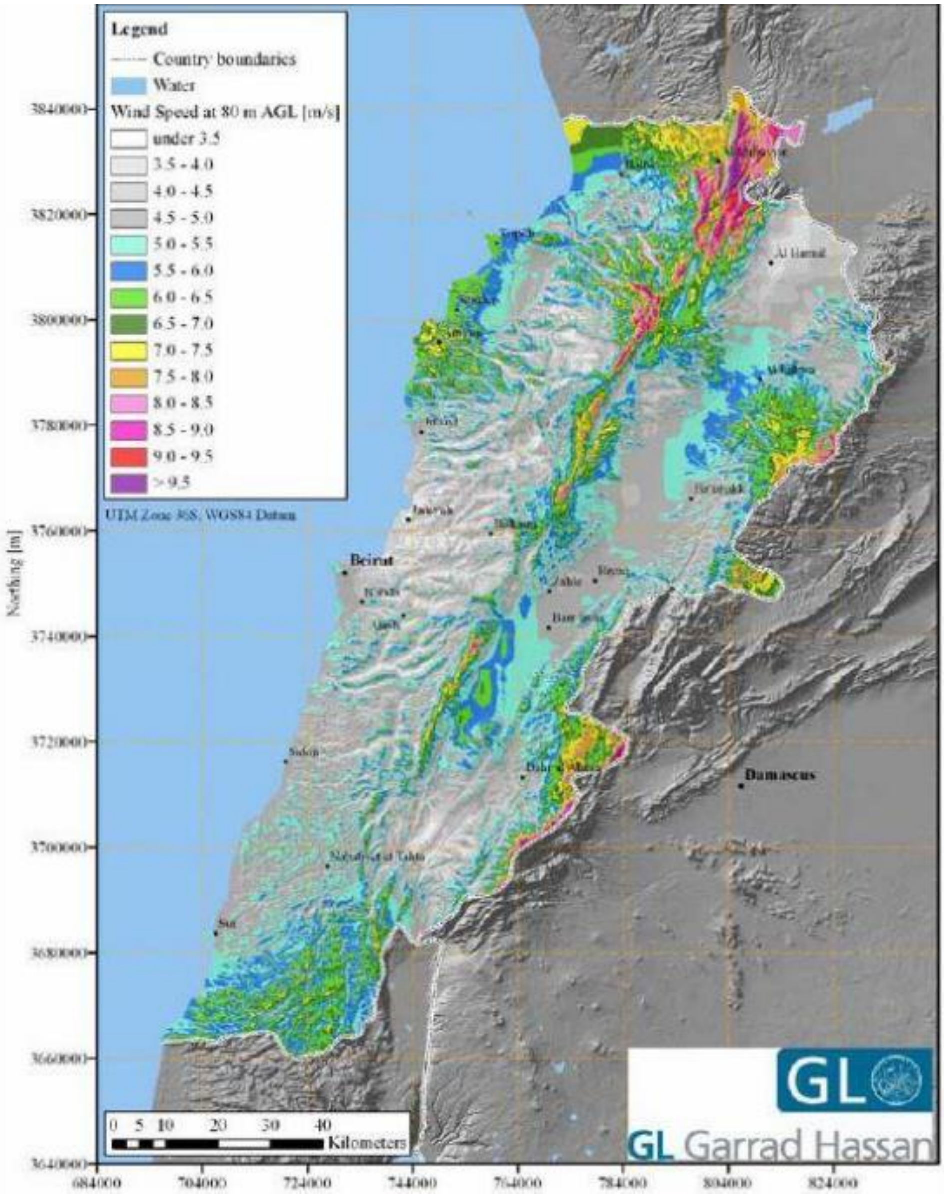

Figure 2 - Distribution of wind speeds across Lebanon for a height of 80m above ground level (CEDRO, 2011)

The estimated 2019 wind energy potential is 6,233MW, more than 1,558km^2 of land in Lebanon is suitable for the installation of wind turbines [4].

Low-power wind turbines can be used at relatively low average annual wind speeds, and their operation is economically favourable only for small sites far from high-voltage power lines. However, the lower starting speed significantly increases their versatility and expands the geography of possible installation sites [18].

Construction of large wind turbines is economically justified for areas with high average annual wind speeds and in the absence of sources of cheap electricity.

The main policy instrument to facilitate wind energy deployment is competitive procurement or auctions conducted by the state.

The first such auction was launched in 2013, when a tender was issued for the construction of three wind farms in the Akkar region with a total capacity of between 200 and 220 MW, depending on the wind speed at the generator installation point.

Figure 3 shows the achieved volume of wind power capacity applications by different regions of the country with the maximum concentration of wind turbines in the Akkar region [4].

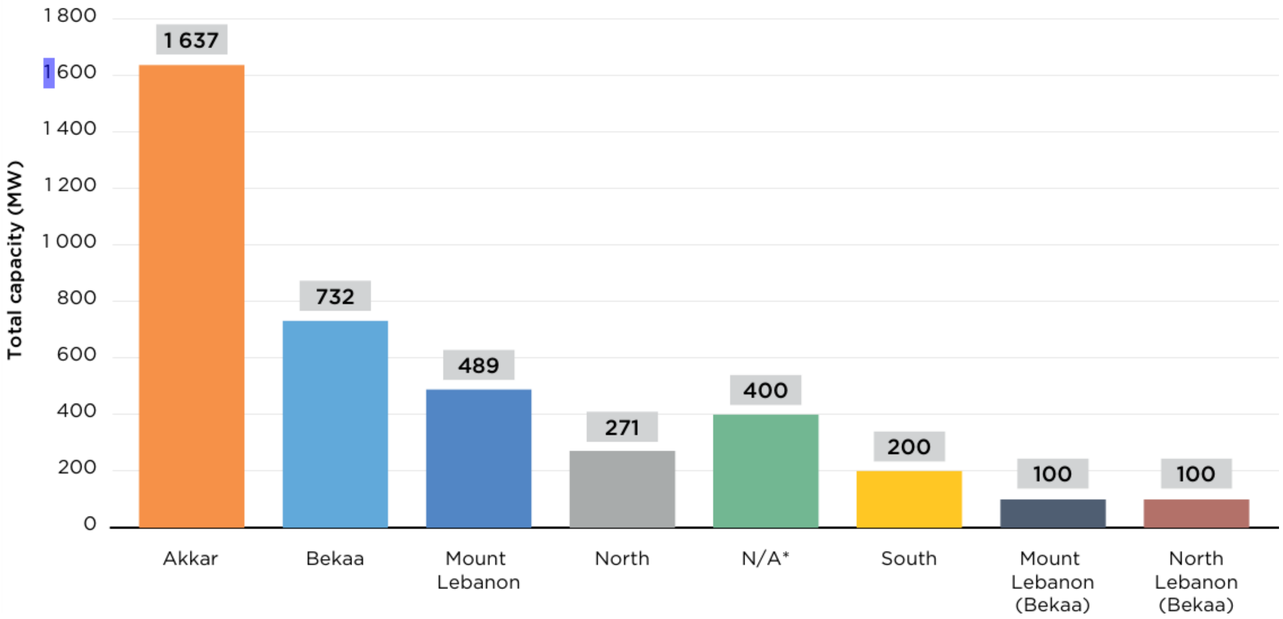

Figure 3 - Achieved wind power capacity bids by region in Lebanon

To date, small wind turbines have been installed in Lebanon, but their capacity is estimated to be around 100 kW (0.1 MW). Such turbines could potentially be useful in high altitude cities where wind speeds may exceed commercially viable thresholds.

One of the limitations of wind turbine distribution is the need for more studies to justify the installation of a wind turbine at a particular location, as wind turbines create certain migration problems for bird populations [19].

Using power purchase agreements (PPAs), a partnership between the private organisation Liban Wind Power SAL (initiator) and the Lebanese government was concluded in 2018 to build three wind farms with a total capacity of 200 MW. This agreement was made possible by Law 48/2017, which was Lebanon's first legislative initiative to promote private sector investment through partnerships (Ramboll US, 2019) [6]. The wind farm will be built in the eastern part of Akkar province [6].

Information on the status of the project for 2024 could not be found.

Hydropower in Lebanon.

As of 2018, the total installed capacity of the five primary power plants is 286 MW. All five plants built along key waterways are summarised in Table 1 (IRENA 2020).

Table 1 - Operational HPPs on Lebanon's rivers

No. of items	River	Year of commissioning	Founder	Plant	Number of operating turbines	Power Installed/ **Effective**, MW
1	Litani/Awali rivers	1961,1964, 1967	Litani Water Authority	Markaba, Awali, Joun	7	**199/47**
2	Nahr Ibrahim river	1961,1955, 1951	Societe Phenicienne des Forces de Nahr Ibrahim des Eaux et Electricite	Chouane, Yahchouch, Fitri.	8	**32/17**
3	Kadisha valley	1924,1957, 1961,1932	La Kadisha, Societe Anonyme d'Electricite du Liban Nord	Bechare, Mar Licha, Blaouza II, Abu-Ali.	11	**25/15**
4	Nahr Al Bared	1936	Al Bared Concession	Al Bared 1, Al Bared 2	5	**17/6**
5	Safa spring	1931	Electricite du Liban	Richmaya-Safa	3	**13/3**
6	Total installed capacity					286 /**88**

Table 1 shows that most of the installed operating HPPs in the country were built and commissioned before 1970 (Table 1) [4], i.e. they require modernisation and reconstruction. Outdated infrastructure has also hindered efforts to truly implement modern hydropower solutions.

As a consequence, in a country that generally has abundant reserves of water resources suitable for electricity generation [6], there is a strong decline in the efficiency of hydropower - 286MW of installed capacity is turning into 88MW of usable capacity.

At the same time, according to the NREAP programme, reconstruction and modernisation of these hydropower plants can increase their annual output by more than 1000GWh [4].

The latter source of hydropower potential stems from micro hydropower and non-revenue sources (waterfalls, rainfall, streams, springs) and is estimated to be in the order of 5MW (CEDRO, 2013) [4].

According to the Lebanese Ministry of Energy and Water, there are about 40 major streams and 2000 springs in Lebanon, representing an average annual flow of 8600 million cubic metres (Mm^3) (El-Fadel et al., 2000) [6].

The overall picture of the hydroelectric potential of the Lebanese Republic as of 2021 [4] is shown in Figure 4.

Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and

Figure 4 - Map of Lebanon's hydroelectric potential as of 2021

Studies conducted under CEDRO under the auspices of the UN in 2013 showed that it is possible to generate up to 1363 GWh of electricity per year from hydropower when using dam infrastructure in peak schemes, and up to 1271 GWh per year when using stream schemes; enough flow to supplement the grid with up to 12% additional capacity (CEDRO, 2013). The country's constructed water balance models showed net positive water availability, which theoretically gives Lebanon a uniquely high water utilisation potential (UNDP, 2018) [6].

One of the main challenges to hydropower development in Lebanon is the arid climate and lack of "free" water, resulting in most river concessions being used for agricultural purposes rather than for hydropower generation [10].

Based on the above, it seems appropriate to use a microgrid with the following enlarged structure:

1) Solar power plant
2) Wind farm

3) Standby generator

4) Servicing infrastructure - Batteries or other energy storage, inverters, AC to DC and DC to AC converters, etc.

The standby generator is expected to be selected to provide full coverage of critical load requirements in the event of failure of the solar and wind farms.

Using other alternative energy sources in the microgrid does not seem to be efficient enough as it reduces the versatility of the proposed microgrid structure.

1.2 Overview of similar developments

In this paragraph, we will look at examples of microgrid design and application in the works of other researchers.

The topic considered in the paper is relevant and in demand for many countries, which is confirmed by the results of analysing the works of scientists from Ghana, Japan, the USA, China and other countries [20].

Many laboratories, including Oak Ridge National Laboratory, USA, have established microgrid demonstration projects based on various distributed power generation systems to provide a practical basis for further microgrid research [21] .

Microgrid research by Japanese research institutes is not limited to new energy sources, but also includes traditional power sources. Unlike American researchers, the Japanese view the microgrid as a small controllable system including power supply, load, and other equipment integrated through the microgrid and then combined into a larger power system for operation. Japan has established a number of research and experimental microgrid systems in Japan, conducted a large amount of research work on microgrid operation control and grid-related effects, and established a distributed power microgrid demonstration project led by Kyoto [22].

Much attention is also paid to microgrid research in China [23]. Particular attention is paid to the formation of microgrids adapted directly to the national conditions of China [24].

In the work of a Chinese researcher [20], a model of a distributed microgrid made up of an PVS, a wind generator, a gas turbine power generation system, a diesel generator, fuel cells and an energy storage (storage) system, and control algorithms are considered. The distributed power source is sunlight, wind, diesel power plant, gas turbine and fuel cell, and the energy storage system is battery. And according to their working principles, the mathematical model of the power generation system is created [20].

The work [20] is aimed directly at optimising the control of such a microgrid. In this work, the methods of data analysis of literature sources, as well as Particle Swarm Optimisation method and NSGA-II algorithm (**Non-Dominated Sorting Genetic Algorithm**) are used. Mathematical models for optimisation of both algorithms are proposed.

In [25], such issues as load profiles, solar energy availability tariff structure and their impact on microgrid design and operation costs are discussed. The authors used 2 hospitals and 2 high schools - Palomar Medical Centre Escondido (Hospital), Golisano Children's Hospital (Hospital), Camino Nuevo High School (High School), Beacon High School (High School), California and New York, USA, as a research site.

A different microgrid was considered for each site, according to Table 2.

Table 2 - Microgrids from the paper [Optimal microgrids]

No. of items	Elements of the microgrid	Palomar Medical Centre Escondido (Hospital)	Golisano Children's Hospital (Hospital)	Camino Nuevo High School (High School)	Beacon High School (High School)
1	Solar capacity	257 kW PV size	95 kW PV size	16 kW PV size	127 kW PV size
2	Wind installation size	0 kW wind size (no wind installation)	0 kW wind size (no wind installation)	0 kW wind size (no wind installation)	0 kW wind size
3	Battery power and capacity	No batteries	23 kW battery power 0 kWh battery capacity (no batteries)	15 kW battery power 22 kWh battery capacity	273 kW battery power 1481 kWh battery capacity
4	Diesel generator size	1362 kW generator size	552 kW generator size	0 kW generator size (no generator)	0 kW generator size
5	CHP electric capacity	387 kW CHP reciprocating engine size	100 kW CHP reciprocating engine size	0 kW CHP reciprocating engine size (no CHP)	209 kW CHP reciprocating engine size
6	Hot water TES tank size	4176 gal hot water TES tank size	5084 gal hot water TES tank size	0 gal hot water TES tank size (no hot water TES)	0 gal hot water TES tank size
7	Chilled water TES tank size	824,649 gal chilled water TES tank size	256,176 gal chilled water TES tank size	0 gal chilled water TES tank size (no chilled water TES)	0 gal chilled water TES tank size
8	GHP and ground loop system size	0 tons heat pump capacity size (no GHP system) 0 vertical heat exchange wells	0 tons heat pump capacity size (no GHO installation) 0 vertical heat exchange wells	67 tons heat pump capacity size 8 vertical heat exchange wells	588 tons heat pump capacity size 217 vertical heat exchange wells
9	Potential life cycle savings (25 years)	USD 319.915	USD 136. 957	USD 51.771	USD 975.440

The authors [25] found that the electrical load profiles by month throughout the year at these facilities do not have significant differences except that the load of the educational facilities decreases sharply during the summer months. Thermal loads at all facilities drop sharply in the summer months. And synchronously, the load on cooling systems increases sharply.

A comparative economic analysis of microgrid efficiency was also carried out, taking into account differentiated electricity tariffs.

As a result of the work, the authors concluded that it is difficult to obtain optimal results of microgrid design, in terms of reliability, economy and efficiency of the system. Especially difficult is the consideration of electric and thermal energy storage and its influence on the parameters of the whole system [25].

The results show that the use of microgrids is an effective solution to provide the necessary electricity needed in case of power outages using a combination of diesel generation and CHP [25]. In the case of hospitals, it was possible to both increase the resilience of the power system to CHP outages and reduce the energy consumption from CHP by generating from RES during the daytime hours when electricity tariffs are highest [25]. In the case of secondary schools, the critical load was lower and battery storage was used as the power supply system.

Thus, it has been shown that the use of microgrids in critical-load buildings is a technical and economically optimal solution that can be applied in different locations, scenarios and building typologies, and that optimising both the microgrid design and the dispatching strategy ensures maximum sustainability and cost-effectiveness [25].

In [26], microgrids consisting of renewable energy sources, energy storage, generators, a central grid and load connected to it, a combined heat and power system, and an electric vehicle charging station are considered.

The authors note that given the small scale of the microgrid, it is important to implement a suitable energy management and control system to ensure efficient operation of the microgrid [26].

As distributed sources of electricity the authors specify microturbines, fuel cells, hydropower plants, PVS, wind and biomass. As energy storages - batteries, magnetic storages, FlyWheel storages.

The work investigates different types of grid-connected and autonomous microgrids - using solar and wind power, solar and hydroelectric power, purely solar and hydroelectric RES, etc. All microgrids are connected through AC and DC busbar systems using AC to DC and DC to AC converters [26].

In rural areas, the advantage of using a grid system is the ability to sell excess electricity generated from renewable energy sources (RES) back to the utility grid [27].

Currently, most hybrid solar-wind renewable energy systems are integrated with Internet of Things (IOT) devices. These systems operate using a database management system and utilise artificial intelligence in a PEAS (Perceive, Enact, Analyse and Store) task environment [28, 29].

A hybrid model including hydrogen and heat storage systems is proposed to solve the power balancing problems in the microgrid.

To solve the optimisation model, it is recommended to use a flexible weighted predictive model control (weighted-MPC) method with the ability to adapt the distant horizon based on the system uncertainty predictions [30].

Careful case studies are conducted to verify the effectiveness of this hybrid microgrid energy planning approach. Figure 5 shows a hybrid microgrid system in which electrical and thermal load control is implemented. The thermal load controller is connected to the thermal load systems, AC buses and DC buses. In addition, a hydrogen tank and an electrolyser are used to ensure efficient operation of the microgrid system based on electrical and thermal load [25].

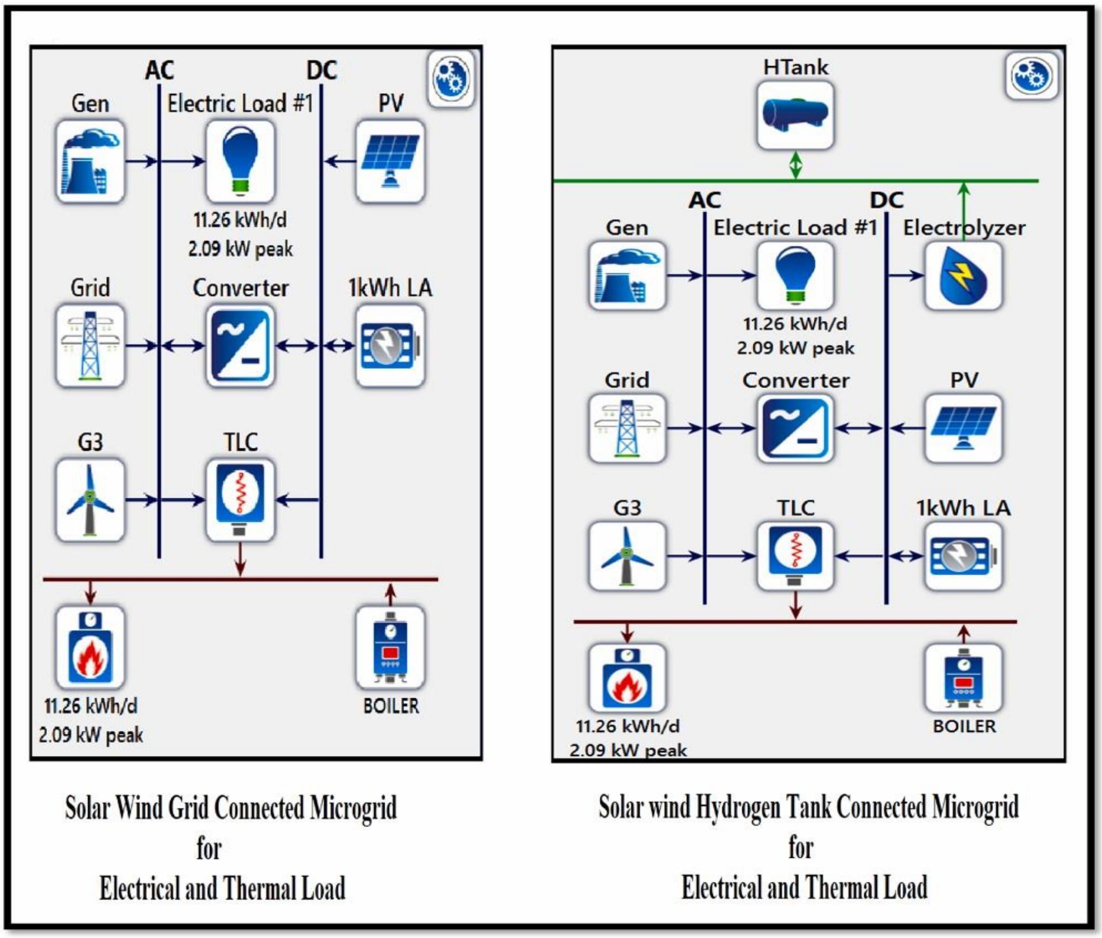

Figure 5 - Hybrid microgrid with electric and thermal load control

A microgrid with a vehicle-to-grid system based on a multi-agent approach is used to model the system, and the components of the microgrid are modelled as agents. Grid-connected electric vehicles can operate as energy sources along with wind and solar power generation, using collective PEV car batteries as a virtual power plant.

Improving the performance of microgrids requires a nonlinear control system based on artificial intelligence, focusing on stability and bidirectional flow in DC microgrids [26].

Artificial intelligence approaches such as Bacterial Food Finding Optimisation (BFO), Particle Swarm Optimisation (PSO) and Genetic Algorithms (GA) [30.1] are used to efficiently tune critical parameters simultaneously in microgrid AGCs.

According to the authors [26] future research in the field of microgrids may focus on the development of improved microgrid control algorithms.

The authors [32] consider a microgrid with a photovoltaic system, a fuel cell, and a doubly powered induction generator. Each system is individually powered on an infinite bus with a constant frequency of 60 Hz and a voltage of 690 V (linear). Computer modelling in the MatLAB package for 0.5 seconds is used. The DFIG is the main source of power. In the event of failure of the entire DC system, the generator can independently provide power to the grid. The DFIG is called dual power because it has two input sources. The rotor must be fed with three-phase alternating current with a frequency of 60 Hz to produce a synchronously rotating magnetic field [33]. In the event of an interruption in the DC system, the DFIG takes over and supplies output power to the entire system.

The authors argue that too large a number of microgrid elements is unjustified because along with the power generation benefits, the total number of elements of the microgrid itself and its control system increases, a large number of devices combined together will significantly increase the cost and increase the harmonics in the system [34].

However, integrating the wind turbine generator with PV cells and battery system will improve the power quality and the additional active power will result in higher voltage. The losses in the system reduce the power, but the additional active power flow will fill the gaps and improve the efficiency, system performance and power quality. on the load side [35].

The efficiency of a PV system operating separately can only provide 20-30%. But with the inclusion of DFIG, the overall efficiency of the system has increased, making the system more reliable. The system provides uninterrupted voltage without any deviation. The capacity of the photovoltaic system is 136 kW. The power provided by the battery system is 81.56 kW. The total DC output power on the inverter side is 198.6 kW. Thus, the efficiency of the DC system is 91.28%. The efficiency of the DFIG is approximately 85%. Hence, the total efficiency of the system is 77.59%. The cost of the SunPower PV cell is about $14,000 to $30,000. The cost of a 600V battery system is about $1,000. The cost of a Schneider Electric three-phase 1 kV inverter is about $14,000 and the cost of a 2 MW wind turbine is about $2.8 million. This brings the total system cost to about $2.9 million. A linear output voltage of 1 kV is created and a linear current of 138 kA is created [32].

Different types and concepts of microgrids are also discussed in [36]. It is argued that a microgrid can accommodate different types of microgenerators (wind generator, photovoltaic (PV) battery, diesel generator and wave generator), local storage elements (capacitors, flywheel) and loads. The distributed generator can be a diesel generator that can be connected to the grid directly or a solar panel that will require a DC/AC inverter or an induction wind turbine (DG1), AC-DC-AC inverter for proper connection to the grid [36]. Energy storage devices may or may not require an inverter interface in the case of capacitor banks and flywheel respectively. The microgrid can be DC [37], AC or even high frequency AC [38]. It can be a single or three phase system and can be connected to low voltage or medium power distribution networks [39].

In [Taha Selim], examples of microgrids from the European Union, Japan, Korea, North America, Australia are also discussed.

EU. The first EU funded project called "Microgrid Prolect" was set up by a consortium led by the National Technical University of Athens (NTUA). The aim was to investigate the dynamics of distributed generators in microgrids and to develop strategies for a number of issues such as control algorithms, protection schemes, black start strategies, as well as determining the distributed generator interface response and intelligence requirements. The pilot plant was erected on the island of Kythnos, Greece. A comprehensive study of microgrid control techniques was investigated in the ISET microgrid in Germany. The project continued with the project "More Microgrids" again led by NTUA. The aim of this project was to investigate alternative methods, strategies along with universalisation and the plug-and-play concept. The demonstration site is an ecological estate in Mannheim-Wahlstadt, Germany [40]. Other smaller scale realisations include Labein Microgrid in Spain, Frielas Feeder in Portugal, CESI Microgrid in Italy, Continuon Holiday Camp Microgrid in the Netherlands, Am Steinwag settlement in Germany [40-42].

Japan. Since microgrids are able to cope with the disadvantage of solar and wind power such as intermittency of power generation, Japan, where solar and wind are the main RES used, leads the world in the number of implemented microgrid projects [43]. Most of the projects are funded by the New Energy and Industrial Technology Organisation (NEDO) Development Programme. The first project started operation at the 2005 World Expo in Aichi, although it was moved to Tokoname City near Nagoya in 2006. This system utilises fuel cells, photovoltaic panels and a NaS battery storage system. This microgrid is used to power some large pavilions. It has been tested twice for independent operation in 2005 and 2007.

The second demonstration site is in Kyotango, where the biogas plant is connected to two photovoltaic systems and a small wind turbine. This network operates as a VPP and utilises conventional information networks such as ISDN and ADSL [41, 42]. The third project in Hachinoha is implemented by Mitsubishi Research Institute and Mitsubishi Electric [43]. This system has its own distribution line and consists of photovoltaic systems, wind turbines and gas engines and storage. The control scheme developed here ensures stability and fulfils the construction requirements. NEDO has established an additional project in Sendai City in which the impact of 4 levels of electricity consumers will be studied. The system has a power quality redundancy system. in order to reduce outages and voltage fluctuations. This project aims to study the feasibility of providing different levels of service to customers in the same area. The system has improved the power quality since its introduction in 2007 [44].

There are several private research projects in the field of microgrids. For example, Shimizsu Microgrid is being developed by Shimuzu Corporation in collaboration with Tokyo University to develop an optimal operation and control system. Tokyo Gas, again in collaboration with Tokyo University, is trying to develop integrated gas generation management through modelling and experimentation at its Yokohama facility [44].

Crossing the borders, Mitsubishi Corporation has installed a small grid in Xinjiang, China and it can be supplied through distribution network, photovoltaic systems, battery storage and generator set operation [45].

Korea. Korea's only microgrid project is developed by the Korea Energy Research Institute (KERI). The test system is very complex as it includes several types of power generators such as photovoltaic simulator, fuel cells, diesel generators, wind turbine simulator, and at significant and minor loads. The grid is equipped with power storage and quality control devices. A control system is being implemented that takes into account even weather conditions and interacts with the components through a gateway. The whole project was implemented in two phases, where in the first phase the microgrid was maintained as a 100kW plant, in the second phase it was extended for further research [46]. Jeju Island and other similar Korean islands are the best candidates for microgrid implementation in Korea in the future - the total wind energy in Jeju was estimated to be 230MW in 2009 [47,48].

North America. CERTS (Consortium for Electric Reliability Technology Solutions), shown in Figure 6, is the best known of the US microgrids. It is a collaboration between AEP, TECOGEN, Northern Power Systems, S&C Electric Co, Sandia National Laboratories and the University of Wisconsin [42].

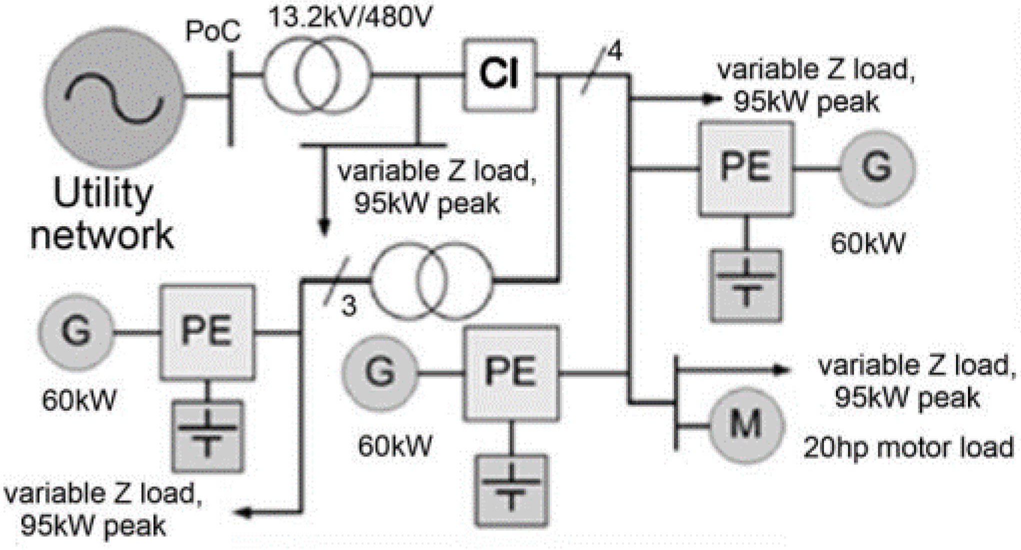

Figure 6 - CERT Microgrid

It consists of several distributed generators and a thyristor switch providing isolation from the grid. The main objective of this research was to facilitate the connection of small distributed generators to the grid. As a result, three advanced concepts, also called the CERTS microgrid concept, were developed and demonstrated to reduce the amount of engineering work on microgrids.

Two software tools for microgrids are also being developed using CERTS as an example. These are Grid analysis tool (Grid) developed by Georgia Institute of Technology and Distributed Energy Resources Customer Adoption Model (DER-CAM) used at Berkeley Lab [41]. Other projects currently underway in the Mad River Waite area include those conducted by Northern Power Systems, British Columbia Institute of Technology, and General Electric Microgrid [42]. These systems are currently in the research and development phase and the goal is to design control and protection strategies for different types of microgrids.

Australia. There are currently no microgrid pilot projects in Australia. But there is great potential and extensive research into distributed energy and microgrids has been carried out due to government incentives. The communities of Yungngora and Kalumburu in Western Australia [49] and the community of Windora in Queensland [50] are examples of remote communities that are candidates for microgrid operation. Some energy companies are trying to operate microgrids on islands, such as Thursday Island in Queensland [50] and King Island in Tasmania [51].

In [52], the description and reliability modelling of an off-grid solar-wind microgrid with battery energy storage installed in the private sector of Lima city, Peru, is investigated. The system is a Behind the Meter–Behind the Meter or BTM type microgrid including solar, wind and battery energy storage system (BESS) generation sources. The grid topology is assumed to be a single AC bus where loads are aggregated and connected as schematically shown in Figure 7.

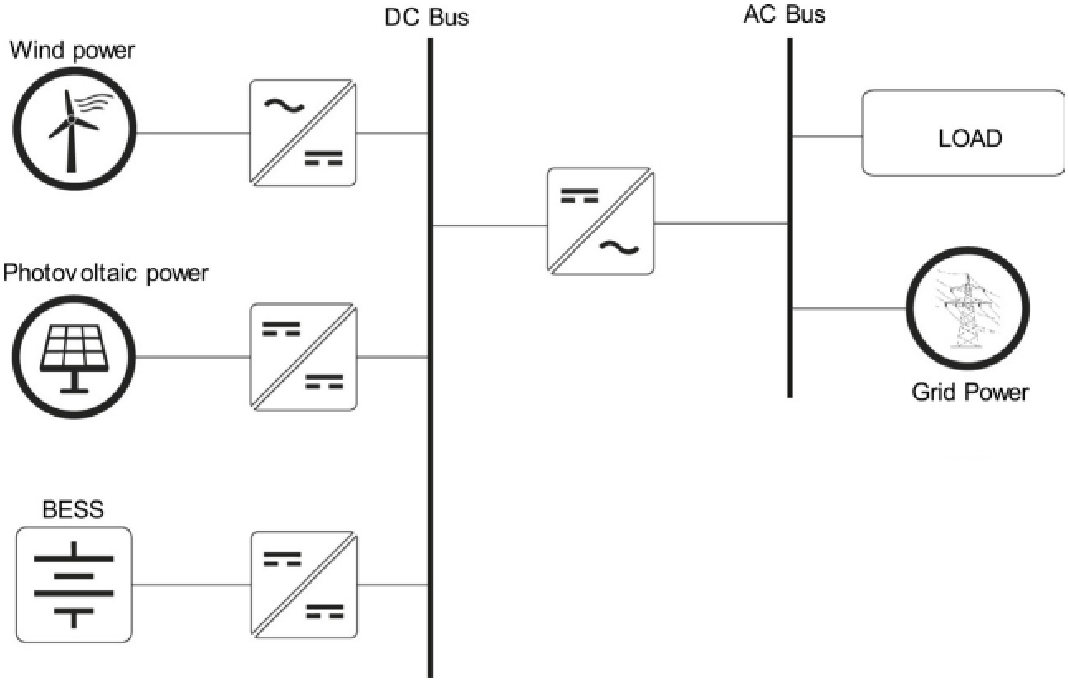

Figure 7 - Topology of a photovoltaic (PV)/wind system with battery energy storage system (BESS)

Table 3 shows the parameters of the system under study, used also in modelling the reliability of its operation.

Table 3 - Parameters of photovoltaic (PV)/wind system with battery energy storage system (BESS)

250 W solar panel	Hybrid solar inverter	BESS	Wind turbine
Power max (Pm): 250 W Short circuit current (Isc): 8.95 A Maximum voltage (Vmp): 29.95 V Open circuit voltage (Voc): 37.25 V Efficiency: 19.9% Max power current (Imp): 8.35 A	Max. output power: 3000 W Inverter efficiency: 99.5% PV volt. Range: (150-550) V Output current: 16-27 A Input voltage: 150-550 V Nominal AC output: 230 V Number of MPP trackers: 2	Nominal voltage: 48 V Nominal capacity: 2400 Wh Usable capacity: 2280 Wh Charge voltage: 52.5-53.5 V Discharge Vol.: (44.5-53.5) V Charge/discharge current: 25 A (Recommend). 50 (Max), 90 (Peak@ 15s)	Rated power: 1000 W Maximum power: 1300 W Start-up wind speed: 2.5 m/s Rated wind speed: 10 m/s Rated voltage: 48 V Wheel diameter: 2.5 m Number of blades: 3

It is found that hybrid (solar-wind in hybrid mode of operation) microgrids exhibit increased flexibility in response to consumer energy demand. The PV/Wind/BESS configuration significantly improves system performance during daytime. The combined output power of the PV panels and wind turbine is sufficient to meet the required loads for most of the day. Moreover, any excess PV/wind energy is channelled to the BESS in the event of an energy shortage. Consequently, energy from the public grid is only supplied when the BESS cannot fulfil the Load Requirements. As a result, the public grid usually serves as a backup power source during nighttime and off-peak times [52]. The optimum size of a hybrid microgrid system is 2.4 kW for PV system and 1.5 kW for wind turbine, 2.4kWh for BESS. In this study, only 42.5% of the total PV/wind energy used by the residence was sent via BESS. Consequently, 57.5% was delivered directly to the residential load, bypassing the BESS [52]. However, complete consumer autonomy from the central grid cannot be achieved in the studied microgrid configuration, and the common centralised power grid remains a backup source for the microgrid during nighttime and off-peak hours.

The authors of [52] also conclude on the recommendation to rely on real energy consumption data for the calculation of microgrid parameters, to use high frequency time series for prediction, to achieve the optimal result and to determine the optimal BESS size, as it minimises the initial installation cost, adjusting the microgrid parameters and reducing the energy deficit.

In [53], different types of microgrids (DC, AC, hybrid, cascaded) and modes of microgrid operation (stand-alone or islanded and grid connected), different types of microgrid elements and microgrid control schemes for Bangladesh are investigated. The overall microgrid structure considered in [53] is shown in Figure 8.

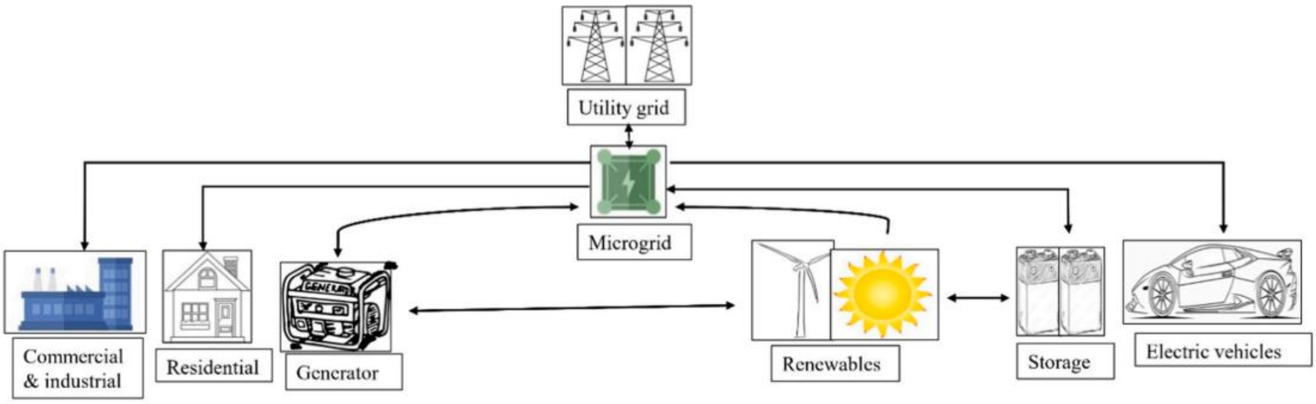

Figure 8 - General structure of the microgrid

In this grid, electric vehicles, household consumers and industrial plants are the loads, generators, renewable energy sources (solar, wind, water, etc.) are the sources, and BESS is included. The microgrid concept is prevalent in both AC and DC systems and is defined as a small low or medium voltage network consisting of generators, storage and loads. Such a system is capable of operating in both grid-connected and isolated modes [53].

In an AC microgrid, the bulk of the consumers are oriented towards AC supply. They are a relatively new subject in microgrid research and require consideration of the variation in voltage and frequency supplied by the microgrid to the central grid or consumers.

It is noted that DC microgrids have advantages over AC microgrids: no skin effect, lower operational losses, no synchronisation requirements and simpler control architecture. In addition, the majority of residential consumers use DC. It should be noted, however, that when building DC microgrids, ensuring safety and stability of DC generators during short circuits is one of the main challenges [53]. Also, such systems are much more easily scalable compared to AC microgrids and can be easily integrated with RES and BESS [54].

The integration and operation of ESSs that balance load demand and energy supply is a key component of DC microgrids [55].

However, due to their structure, AC microgrids are not able to transfer surplus energy to the centralised grid. Hybrid microgrids do not have this disadvantage. In such systems, there are both AC and DC powered consumers, as well as various sources, loads and storages that are connected to either bus [56].

In essence, a hybrid microgrid consists of a centralised AC supply network, a DC submicrogrid comprising DC consumers, energy storage systems and PV panels, and an AC submicrogrid comprising AC loads and wind turbines. Several kinds of generators, storage components and loads connected to the same AC bus or sub-grid in make the hybrid microgrid the dominant structure. The overall structure of the hybrid microgrid is shown in Figure 9.

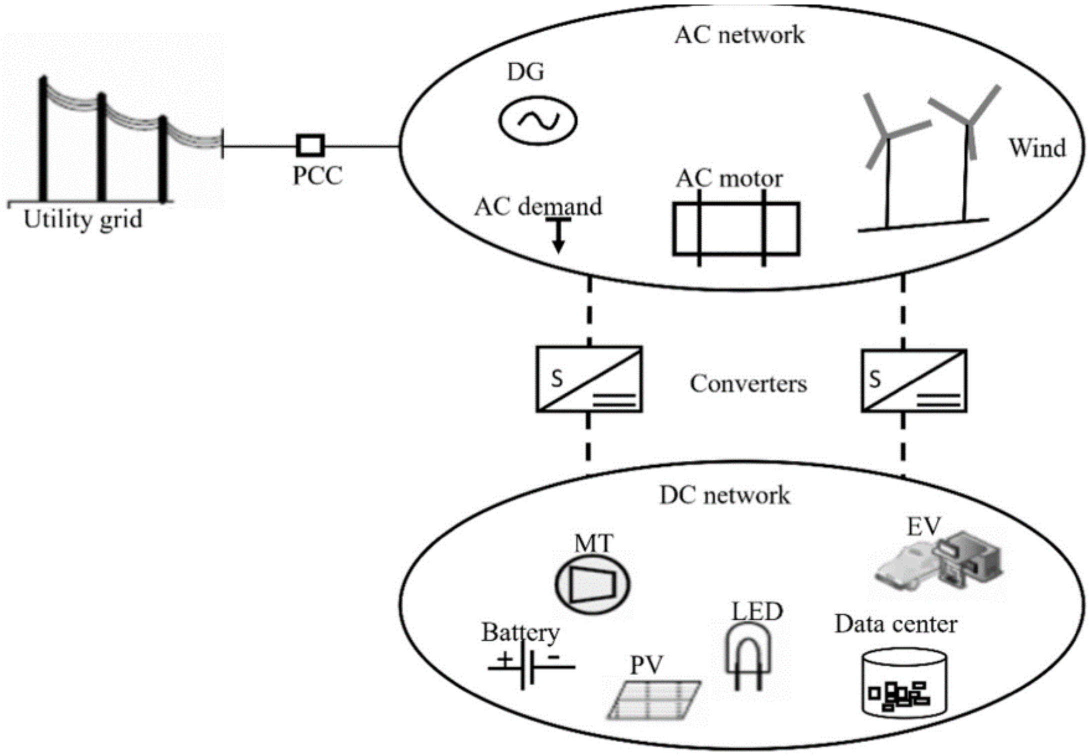

Figure 9 - General structure of a hybrid microgrid

The photovoltaic component is connected to the AC bus via a DC to AC converter, while the AC loads are also directly connected to the AC bus. The battery is used as a storage element and is connected directly to the DC bus using a bidirectional DC to AC converter to control charge and discharge, and finally the fuel cells use a DC to AC converter to achieve a constant power output in the DC microgrid [57].

Unlike separate AC and DC generators, hybrid generators can link both DC and AC power sources and directly power both types of loads [53].

Thus, a hybrid microgrid has the advantages of each of the previously discussed types of microgrids.

As a control scheme for hybrid microgrid, [53] proposes a decentralised control scheme as less complex and more affordable to implement.

The above excerpts from the studies of scientists from different countries confirm the relevance of the chosen research topic in general, and the need to improve the energy security of the country - in particular for Lebanon. The country has a large enough potential for the creation of hybrid microgrids with the predominant use of wind and solar energy as sources of alternative energy.

1.3 Definitions, simplifications and assumptions made in the study

The accurate calculation of microgrid parameters for critical loads using a distributed renewable energy generation system is complex and requires large computing power. Therefore, based on the above, the following simplifications and assumptions are made:

- A hybrid microgrid was selected for development, with photovoltaic panels, batteries, and part of critical loads powered by direct current connected to the DC subnetwork, and wind turbines and the centralised power supply network connected to the AC subnetwork.

Other sources of alternative energy are not considered to avoid over-complicating projects.

- The photovoltaic plant utilises monocrystalline rigid solar panels with a one-way installation of panels on the roof and on the support;
- the angle of installation of PV panels is determined by the geographical latitude of the installation site [58] with the orientation of part of the panels under the first half of the daylight, part - under the second half [59].
- Batteries are used in hot standby mode, which affects the calculation of the number of batteries required
- MPPT controller is used to regulate the operation of the PV panels
- A hybrid inverter is used to ensure that surplus energy is fed back into the central grid, which can mix energy from renewables with grid energy
- the projected microgrid covers one building

- the amount of critical loads is assumed to be 50 per cent of the total energy consumption, as for a hospital [35], since the uninterrupted supply of hospitals is more critical than that of educational institutions.

- critical loads are supplied 24 hours a day, but for a limited period of time necessary, for example, to repair the main part of the microgrid or to eliminate a power failure of the central supply network.

I.e. the microgrid operation time for critical loads averages 22 hours - the time of interruption of power supply from the central grid.

- DC/AC and DC/DC converters are used in the microgrid structure

- The microgrid consists of main supply generators that cover 50% of the loads (non-critical) and reserve supply generators that cover the remaining 50% as critical loads.

The calculation of the main supply system is not considered in this paper. It is assumed that it is also a photovoltaic plant.

It is also assumed that the main and backup supply system are electrically decoupled and used in parallel, covering 100% of the power demand of the supply facility. And in case of failure of the main system, non-critical loads are disconnected from the grid and critical loads are fed from the backup part.

That is, the main and reserve parts of the microgrid operate in the "hot" redundancy mode - they produce and supply electricity simultaneously.

- The critical load microgrid must include a generator for the entire required volume of critical loads.

Such a generator is used when the renewable portion of the microgrid fails for critical loads or in cold standby mode.

- All inverters and converters in the microgrid are redundant with "cold" redundancy to ensure uninterrupted power supply to the facility.

- wires, connectors, connectors and fuses will also be required to assemble the elements into a single microgrid.

- An intelligent control system for hybrid microgrid should preferably use artificial intelligence, but is not considered in this paper as well as microgrid control algorithms.

1.4 Conclusions to Chapter 1

1. The analysis of data from literature sources confirms the relevance and demand for the selected topic for research: microgrids as a way to overcome the shortcomings of the traditional power supply system are becoming increasingly popular around the world; the share of alternative energy, according to expert forecasts, will grow in the coming years. At the same time, consumers from the category of critical loads should receive uninterrupted power supply at any time of the day.
2. Long-term regular (up to 22 hours daily) power cuts from the central grid force Lebanon to look for other ways of obtaining affordable energy, the efficiency of which does not depend on the external geopolitical situation. Microgrids based on a combination

of standby generators (gas turbine or diesel) and renewable energy sources could be a solution. For Lebanon, taking into account the requirement of suitability for use throughout the country, such elements of micro-grids can be photovoltaic power plants, wind turbines, in most of the territory - small HPPs on local rivers.

3. Due to the difficulty in accurately calculating microgrid parameters, a number of assumptions and simplifications have to be made. As a prototype for the designed microgrid for critical loads, a hybrid microgrid consisting of several wind turbines and photovoltaic plants, energy storage systems, a hybrid inverter with the function of mixing different types of electricity, and the necessary electrical isolation is used. A more detailed calculation of the parameters of such a microgrid will be discussed below.

CHAPTER 2 - JUSTIFICATION AND DEVELOPMENT OF MICROGRID STRUCTURE FOR CRITICAL LOADS

2.1 Selection of methods for development

The following methods were used in this study: analysis, synthesis, analogy, comparison, systematic method, search for information on the Internet.

Analysis - dissection, decomposition of the object of research into its constituent parts. It is the basis of the analytical method of research. [60,61].

Synthesis is the connection of separate sides, parts of the object of research into a whole [60,61].

Analogy is a way of obtaining knowledge about objects and phenomena on the basis of the fact that they have similarities with others; reasoning, in which from the similarity of the studied objects in some features a conclusion is made about their similarity in other features [60,61].

Comparison - comparison of features inherent in two or more objects, establishing the difference between them or finding them in common [38, 39].

The system method consists in the study of a system (i.e., a certain set of material or ideal objects), the connections of its components and their links with the external environment [60,61].

Internet search method was also used to analyse the data from literature sources

Regarding the direct design of the microgrid structure, the following methods are appropriate:

1) Worst case calculation method for determining the operating mode of microgrid elements [59]

2) The average output method is used to determine the capacity of individual solar and wind power installations.

The choice of the worst case calculation method for determining capacity is due to the need to ensure that electricity demand is covered regardless of the season of the year.

The average production method is used to compensate for the imbalance between excess production in the summer months and insufficient production in the winter months.

In general, the *calculation methodology* used *in the design of a* renewable energy *microgrid* for critical loads may contain the following steps:

1. Determination of power and total energy consumption of critical loads

It can be obtained in two ways: by actually reading electricity meters for already operating facilities, or by setting a percentage of total energy consumption for facilities being designed and/or modernised.

In case of assignment, a threshold of 25 per cent of total energy consumption for educational institutions and 50 per cent for hospitals should be targeted.

In specialised facilities like cryopreservation, the entire energy consumption is critical loads

2. Determining the type of microgrid and its mode of operation

Three types of microgrids are proposed: AC, DC and hybrid. If there is insufficient information on the structure of electricity consumers, and if it is desired to provide for the transfer of surplus electricity to the centralised grid, it is recommended to use a hybrid grid.

The surplus is also fed back into the grid by the hybrid mode of operation, due to the use of an intelligent hybrid inverter with the function of feeding energy into the centralised grid.

3. Selection of redundancy scheme to ensure uninterrupted operation of microgrid for critical loads.

Part of the network is used in the "hot" redundancy mode, which, on the one hand, reduces the load on each of the elements of such a subnetwork, as they are used simultaneously, part in the "cold" redundancy mode, when the backup element is connected through a switching device that uses the control signal from the comparator.

4. Determination of the enlarged structure of the microgrid depending on the selected type and mode of operation and energy characteristics of the place of microgrid organisation.

At this stage, it is recommended to carry out additional exploratory studies aimed at developing an energy profile of the region where the microgrid elements are to be installed/modernised. It is strongly recommended to rely on renewable energy sources.

In the widest possible configuration, a microgrid with renewable energy sources may include a photovoltaic plant, a wind power plant, a solar heater, a small hydropower plant and/or a dam-less hydropower plant that does not require the construction of dams and dikes, a hydropower plant based on the energy of sea waves or geothermal sources, a biogas plant. In the minimum configuration it can be a photovoltaic plant or a wind power plant (in number of several pieces).

In addition, provision should be made for a standby generator to provide critical loads in the event that renewable energy installations fail or do not provide the required supply of electricity.

5. Selection of the microgrid control and management scheme and system (not discussed in detail in this paper)

6. Determining the required usable power for each of the microgrid elements.

At this stage, it is necessary to specify what percentage of the required useful power of the microgrid should be generated by each element of the microgrid. The previously obtained energy profile of the area, climatic and weather conditions and the state of the distribution network infrastructure are taken into account.

7. Determine the required rated and installed power of each of the microgrid elements using basic physical formulae.

The installed capacity is determined taking into account losses in inverters, batteries, and the requirement to provide a 20% power reserve for electrical equipment.

8. Refined definition of the microgrid structure - type and number of standby generators, solar panels, wind turbines, etc., allowing for the required rated capacities.

It is determined by taking into account the known unit power, for example, the power of one solar panel is 150W, to remove 1500W such panels will require 10 pieces.

9. Definition/calculation/selection of the serving infrastructure of the microgrid - type and number of converters, type and number of inverters, energy storage.

The type and method of installation of elements in a single microgrid, voltages and currents of supply and information signals, DC/DC, AC/DC, DC/AC converters, energy storage devices are taken into account.

10. Specifying the number of elements in the microgrid and the way they are connected

Recalculation of the previously calculated quantity taking into account the foreseen losses and the selected redundancy modes.

11. Calculation and selection of protection devices in a microgrid

12. Selection of devices and systems, in accordance with previous calculations, that allow for the integration of elements into a single microgrid for critical loads.

Items 11 and 12 are not considered in this paper.

Let's calculate the elements of the microgrid on solar-wind renewable energy in accordance with the described methodology.

2.2 Basis for development

It has already been reported in the previous chapter that Lebanon has a good potential for solar and wind energy development.

To determine an aggregated structure of renewable energy installations for a microgrid to supply critical loads in Lebanon, it is useful to analyse the prerequisites for each source in numbers.

Hydropower, biomass and experimental renewable energy resources are not considered in this paper as there is no reference to a specific region/city in Lebanon, and solar and wind energy installations are recommended for use throughout the country.

Tables 4-5 show the distribution of solar radiation intensity and duration of direct sunshine over Lebanon by month and by zone of the country [12, 13].

Table 4 - Daylight hours in Lebanon by month

№	Month	Average Sunlight Hours/ Day	Average Daylight Hours & Minutes/ Day	Percentage of Sunny (Cloudy) Daylight Hours		Sun altitude at solar noon on the 21st day (°)
1	january	4,22	10	42	58	36,3
2	february	5,05	11	47	53	45,6
3	march	6,15	12	52	48	56,4
4	april	8,1	13	63	37	68,1
5	may	10	14	73	27	76,4
6	june	11,6	14	82	18	79,6
7	july	11,6	14	83	17	76,6
8	august	10,77	13	81	19	68,3
9	september	9,6	12	79	21	56,8
10	october	7,9	11	71	29	45,3

Continuation of Table 4

11	november	6,67	10	65	35	36,2
12	december	4,73	10	48	52	32,8
13	Average	8,03	12	65,5	34,5	56,53

Table 5 - Solar incident radiation in Lebanon by zone and by month

№	Month	Irradioation data by climatic zone, W-h/m^2			Irradioation data average, W-h/m^2	Possible generated sun energy due to 21% efficiency of PVS, W-h/m^2	Average Sunlight Hours/ Day	Generated sun power data, W/m^2 in relation to sunlight hours
		COASTAL-BEIRUT	COASTAL - BAYSSOUR	INLAND				
1	january	2388,6	2129	2658,7	2392,1	502,34	4,22	119,04
2	february	2887,9	2628,3	3129,4	2881,867	605,19	5,05	119,84
3	march	4012,3	3767,6	4160,7	3980,2	835,84	6,15	135,91
4	april	5091,2	4883,7	5184,2	5053,033	1061,14	8,1	131,00
5	may	6311,9	6353,7	6995,6	6553,733	1376,28	10	137,63
6	june	6193,4	6044	7328,2	6521,867	1369,59	11,6	118,07
7	july	6674,9	6255,7	7329,7	6753,433	1418,22	11,6	122,26
8	august	5790,9	5254,4	6579,5	5874,933	1233,74	10,77	114,55
9	september	4732,8	4853,9	5532,5	5039,733	1058,34	9,6	110,24
10	october	3571	3883,3	4083	3845,767	807,61	7,9	102,23
11	november	2977,1	3175,9	3340,4	3164,467	664,54	6,67	99,63
12	december	2005,6	2144	2215,6	2121,733	445,56	4,73	94,20
13	Average	4386,467	4281,125	4878,125	4515,239	948,20	8,03	117,05

To date, the efficiency of solar panels ranges from 18% to 24% [62]. For the calculations in this paper, we take the panel efficiency of 21% as the middle of the range and a technically achievable figure.

Table 4 shows that the minimum duration of direct sunshine time is observed in January and is 4 hours per day.

However, the minimum intensity of sunshine is observed in December, not January, and the total solar energy production in these months may be comparable.

Therefore, for further calculations we will use the worst-case method - the duration and intensity of sunshine will be taken by December.

Thus, when calculating the required capacity of a solar power plant, we start from the fact that it should supply the fully required amount of kWh of energy in 4 hours in combination with a wind power plant, the operating time of which is conventionally taken as 10 hours.

The commercially reasonable wind speed is approximately 5m/s or 18km/h [62]. Let us compare the duration of open sunshine and the duration of commercially reasonable winds in Lebanon by month according to Table 6.

Table 6 - Summary of solar radiation and wind speed in Lebanon by month [12, 13]

№	Month	Average Sunlight Hours/ Day	Average Daylight Hours & Minutes/ Day	Irradioation data average, W-h/m^2	number of days with wind speeds of 18 km/h
1	january	4,22	10	2392,1	5,3
2	february	5,05	11	2881,867	5,2
3	march	6,15	12	3980,2	8
4	april	8,1	13	5053,033	12,1
5	may	10	14	6553,733	11,5
6	june	11,6	14	6521,867	8,5
7	july	11,6	14	6753,433	6,2
8	august	10,77	13	5874,933	4,8
9	september	9,6	12	5039,733	7,8
10	october	7,9	11	3845,767	11,8
11	november	6,67	10	3164,467	9,2
12	december	4,73	10	2121,733	6,5
13	Average	8,03	12	4515,239	8,075

Table 6 shows that the maximum of windiness almost coincides with the maximum of sunshine, so due to the different complexity of technology implementation, we take solar PV panels as the main source and wind turbines as an additional source. A more precise ratio of capacities will be determined further on.

2.3 Determination of the structure and calculation of the minimum required parameters of the designed microgrid for critical loads

So, based on the above and according to the proposed methodology:

1. Energy consumption of critical loads

We assume the power consumption of critical loads to be constant and independent of the **time of year.**

It is stated in [63] that a 540kW PVS plant covers 70% of the electricity demand of Martyr Salah Ghandour Hospital in Bint Jebeil, South Lebanon.

These figures will be used in the calculations, as they will be different for each particular hospital or school, but they will be quite suitable for demonstrating the calculation algorithm.

Then, according to the rules of mathematics, the total power required at this facility is (1):

$$P_{full} = \frac{P_{PVS}}{0,7} = \frac{540000}{0,7} = 771428,5(W) \tag{1}$$

Then the power consumed by critical loads according to methodology 2.1 (2):

$$P_{crit} = P_{full} \cdot 0,5 = 771428,5 \cdot 0,5 = 385714,29(W) \tag{2}$$

The same power is provided by the main part of the microgrid, which is not considered in this paper, but it is also quite possible to design it based on renewable energy sources.

2. Determining the type of microgrid and its mode of operation

Since the designed microgrid ideally not only supplies critical loads but also feeds the surplus to the central network, we choose a hybrid microgrid in hybrid operation mode.

3. Selection of microgrid redundancy scheme

The power sources in the microgrid will operate in the "hot" redundancy mode, i.e. simultaneously, while inverters and converters from one type of current to another - in the "cold" redundancy mode using switching contacts.

The use of "hot" redundancy for energy sources allows each of them to be designed for less useful and installed capacity, i.e. to minimise costs. Parallel operation of all energy sources allows supplying not only critical but also non-critical loads.

4. Determination of the enlarged microgrid structure

At this stage it is necessary to decide on the type of renewable and non-renewable energy sources for the microgrid.

Based on the data in Chapter 1, in this paper the designed microgrid will include:

- supply from centralised AC230V network
- standby petrol or gas turbine generator
- photovoltaic systems
- wind turbines
- servicing infrastructure - inverters, converters, batteries as energy storages.

5. Selection of the scheme and system for monitoring and controlling the microgrid

Decentralised management scheme, this stage is not discussed in more detail in this paper

6. Determining the required usable power for each of the microgrid elements.

Generator.

The useful capacity of the generator must fully cover the power consumption of the critical loads. Then the useful capacity of the standby gas turbine or petrol generator (3):

$$P_{gen} = P_{crit} = 385714,29(W) \tag{3}$$

Let's define the useful capacity of PV and solar installations.

To do this, we need to set the percentage of power in the solar-wind system.

Given the data in Chapter 1 of this paper, we assume a 75%/25% ratio - 75% of the critical load power should be provided by PV and 25% by wind.

Then the minimum required power from solar and wind power plants is determined by expressions (4) and (5):

$$P_{sun} = 0,75 \cdot P_{crit} = 0,75 \cdot 385714,29 = 289285,71(W) \quad (4)$$

$$P_{wind} = 0,25 \cdot P_{crit} = 0,25 \cdot 385714,29 = 96428,57(W) \quad (5)$$

Thus, a photovoltaic plant with 289.286kW of useful capacity and a wind power plant with 96.429 kW of useful capacity are to be calculated.

The rated plant capacities, types and characteristics of solar panels, wind turbines, converters, inverters and other microgrid elements for critical loads will be specified in Chapter 3.

This is due to the fact that the nominal (installed) capacity of such installations depends on the losses in the distribution network.

Losses, in turn, depend on the number and method of installation of solar panels and parameters of wind turbines, rated voltage and current in the grid, selected cables, fuses, inverters, etc.

In this case, the type and method of installation of solar panels should be determined first.

The structural diagram of the designed microgrid is shown in Appendix A.

2.4 Conclusions to Chapter 2

1. The process of designing a microgrid for critical loads can be broken down into several stages, with the ability to take into account all influencing factors, including the state of conventional and unconventional energy at the microgrid location, climatic, seismic and weather conditions.
2. For the designed microgrid for critical loads with operation in the conditions of the Republic of Lebanon, it is advisable to use a hybrid microgrid in hybrid mode of operation - this will allow to fully cover the energy demand of critical loads and give the surplus energy to the centralised power supply network.
3. The enlarged structure of the projected microgrid includes a centralised grid, photovoltaic plants, wind power plants, a backup diesel or gas turbine generator, and service devices.
4. According to weather and climate data, the lowest intensity of sunshine in Lebanon is observed in December, while the shortest daylight hours are observed in January. However, due to the difference in sunshine intensity, the minimum output of the PV plant will also be observed in December. Therefore, for the calculation of useful and installed PV capacity using the worst case method, the data for December is used.
5. The ratio of useful capacities of photovoltaic and wind power plants is assumed to be 75% and 25%, as the construction of large-scale wind turbines requires consideration of technological difficulties and high starting wind speeds. The capacity of the standby generator should be such that it can fully cover the needs of critical loads.

CHAPTER 3 - ADJUSTMENT OF PARAMETERS OF THE ELEMENTS OF THE DEVELOPED MICROGRID FOR CRITICAL LOADS

3.1 Determination of the rated capacity of solar and wind power plants for the microgrid being developed

Let's continue the calculation according to the previously proposed methodology.

7. Determination of the required nominal and installed power of each of the microgrid elements using basic physical formulae

Photovoltaic installation.

To select specific solar panels, it is necessary to calculate the required receiving surface area and determine the specific power of the panels and their overall dimensions.

For this purpose, the required daily output from the PV plant must first be calculated.

Since power cuts from the centralised grid reach up to 22 hours per day in Lebanon, according to the worst case calculation method, we consider the operating time of the PV plant to be 22 hours.

The required generation value (energy consumption per day) of a PV plant can be found as the product of the required useful solar capacity by the number of hours of operation (6):

$$E_{day} = P_{sun} \cdot 22 = 289285,71 \cdot 22 = 6364285 \approx 6364,29(kW \cdot h) \tag{6}$$

Then the required capacity of the PV plant, taking into account the hours of direct sunshine in December, is determined by expression (7):

$$P_{req.sun} = \frac{E_{day}}{t_{\min}} = \frac{6364,29}{4,73} = 1345,51(kW) \tag{7}$$

However, losses in the battery, inverters and inverter must also be considered. Modern batteries have power transfer efficiencies of up to 98%. And the efficiency of the best inverter models reaches 0.995 or 99.5%.

Then, taking into account all transmission losses, the total required power of the PV power plant (8):

$$P_{req.sun.full} = \frac{\frac{P_{req}}{0,995}}{0,98} = \frac{\frac{1345,51}{0,995}}{0,98} = 1379,8738 \approx 1380(kW) \tag{8}$$

And it amounts to 1.38MW.

Backup generator.

The standby generator should have a 20% margin in rated power over useful power, just like any conventional electrical equipment [Al Hassan].

Therefore, the rated capacity of the standby gas turbine or diesel generator (9):

$$P_{gen} = P_{crit} \cdot 1,2 = 385714,29 \cdot 1,2 = 462857,14(W) \tag{9}$$

460kW is suitable as the installed capacity of the standby generator

Wind turbine.

According to chapter 2, its useful power should be at least 96.429kW. Again, to ensure that the losses on the battery are taken into account, we take the nominal power of the wind turbine (10):

$$P_{wind.full} = \frac{P_{wind}}{0,98} = \frac{96,429}{0,98} = 98,39694(kW) \tag{10}$$

It is quite possible to stop at an installed capacity of 100kW for wind turbines.

Thus, the microgrid to meet the critical loads with energy consumption of 6364.29kWh per day, requires the following rated and installed capacities:

- 1.38MW from photovoltaic plant
- 460 kW from standby generator
- 100 kW from a wind turbine

3.2 Refined definition of the microgrid structure

8. Refined definition of the microgrid structure - type and number of standby generators, solar panels, wind turbines, etc., allowing for the required rated and installed capacities.

Let's start with the photovoltaic system.

It seems reasonable to use rigid monocrystalline solar panels with a fixed installation angle to the horizon, approximately equal to the geographic latitude of the installation site.

For the selection of solar panels, it is necessary to take into account the area of the receiving surface, the power and the overall dimensions of a single solar panel.

We determine the required receiving surface area based on the solar intensity density in December and the required solar power (11):

$$S_{PV} = \frac{P_{req.sun.full}}{94,20} = \frac{2253790}{94,20} = 14648,4(m^2) \tag{11}$$

That is, at least 14648.4 m^2 of PV panel surface must be utilised.

Other factors influencing the choice of solar panels are described in [18] in some detail.

Let's carry out a comparative analysis of several models of solar panels with different sizes and power. The results will be entered in Table 7 [64-70]

Table 7 - Towards the selection of solar panels

Parameter	Solar panels						
	AC-545MH/144V (545W)	**BSM550M10-72HBD (550W)**	**CS6W-550MS (550W)**	**HT72-18X-550 Transparent (550W)**	**LR5-72HTH-585M (585W)**	**TSM-555DE19 (555W)**	**ZXM7-SHDB144-555/M (555W)**
STC Power Rating	545W	550W	550W	550W	585W	555W	555W
PTC Power Rating	510.1W1		521.96W2	515.74W3	553.8W4	522.98W5	
STC Power per unit of area	19.6W/ft2 (211.0W/m2)	19.7W/ft2 (212.3W/m2)	19.9W/ft2 (214.5W/m2)	19.7W/ft2 (212.4W/m2)	21.0W/ft2 (226.5W/m2)	19.7W/ft2 (212.4W/m2)	20.0W/ft2 (214.8W/m2)
Peak Efficiency	21.1%	21.23%	21.45%	21.24%	22.65%	21.24%	21.48%
Isc	13.93A	14A	14A	14A	14.27A	18.56A	13.95A
Voc	49.75V	49.92V	49.6V	49.8V	52.36V	38.1V	50.4V
Series Fuse Rating	25A	30A	25A	25A	25A	30A	30A
Maximum System Voltage	1500V	1500V	1500V	1500V	1500V	1500V	1500V
Type	Monocrystalline Silicon	Monocrystalline Silicon	Mono PERC	Mono PERC	Monocrystalline Silicon	Monocrystalline Silicon	Mono PERC
Electricity cost based on the cost of the panels, USD/Wp	0,67	0,25	0,195	0,46	0,18	0,20	0,22

According to the combination of characteristics from Table 7, we choose to use LR5-72HTH-585M solar panels.

Their overall dimensions are 2.278m×1.134 m. Then the area of one panel is (12):

$$S_{panel} = 2,278 \cdot 1,134 = 2,58 (m^2) \tag{12}$$

And the number of panels required is determined by the ratio of the required receiving surface area to the area of one panel (13):

$$n = \frac{S_{PV}}{S_{panel}} = \frac{14648,4}{2,58} = 5677,68 \approx 5678 (pcs) \tag{13}$$

It remains to be seen whether this number of panels will give the required power rating (14):

$$P_{sun.check} = n \cdot P_{panel} \cdot 0,98 \cdot 0,995 = 5678 \cdot 500 \cdot 0,98 \cdot 0,995 = 2768308,9 (W) \approx 2,77 (MW) \tag{14}$$

I.e. almost twice the required capacity. We decide to limit the number of solar panels to 5000. Then the power generated by them is (15):

$$P_{sun.check} = n_1 \cdot P_{panel} \cdot 0,98 \cdot 0,995 = 5000 \cdot 500 \cdot 0,98 \cdot 0,995 = 2437750(W) \approx 2,438(MW) \quad (15)$$

Also much more than is required. However, further limiting the quantity does not seem appropriate, as there will still be other infrastructure losses unique to each case when the actual panels are installed in PV installations. Thus, the seemingly excessive capacity margin guarantees uninterrupted power supply to critical loads from the solar power plant.

The parameters of the photovoltaic system are 5,000 solar panels with a total generated capacity of 2.438 MW.

Wind turbines.

It was mentioned earlier that the installed capacity of wind turbines is 100 kW.

A distinctive feature of wind power is that it can be more cost-effective to put in several low-power generators than one higher capacity one.

For verification, we summarise the parameters of different wind turbines with a total capacity of 100 kW in Table 8 [71-75].

Table 8 - Towards the selection of wind turbines

Parameter	Wind turbines					
	Horizontal-axis wind turbines Condor Air Series	Horizontal-axis wind generators Condor Air Series	Ryse Energy E-20	Aeolos wind turbine	ROSVETRO FK-20K	Horizontal-axis wind generators Condor Air Series
Unit power, kW	20	50	20	50	20	10
Quantity, pcs	5	2	5	2	5	10
Total power, kW	100	100	100	100	100	100
Starting wind speed, m/s	2.5 metres per second	2	2	2,5	3	2
Operating wind speed, m/s	3-20	3-20	2-30	2,5-59,5	3-13	3-20
Wind speed for rated power, m/s	7,5	8	11	9	12	7,5
Price, USD	13664	33716	-	-	29575	9109
Cost, USD	68320	67432	-	-	88725	91090

As shown in Table 8, it is economically and technologically more favourable to put 2 wind turbines of 50 kW rated capacity rather than 5 generators of 20kW or 10 generators of 10 kW.

Thus, the projected microgrid for critical loads will comprise 2 horizontal-axis wind turbines of "Condor Air" series with nominal (installed) capacity of 50 kW each. In addition, it is characterised by a lower starting wind speed.

The nominal wind speed for this wind turbine is 8m/s. It is clear that the corresponding nominal power and output will not be observed for the entire time of operation of the wind generator, and here the power reserve from solar panels provided in the calculations is very favourable.

Backup diesel or gas turbine generator.

Due to higher power efficiency, possibility to work for a long time without interruption, lower fuel cost of diesel generators in comparison with gas turbine generators [76], we decide to use a diesel generator with installed active capacity of 460 kW as a backup generator.

Table 9 summarises the characteristics of different models of diesel generators.

Table 9 - Towards the selection of a diesel generator [77-79]

Parameter	Generator		
	AD-460S-T400-1RM23	AKSA AD630	FOGO FDG 600 D
Rated active power, kW	460	460	460
Total power, kVA	575	575	575
Generator type	three-phase	three-phase	three-phase
Execution	Open on frame	Open on frame/in protective cover	encased
Operating voltage, V	230/400	220/380	230/400
Frequency, Hz	50	50	50
Fuel consumption at 100% load, l/hour	118,5	123	123,6
Price, USD	81714	78098	45250

Despite the higher fuel consumption at 100% load, we choose to use a FOGO FDG 600 D diesel generator in the microgrid, which is characterised by almost half the cost. Total refined structure of generating capacities in the microgrid includes:

1) Centralised power supply network
2) 5,000 LR5-72HTH-585M solar panels with a total capacity of 2.438 MW
3) 2 Condor Air series horizontal-axis wind turbines of 50kW each with a total capacity of 100 kW
4) FOGO FDG 600 D diesel generator with a nominal active power of 460 kW.

3.3 Determination of parameters of the serving infrastructure for the developed microgrid

9. Determination/calculation/selection of microgrid serving infrastructure - type and number of converters, type and number of inverters, energy storage units

The concept of service infrastructure in the projected microgrid includes:

- ACB
- AC-to-DC converters for wind turbines
- hybrid three-phase inverter with mixing function
- MRRT solar controller

Fuses, connectors, switching contacts, fasteners and trusses for mounting the solar panels and wiring must also be provided. However, these issues are not dealt with in detail in this paper, as their parameters depend very much on the characteristics of the locations and distance from each other of the microgrid elements.

It is strongly recommended to use a microgrid monitoring and control system for critical loads based on advances in artificial intelligence. This issue was also not considered in this paper.

Battery

The batteries in the system will be of two types - for the solar part and for the wind part.

Battery for wind turbine generator

For wind turbines, the manufacturer recommends the use of 40 battery packs with a capacity of 200 Ah each for each wind turbine. A total of 80 batteries of 200 Ah each will be required for two wind turbines.

We select Vektor VPbc12-200 200 Ah 12V battery in the amount of 40 batteries for 1 wind generator [80].

Batteries for solar panels.

In a worst case calculation, the solar panel batteries should be able to charge in 4 hours per day (in winter).

Considering the capacity of the solar plant is 2.43 MW with the required 1.38 MW, this leaves an "extra" capacity of 1.05MW.

With a charging time of 4 hours we get a capacity of 4.2 MWh. It becomes necessary to use not even a battery, but a BESS as it is more suitable for such capacities.

In this case, theoretically, a battery or BESS should be able to supply critical loads during the dark and windless hours of the day, which in winter is about 8 hours (24h day minus 10h theoretical windiness and 4h sunshine).

Then the required capacity is determined by the power consumption of the critical loads during this time (16):

$$C = \frac{E_{day}}{t} \cdot t_1 = \frac{6364,29}{22} \cdot 8 = 2314,28(kWh) \qquad (16)$$

Or 2.315MWh or .

BESS brand 40FT- ESS container soltuion 1.8MWH 716.8V/2500AH with capacity of 1.8MWh in quantity of 1 piece [81] is suitable. Voltage 716V, charging current 1250A.

And then there's an additional 1.2MWh BESS of the same line.

The total capacity will be 3.0MWh even with power and capacity reserves. The excess energy generation after charging the BESS is fed back to the grid via an inverter.

AC to DC converters for wind turbines

Selected 50kW wind generators should be equipped with controllers (AC to DC converters for battery charging) 100KW AC to DC Rectifier System Converter Battery Charger [82]. The input voltage is 380-530V from a wind generator. Output voltage from 150 to 750V.

Inverters.

The designed microgrid will use two modifications of hybrid three-phase inverters with power mixing function - for the PV plant and for the wind generator.

Let's start with the wind turbine.

Three phase Pure sine wave inverter Three phase Pure sine wave inverter;50kw DC input:360v is quite suitable for this purpose. [83]. Output current 15-20A, output voltage 380-415V.

Inverters for photovoltaic power plant.

According to [81] it is possible to use such an inverter for a photovoltaic power plant - Pure sine wave 500KW inverter with a layout of 3 inverters in a container, which in total gives 1.5MW, i.e. to the required 2.34MW it is necessary to increase the number of inverters.

MPPT solar controller.

The MPPT controller of the same company as BESS - MPPT PV On grid inverter model: 125KW*12 [81] with 125kW modules arranged in 12 units, i.e. the total power of the controller will be about 1.5MW. If two such controllers are used, all the required power will be covered.

10.Specifying the number of elements in the microgrid

Under all assumptions, refinements, power transfer margin, and efficiency, a renewable microgrid structure for a 385.714kW critical load power consumption, not counting protection apparatus, fixtures, and other associated minor items, would include:

1) 5,000 LR5-72HTH-585M solar panels with a total capacity of 2.438MW
2) 2 Condor Air series horizontal-axis wind turbines of 50kW each with a total capacity of 100kW
3) FOGO FDG 600 D diesel generator with a nominal active power of 460kW.
4) 80 Vektor VPbc12-200 carbon 200Ah 12V batteries (40 for each wind turbine).
5) 1 BESS brand 40FT- ESS container soltuion 1.8MWH 716.8V/2500AH with a capacity of 1.8MWh
6) 1 BESS brand 40FT- ESS container soltuion 1.2MWH 716.8V/2500AH with a capacity of 1.2MWh
7) 1 100KW AC to DC Rectifier System Converter Battery Charger - wind turbine controller, one per total capacity
8) 2 three phase inverters Three phase Pure sine wave inverter;50kw DC input:360v
9) 4 three-phase Pure sine wave 500KW inverters with 3 inverters per container, giving a total of 1.5MW

The number of inverters is doubled because the microgrid uses a cold redundancy scheme of inverters to guarantee the transfer of stored power to the grid.

10) 2 MPPT PV On grid inverter model:125KW*12
11) Switching contacts, fuses, comparators, etc.

Items **11 and 12 of the calculation methodology have** not been considered in this paper.

3.4 Conclusions to Chapter 3

1. The rated capacities of the microgrid components for critical loads are determined from the required output during the time of microgrid power generation and the minimum possible time of efficient use of renewable energy sources.
2. The installed or nameplate capacities of the microgrid elements for critical loads exceed the nominal capacities. The degree of excess depends on the required power reserve of the installation. For a standby generator this reserve is 20 per cent, for solar and wind installations it is determined by the power efficiency of the inverter and the battery.
3. Critical loads of 385.17 kW will require a microgrid with a rated solar plant capacity of about 2.38MW, installed capacities of standby generator and wind turbines of 460kW and 100kW respectively.
4. The choice of the brand and number of solar panels is determined by several factors, including the host surface area standard, the efficiency of the solar panel, the power rating of a single panel, and the required power rating of the entire PV system. For the considered critical load microgrid with a useful capacity of 1345.51kW (1.345MW), it is sufficient to use 5000 LR5-72HTH-585M (585W) solar panels with a total generated power of 2.438MW.
5. FOGO FDG 600 D diesel generator with a nominal active power of 460kW was selected as a standby generator. The main advantage of diesel generators over gas turbine generators is their higher efficiency and the ability to work in a long period of time without stopping. An additional advantage of the selected generator is its design in a protective casing.
6. The wind turbines used in the microgrid are horizontal axis wind turbines of "Condor Air" series, 2 units of 50kW each with a total capacity of 100kW, starting wind speed of 2m/s, which makes it possible to include such wind turbines in microgrids throughout Lebanon.
7. The designed microgrid for critical loads will also include Vektor VPbc12-200 carbon 200Ah 12V battery, BESS 40FT- ESS container solution 1.8MWH 716.8V/2500AH and 40FT- ESS container solution 1.2MWH 716.8V/2500AH, Three phase Pure sine wave inverter;50kw DC input:360v and Pure sine wave 500KW inverter, MRRT solar controller MPPT PV On grid inverter model:125KW, 24 inverters 1 100KW AC - DC Rectifier System Converter Battery Charger. The number of these elements is determined by the redundancy scheme and the way the elements are installed in a single network.
8. It is highly recommended to provide an intelligent monitoring and control system for the designed microgrid for critical loads.

CONCLUSION

This master thesis addressed the development and design of microgrids for critical loads with the operation of the microgrid under the conditions of the Republic of Lebanon.

The current state and prospects of alternative energy development in the Republic of Lebanon were studied, the experience of similar developments in a number of other countries was analysed, and the simplifications and assumptions used in carrying out the work were determined, since the task at hand is complex and complex, due to the multivariant nature of the layout of microgrid elements and their characteristics. Multivariability is caused by different influencing factors that determine the expediency of using one or another energy source in specific locations where microgrid elements are installed.

The analysis of data from literature sources confirms the relevance and demand of the selected topic for research: microgrids are becoming more and more popular all over the world, as they are distributed energy sources, are equipped with capacity reserves, are able to overcome the disadvantages of the traditional system, regular power outages in the Republic of Lebanon can reach 22 hours a day, but consumers included in the list of critical loads should receive uninterrupted power supply at any time of the day.

Preferably, the main capacities generated in microgrids should be obtained from renewable energy sources. It is recommended to consider energy from photovoltaic installations, wind generators as the main RES for the Lebanese Republic, and energy from small HPPs on local rivers, including damless types of HPPs for the most part of the territory.

Methods for the research were also selected, and a methodology for calculating microgrid elements and characteristics for critical loads that sufficiently accounts for this multivariation was proposed.

Due to the possibility not only to cover the power needs of the critical loads object, but also to return the excess energy to the centralised grid, as well as due to the presence of mixed AC and DC consumers, a hybrid grid in hybrid operation mode, which is ensured by the presence of hybrid grid inverters, is adopted for development.

According to the simplifications and assumptions adopted, an enlarged and then a more detailed microgrid structure was proposed using the energy consumption data of a real critical load facility as an example.

The aggregated structure of the proposed microgrid includes photovoltaic systems, wind turbines, backup diesel generator, energy storage, converters, inverters. Smaller elements of the microgrid - wires, fasteners, trusses for installation of solar panels, protection devices were not considered in this paper.

In order to guarantee critical loads, the minimum generation data for solar energy and average data for wind power plants were used to calculate source capacities. Due to the varying degrees of complexity of technology implementation, it is suggested that 75% of the critical loads be covered by solar power and 25% by wind power.

A diesel generator is included in cases where energy generation from renewables is difficult, minimized or impossible. Its capacity is selected to fully cover the energy demand of critical loads.

On the example of a specific object the approximate calculation of parameters and characteristics of the main elements of the microgrid was made.

A facility with a critical load capacity of 385.715 kW will require a microgrid consisting of: 5000 solar panels LR5-72HTH-585M (585W) with a total generated capacity of 2.438 MW, 2 Condor Air series horizontal-axis wind turbines with a total capacity of 100 kW, 1 FOGO FDG 600 D diesel generator with a rated active capacity of 460kW, 80 Vektor VPbc12-200 200Ah 12V batteries, 1 BESS brand 40FT- ESS container solution 1.8MWH 716.8V/2500 AH with a capacity of 1.8MWh, 1 BESS brand 40FT- ESS container solution 1.2 MWH 716.8V/2500 AH with capacity of 1.2 MWh, 1 100KW AC - DC Rectifier System Converter Battery Charger for 100 KW rated wind generator, 2 three phase inverters for 100KW wind generator, 8 three phase inverters of 500 KW each, 2 MPPT PV On grid inverter model:125 KW, 24 units for solar panels.

Verification calculations have shown that in such a configuration the designed microgrid not only provides critical loads, but is also capable of feeding the centralized grid.

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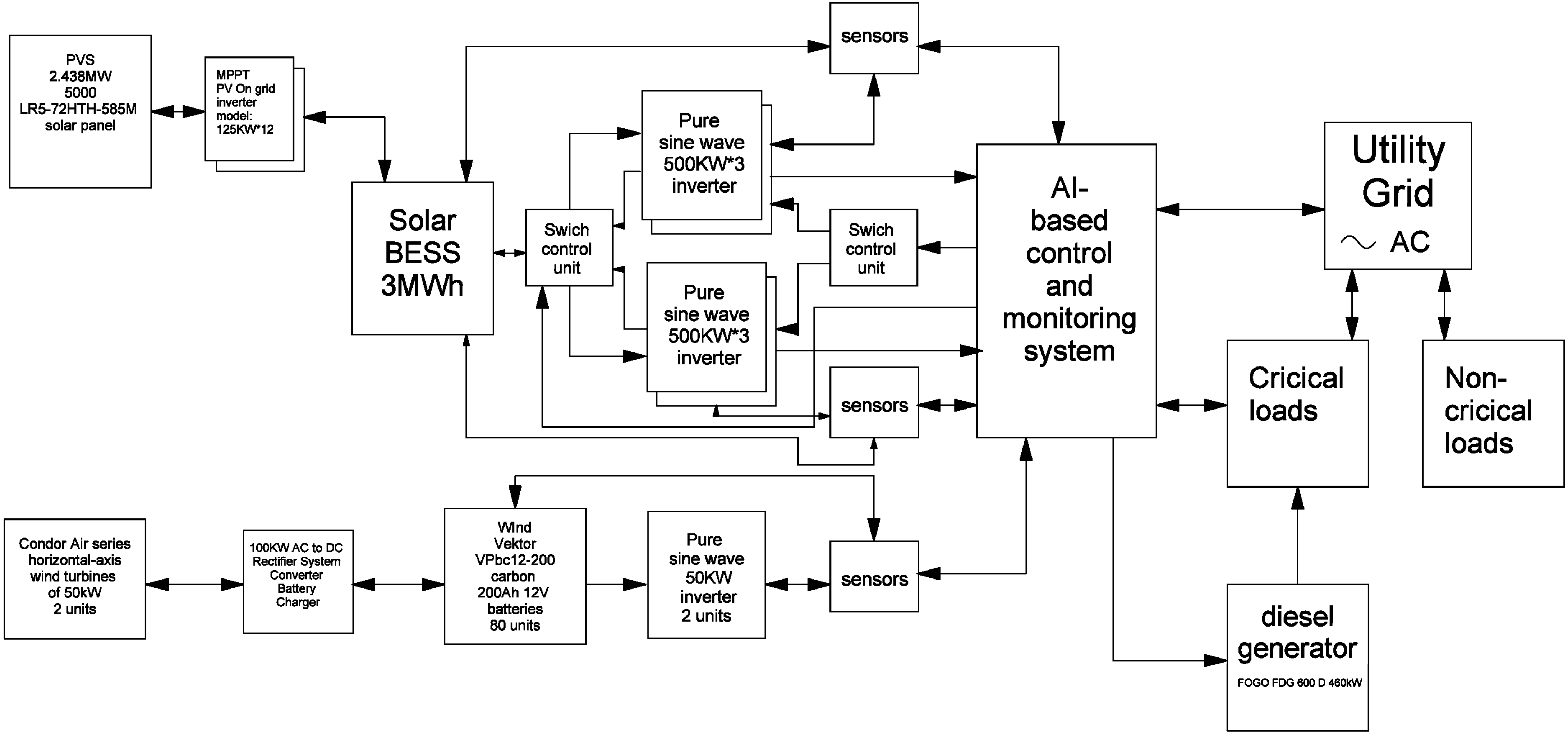
APPENDIX A
ELECTRICAL STRUCTURAL DIAGRAM OF THE DEVELOPED MICROGRID FOR CRITICAL LOADS


PVS
2.438MW
5000
LR5-72HTH-585M
solar panel
MPPT
PV On grid
inverter
model:
125KW*12
sensors
Pure
sine wave
500KW*3
inverter
Solar
BESS
3MWh
Swich
control
unit
Swich
control
unit
Pure
sine wave
500KW*3
inverter
AI-
based
control
and
monitoring
system
Utility
Grid
AC
sensors
Cricical
loads
Non-
cricical
loads
Condor Air series
horizontal-axis
wind turbines
of 50kW
2 units
100KW AC to DC
Rectifier System
Converter
Battery
Charger
WInd
Vektor
VPbc12-200
carbon
200Ah 12V
batteries
80 units
Pure
sine wave
50KW
inverter
2 units
sensors
diesel
generator
FOGO FDG 600 D 460kW