AMERICAN UNIVERSITY OF BEIRUT

ECONOMIC FEASIBILITY OF ALTERNATIVE GREEN TECHNOLOGIES DEPLOYED TO ACHIEVE 2030 UNSDG TARGET

by
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ABSTRACT
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In the twenty-first century, the world is experiencing an essential increase in energy consumption. Factors contributing to this significant crisis are a rise in population, advancement of technology, and economic development. The current trend causes rapid depletion of the earth’s resources and increasing carbon dioxide emissions. Primary activities harming the environment are burning traditional energy resources like fossil fuels.

The main objective of this study is to examine and assess different scenarios for the energy composition in Lebanon, emphasizing their efficacy and economic viability. This will be accomplished through a thorough assessment and utilization of renewable energy sources to facilitate the shift towards sustainable energy in compliance with the UN 2030 SDGs Target.

This thesis aims to conduct a comprehensive study employing a multifaceted strategy, integrating extensive analysis and practical application. The assessment will evaluate many alternative technologies, including solar, wind, and hydropower, to establish their matching operations in the Lebanese context. The study aims to assess the cost-effectiveness of implementing these technologies, considering installation capital costs (capex), operation and maintenance costs (opex), and energy production.

This thesis will assess Lebanon's transition to clean energy as an imperative step toward attaining the 2030 SDGs targets while promoting economic viability and correlating the most cost-effective energy mix. By assessing alternate technologies, the research aims to supply practical perceptivity that will lead the country toward a sustainable and economically feasible clean energy future.

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ABBREVIATIONS

SDG	Sustainable Development Goal
EDL	Electricite du Liban
PV	Photovoltaic
CSP	Concentrated Solar Power
GHG	Greenhouse Gas
GW	Giga-watt
MW	Mega-watt
kW	Kilowatt
GWh	Giga-watt hour
IRENA	International Renewable Energy Agency
NREAP	National Renewable Energy Action Plan
UNDP	UN Development Program
UN DESA	UN Department of Economics and Social Affairs
LCEC	Lebanese Center for Energy Conservation
BRSS	Beirut River Solar Snake
EPC	Engineering, procurement, and construction
PPA	Power Purchase Agreement

CHAPTER 1

INTRODUCTION

Frequent and long power outages have been a common experience for the Lebanese people, not only amid the protests but before the COVID-19 pandemic, extending even earlier (Human Rights Watch, 2023). The problems in the country's electrical industry are complex and longstanding. EDL's disruptions exposed a staggering level of technical inefficiencies in the transmission and distribution systems, creating an ever-extending gap between electricity availability and demand. The root of the current challenges in Lebanon's power section, however, does not stem from capitalism but from the civil war, which took place between 1975 and 1990to and inflicted enormous damage to EDL's infrastructure, which included generation, transmission and distribution capacities.

Therefore, significant investment was made during the peacebuilding phase following the Lebanese Civil War, with most of it focusing on the increasing power-generating. This resulted in a growth of 900 MW between 1990 and 1998 (World Bank Group). However, these and subsequent governments, preoccupied with other urgent matters, provided only minimal consideration to the needs of transmission and distribution networks and EDL's longstanding financial problems. This negligence resulted in massive difficulties and forced the Lebanese to struggle with an insufficient and unreliable electricity supply.

Consequently, executing a new energy mix in Lebanon may catalyze vital change, creating opportunities to conserve and utilize power effectively. Specifically, the implementation comprises power conservation during power inadequacies and the development of an innovative framework, the government's pursuit of a well-rounded and self-maintainable energy portfolio, and such optimism should be displayed. The new policy introduces a paradigm that emphasizes additional deployment of renewable sources and renewable energy efficiency. Its purpose is to reduce electricity use and reliance on gas power plants and provide a more sustainable and environmentally favorable energy source for the country. (IRENA, 2020).

Renewable resource exploitation benefits two-fold: it saves formation and influences the natural environment (Alsharif, Kim, & Kim, 2018). Initially, saving energy is a more reasonable objective and cost-effective energy policy than creating added energy due to demand, making it effective for the 2030 target. Even more importantly, the deployment of RE, such as wind, solar, and hydropower in Lebanon, may not only reduce GHG emissions but also contribute to energy supply and demand instability. Through these strategies, Lebanon may push its energy autonomy and GHG generation objectives further while enhancing the attainability of the SDG to a more economically secure and dependable future.

The results of implementing a new mix of energy sources in Lebanon means diverse preferences, given compatible economic feasibility and compliance with the 2030 SDGs target. On the one hand, diversifying energy sources can decrease the reliance on imports of expensive and volatile fossil fuels and thus stabilize energy costs and increase energy security from a financial point of view (IRENA, 2020). On the other hand, the transition to alternative energy means progress and the creation of new jobs simultaneously. It can boost the growth of traditional, sustainable energy sources and encourage innovations. Moreover, it also means greater energy efficiency, saving money for both consumers and businesses.

From an ecological perspective, the transition to reliable and inexpensive energy sources can reduce Lebanon's carbon and GHG emissions, mitigate air pollution, and ensure environmental sustainability. This way, the shift makes use of natural resources more effectively, helping to achieve SDG goals of affordable and clean energy, climate action, and sustainable economic growth, and it shows that it is essential to make Lebanon's future more sustainable and affordable.

Moreover, the shift substantially impacts society, making renewable energy more widely available (UN, 2018). It means closing the energy deficit gap for native peoples, increasing their quality of life, and making economic development possible. Thus, the alternative energy transition is essential for addressing climate change, protecting energy security, promoting economic development, ensuring job creation and social equality, and making a sustainable and inclusive future possible.

The Zahle Solar Power Plant in Lebanon's Bekaa Valley reflects the possibilities of using renewable energy sources and backup generators to regulate electricity supply and demand (Sewell, 2021). a giant photovoltaic solar panel system collects large quantities of sunlight and feeds it into the local power grid during the day. In the evening or when the sun is obscured by cloud cover, fossil fuel-powered backup generators take over, running on diesel fuel. This combination ensures a continuous energy supply to the population and companies while simultaneously reducing the country's reliance on traditional energy sources. Thus, it fully complies with SDG and demonstrates Lebanon untapped potential of sustainable energy solutions.

The installed capacity versus peak demand, as depicted in Figure 1 from 2016 to 2018, underscores the substantial challenges posed to the country.

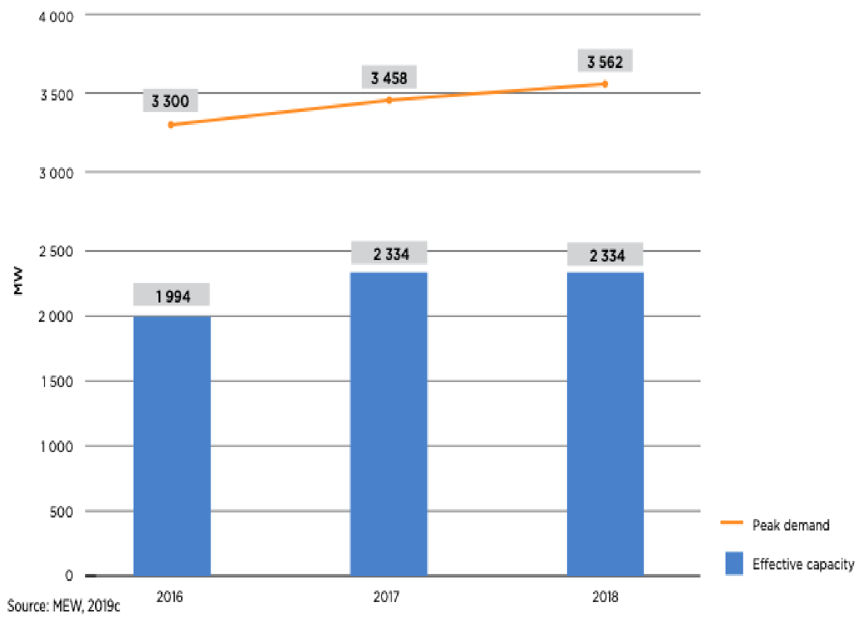

Figure 1: Installed capacity versus peak demand

There was a massive disparity in Lebanon between the electrical capacity produced and the energy demanded from 2016 to 2018. Power generation capacity struggled to adjust as peak electrical demand kept increasing over the period, leading to persistent power outages that included regular blackout episodes.

The projected electricity demand in 2016 was about 20,000 GWh, 25.5% higher than the estimated demand of 15,934 GWh in 2010. Although the Ministry of Energy and Water has presented an inconsistent annual electrical demand in Lebanon by claiming that “the average electrical demand growth rate is 3.8% to 5%,” the model seems reliable enough. For the projections, percentages are used instead of actual demand measurements. The percentage in the annual forecasts is the difference between the estimates for the difference or growth. According to the previous period, electricity demand is increased or decreased. This unpredictability is due to EDL’s various methods of estimating demand and the repercussions of a person’s rapid growth. The widening gap between installed capacity and peak demand has been an overwhelming concern for economic growth as it significantly affects businesses, families, and society.

According to the UN in 2015, “efficiency is in many ways key to SDGs generally by 2030.” Efficiency drives economic efforts in all sectors, such as energy and resources and health and educational access. Sustainability guarantees that UN goals are both conceivable and useful, including renewable energy, food security, or waste. We can address today’s harsh, global questions within the limits of our planet’s resources to achieve a more resilient and sustainable future by 2030. Realizing targets would provide a variety of prospective advantages. These include:

1. Enhanced energy efficiency is relevant in mitigating climate change by efficiently reducing GHG emissions. The effect provided is in alignment with SDG 13 (Climate Action).
2. Energy Security: Energy sustainability enhances the flexibility of energy structures, ensuring a robust supply by a controllable participant. This contributes to SDG 7 (Affordable and Clean Energy).

3. Mitigation of Poverty and Economic Stability: Families and businesses save costs related to technologies and energy use, which impacts SDG 1 (No Poverty).
4. Sustainable practices promote economic growth, which impacts the SDG (Decent Work and Economic Growth).
5. Sustainable Cities and Communities: transport reduces pollution and material use, which is in support of immediate application in urban systems and transport reduces pollution and material use, which supports SDG 11 (Sustainable Cities and Communities).

1.1. Historical Background of Renewable Energy Resources

Wind Energy: Wind turbines have a long history that reaches back thousands of years. grind: wind turbines have been grinding grain for generations. In the final two decades of the 20th century, large-scale commercial wind turbines created electrical power. In the 1980s, architectural advancement was fastened by the oil crises. Various countries have spearheaded the development of modern wind energy, including Denmark, Germany, and the USA. The advancements in turbine technologies are due to materials, aero dynamicity, and control systems, which have boosted wind efficiency while cutting expenses. Wind energy's contribution to the worldwide energy economy regarding electricity creation and carbon emissions has become increasingly important (International Renewable Energy Agency, 2022).

Decentralized PV Energy: Decentralized PV has shown tremendous progress over the last three decades from its inception as a radical notion to a widespread and readily available energy provider. These mechanisms were created in the late 20th century and were primarily used in off-grid remote areas. Concerns about the environment and enhancements have boosted the expansion of decentralized PV in the 21st century, notably in households and businesses. Because innovation continues and costs decrease, decentralized PV has been a primary reason for the transition to renewables. It provides houses, organizations, and cities with inexpensive, clean, and sustainable power (International Renewable Energy Agency, 2022).

Centralized PV Energy: Centralized PV technology has evolved substantially over the last three decades. While it was initially developed for limited applications, enhanced efficiency, production economies of scale, and supporting regulatory frameworks have helped achieve widespread usage. Centralized PV comprises PV plants and large rooftop solutions and accounts for a sizeable percentage of global electricity generation. Ongoing improvements and cost reductions ensure that centralized PV plays a vital role in transitioning to sustainable energy.

Concentrated Solar Power Energy: CSP is a power technology based on mirrors or lenses that concentrate sunlight into a restricted place. Over the last thirty years, CSP has progressed from experimental concepts to full-fledged power plants that are cost-competitive and part of the balanced mix of renewable resources. In the late 20th century and early 21st century, the earliest CSP power plants emerged, largely initiated by first research and development. The CSP was finally brought into commercial operation in the early 21st century because of technology development, economies of scale, and favorable government action. Currently, CSP is expanding through the insertion of larger, more economical plants and the development of thermal storage systems, which allow it to generate electricity when it is most required. However, CSP energy remains a significant issue for deploying a sustainable power system, generating dependable energy with minimal environmental impact (International Renewable Energy Agency, 2022).

Hydropower Energy: Hydropower is rooted in ancient civilizations; it grew notably in the late 19th century due to the establishment of hydroelectric dams. Over the past thirty years, technology has been upgraded significantly, focusing on improving its sustainability and ecological implications. The developments include establishing sustainable turbine systems to reduce sediment issues. Hydropower is rapidly becoming one of the primary sources of electricity production globally and has grown significantly over the years due to technological feasibility (International Renewable Energy Agency, 2022).

1.2. Integration of Renewable Energy

In Lebanon, a broad renewable energy plan is being developed that will include several renewable sources, creating a reliable and sustainable energy industry and closing the gap in different EDL supplies. Another measure is the study of geothermal energy potential and its potential integration with current renewable initiatives, including solar and wind, to provide a more reliable and diverse energy source. As a result, Lebanon will lower its carbon effort and reduce the need for several different imported energy sources. Because imports are costly, this plan is not simply environmentally responsible; the government ultimately wants to stabilize power systems supply to reduce prices, which is the foundation for the country’s progress.

- PV Projects: PV deployment in Lebanon is increasing because of efficient solar insulation and progressive legislation. The Beirut River Solar Snake is an interesting case of constructing a PV system on the river. This project was implemented for the MEW and may be viewed as a symbolic model of the implementation of urban renewable energy. It has a high installed capacity and modern technology and can significantly contribute to the local power system. Moreover, the UNDP has been actively promoting the implementation of PV systems for rural areas, striving to provide electricity to isolated villages and reduce the country's dependence on diesel generators. Therefore, PV is a central element in Lebanese sustainable energy promotion through various programs (UNDP, 2013).
- Concentrated Solar Power Initiatives: Although CSP is less viable in Lebanon than PV due to its greater costs and complexity, the possibility exists. CSP projects can benefit from Lebanon's high solar radiation levels, with the Bekaa Valley known for excellent atmospheric conditions. Implementing a CSP power plant in that area would demonstrate its potential for further use. It is more than mere electricity generation; it provides the ability to store heat, a substantial advantage over standard PV. In the long run, this could lead to a steady and available solar power source, unaffected by rain or nights, formulating Lebanon's energy security (UNDP, 2011).
- Wind Energy Development: The upsurge of wind power is rising in Lebanon, with the country capitalizing on the windy part of the country. The case in point is the Akkar Wind Farm, Hawa Akkar project, which is in the northern part of the country. The project aims to use the high availability of wind in the region to

generate power, increasing the dependence of power available to the citizens. On realization of its potential as a wind farm, the farm is expected to power a good percentage of the country. In addition, the wind farm acts as a pilot for wind generation to prove the viability and benefit of power generation from the wind (IRENA, 2020).

- Hydropower Expansion: A major RE resource of Lebanon's energy sector is the past utilization of hydropower, with many projects being done and still operating. Lebanon is currently exploring potential expansion in this form of sustainable energy, whereby it can rehabilitate past achievements such as the El Bared River Dam. In addition, it is still assessing new projects ideal for various locations, aiming at partaking in the small-scale hydroelectric power plants suitable for this oblige form in line with the rough topography of Lebanon. The country's various rivers and streams act as an ideal source of power from countless water masses, thus ideal for the numerous projects planned, highly benefiting Lebanon in achieving environmental safety and local advantages such as job creation and infrastructure improvement (American University of Beirut, 2013).

1.3. Deployment of Renewable Energy Resources in Different Countries

Germany, China, the United States, and India utilize different combinations of resources in renewable energy to achieve sustainability in their unique perspectives on the world. Germany has predominantly used PV energy in the field of sunlight, spending millions on gaining sunlight onto their lands. China similarly utilizes the energy from sunlight but also those of wind and hydropower. As one of the major countries in renewable energy, the USA primarily focuses on wind, hydropower, and sunlight, spending millions on it too. India, in turn, uses sunlight, wind, and hydropower to sustain their energy needs. PV, wind, and hydropower resources are plentiful in all the four countries. Germany, China, the USA, and India replicate the global trend of utilizing PV, wind, or hydropower and thus underline the growing need for the flexibility of such resources to be widespread for the world.

Germany could be considered one of the global providers in implementing PV systems. Being famous for the energy turnaround, Germany proposes valuable principles on how to introduce renewable sources of energy effectively. The experience of the Neuhardenberg Solar Park is one of them. The project demonstrates an effective initiative in using PV technologies. Having an initial investment cost of around €200 million, the solar park has a capacity of 145 MW and is projected to produce 150,000 MWh power output annually. This energy is enough to provide over 50,000 households with renewable energy to supply them with electricity. In addition to the economic savings, it also has a potential influence on reducing CO_2 emissions. It is projected that the project will cut about 100,000 metric tons of CO_2 annually (The University of Western Ontario, 2017).

Another major wind energy initiative in the renewable energy sector is the Baltic 2 Offshore Wind Farm in Germany. The 288 MW wind farm demands more than €1 billion in capital investment. The wind facility has an annual power generation capacity of over 1,200 GWh, which can cater to the electricity needs of many homes in Germany. It has achieved further reductions in CO_2 emissions by over 900,000 metric tons annually due to this sustainable energy source (Power Technology, 2024).

The municipality of GARS in Bavaria, Germany, has taken a significant leap towards enhancing its renewable energy generating abilities by extending its stream and constructing a new hydropower plant. This plan is for the most excellent use of the site's production abilities. To do this, ANDRITZ was awarded an agreement in 2011 to convey a modern compact Bulb turbine. The critical features of the Bulb turbine are the rotor diameter of 3,650 mm and the capacity of the turbine to deliver 5 MW. The scope of delivery included an integrated, directly connected synchronous generator operating at 6.3 kV, and the entire stack of control and electro-technical equipment was also vital (Andritz Group, 2018). The hydroelectric plant at GARS successfully generated almost 13.7 million kWh of electricity by integrating an additional 100 cubic meters per second of water flow. The substantial increase in clean energy production had a noteworthy impact on the local community, while providing reliable and sustainable electricity for roughly 3,400 families. Importantly, the transition to sustainable energy sources reduced almost 11,000 metric tons of carbon dioxide emissions per year.

China, under its National Energy Administration, has been a source of extensive PV projects across China. Significant investment into manufacturing capacities has drastically reduced production costs, making it more accessible in other parts of the world. Solar energy has become increasingly available for individuals, companies, and nations. Despite still being complex in terms of infrastructure, China has managed to become a prominent global leader in adopting renewable energy sources. Some of the most startling cases about the country include the PV establishment of Longyangxia Dam Solar Park in China, an unprecedented project of its kind. This $1.45 billion investment has a capacity of 850 MW if used fully. The dam produces over 1,100 GWh of electricity annually, providing green electricity to millions of Chinese homes. It should also reduce carbon dioxide emissions by 806,000 tons a year, making it a significant factor in China's desire for clean energy and emission reduction (Power Technology, 2020).

One of the largest wind farms in the world is Jiuquan Wind Power Base, whose capacity is 10 GW, and its investment is almost $17 billion. It generates over 20,000 GWh of electricity annually, enough to supply numerous residences and companies in China. Apart from the savings from power, Jiuquan Wind Power Base causes a considerable decrease in CO_2 emissions, with an expected annual reduction of almost 16 million metric tons. It is in line with China's commitment to reducing GHG emissions. The next most considerable resource in China, a water energy resource, is approximately 80 GW. The country conducted extensive research, revealing that its theoretical water resource reserve is 688 GW, and a potential annual generation totals 5,920 billion kWh (The New York Times, 2017).

China's hydroelectric facilities continued to develop for more than 50 years, creating an installed capacity equal to 92.17 GW as of 2003. This type of power constitutes 24% of the country's electric power and produces an average of 283 billion kWh annually. As such, it is responsible for 14.8% of China's overall energy production. These water energy reserves indicate that China's hydropower development rate and capacity are much lower than that of the countries with vast water resources (Shang, Y., Li, X., & Shang, L., 2022).

The Topaz Solar Farm in the United States is a remarkable example of an operating PV installation. The solar farm produced 550 MW of power and was erected for a total of nearly $2.5 billion. The amount of renewable power produced annually totals above 1,000 GWh, ensuring that a majorly populated community has access to green energy. The Topaz Solar Farm cuts electricity expenses and CO2 emissions by more than 600,000 metric tons per year. It allows California to further use renewable sources and tackle the annual emission targets (Boretti, A., Castelletto, S., 2020).

The Alta Wind Energy Center is a notable wind energy project in the USA. The wind facility has a power output of 1.5 GW and requires investment for nearly $5 billion. This system produces more than 5000 GWh of energy every year, which is enough to power multiple American households (Power Technology, 2014). The Alta Wind Energy Center not only saves electricity costs but also significantly decreases CO2 emissions, with an expected reduction of about 3 million metric tons annually. This significantly intensifies the USA's goals of advancing clean energy and attaining targets for reducing emissions.

Hydropower plants vary in size and form. They account for 28.7% of the overall renewable energy output in the USA and 6.2% of the global electricity generation. Despite the frequent association of hydropower only with such high-profile dams as Hoover Dam, numerous substation facilities can be included in municipal water systems or irrigation streams. For instance, Washington receives about 66% of its energy from hydropower. The work of the National Renewable Energy Laboratory also suggests the versatility of hydropower in the United States, with the calculated firm capacity totaling 24 GW. Replacing this firm capacity with storage would imply a requirement for more storage capacity than currently exists in the United States. Additionally, the flexibility of existing hydropower installations is essential since it will permit the integration of a supplemental 137 GW of wind and solar capacity by 2035 (U.S. Department of Energy, 2022).

Solar photovoltaics are actively deployed worldwide; one example is the Rewa Ultra Mega Solar Park in India. It is an ambitious project established by the government of India and three state authorities, which invested more than INR 4,500 crore in its 750 MW capacity. Furthermore, with more than 1,300 GWh annually, this solar park is placed among the largest facilities of its kind in Asia. It becomes a source of clean energy for India and electricity for millions of residential households. Besides the electricity cost cut, the Rewa Solar Park lowers CO_2 emissions, reflecting India's massive goals (The Pioneer, 2020).

Muppandal Wind Farm is a key wind energy facility that provides an overview of India's wind energy landscape. The wind farm has a capacity of 1500 MW and produces more than 400 GWh of electricity per year. It helps to meet a considerable share of India's energy needs. The Muppandal Wind Farm is reducing power consumption and is an essential partner in decreasing CO_2 emission rates that support the development of renewable energy in India. In 1947, the proportion of hydropower capacity to the total power-production capacity was around 37%, while power production was over 53%. However, in the 1960s. The role of coal in the consumption of power production in India substituted almost half that of hydropower. The outcome was a dramatic drop in hydropower capacity and generation (Natarajan, Vinodh & Kanmony, J. cyril. 2014).

Hydropower constituted 12.5 percent of India's power output in 2022–23. After 2023, India had an operational pumped storage capacity of around 4745.6 MW. Additionally, there were around 57,345 MW of pumped storage capacity under different phases of inquiry and building (Powell, L., Sati, A., & Tomar, V. K. 2023).

1.4. The Case of Lebanon

Before 1975, hydroelectric power plants generated over 70% of Lebanon's energy. In addition, because of the civil war, Lebanon was importing most of the energy to satisfy its energy needs. The imports consisted of different parts: liquid petroleum gas, gasoline, gas oil, kerosene, fuel oil, and asphalt. Starting from the mid-1990s, the Lebanese energy sector faced multiple challenges, one of which was the lack of investment.

Lebanon is an ideal country to study, as it is facing an electrical crisis. The problem is the fluctuation of the energy supply and demand in Lebanon. Moreover, the projection scenario is formulated, meaning that the demand will rise every year, and no power-generating stations will be built; therefore, there will be no expenditure on the new stations.

As shown in Figure 1, the percentage of electricity demand unmet by EDL in Lebanon increased from 22% in 2008 to 37% in 2018. In a "Business-As-Usual" scenario, in which demand would continue to grow and no generation capacity would be added and in which the Jiyeh and Zouk power generation units would be retired in 2022, the supply-demand deficit is expected to grow to 56% by 2025. Moreover, the installed capacity of PV increased from almost 0 in 2011 to around 47 MWp in 2018. 44.8 MWp are placed entirely as decentralized systems after subtracting the capacity of the Zahrani Oil Installations project and the Beirut River Solar Snake project, which total 1.08 MWp and 1.09 MWp, respectively. Regarding electricity output, PV installations generated around 53 GWh, which accounted for 0.4% of EDL's total production and 0.25% of Lebanon's total consumption (World Bank Group, 2019).

The inadequacy resulted in a significant breakdown of the sector's structure clocked by EDL being unable to meet the power needs of the Lebanese people. As a result, other privately-owned diesel generators opened thriving alternative electrical market running parallel to the main one. EDL was shortly unable to generate because of the decrease in capacity due to insufficient maintenance and excessive power consumption. The combination of the Syrian crisis further exacerbated already existing difficulties. A wide range of issues arose because of the influx of Syrian refugees that rose the population, growing more power consumption, and a serious gap between the electricity produced and consumed as it reached 5,524 GWh in 2014 (Bouri & El Assad, 2016). There is a relative long-term inadequacy concerning Lebanon's state-owned EDL energy supply and the country's increasing demand. The difference is due to several factors, including proceeds structure, insufficient investment in new power-producing facilities, and electricity fraud. For every project reviewed, this is the most feasible case, and it shows why Lebanon's electric issues require immediate attention. The EDL has reported a growing higher percent unsatisfied demand since 2006. Even at this, current university capacities have already been exercised because generation capacity lacks adequate infrastructure and investment. So, EDL has always been unable to fulfill a crucial part of the country's electrical demand.

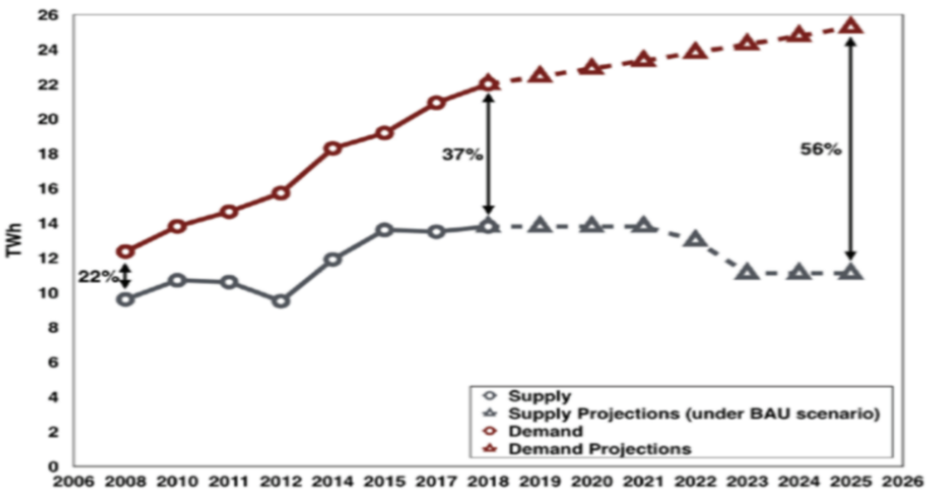

Figure 2: Lebanon's electricity supply and demand balance

Source: ESMAP. 2020

Furthermore, from 2010 and towards the end of 2019, the total installed PV capacity portended an 89% per annum growth. In 2019, PV power represented 0.73% of entire EDL's annual electricity production, elevating from 0.55% in 2018. At this pace, PV projects reached from 25 in 2011 to 360 in 2019. Accordingly, the Lebanese Center for Energy Conservation reported that the PV industry's investments surged from $2.29 million in 2010 to $125.83 million in 2019. Presently, the Lebanese energy state exists with high dependence on diesel generators to cover for its deficiency and precariousness of electricity provides through the national grid. Even though this is a short-run recourse accompanying a demand, it also experiences substantial disadvantages for ecology and public health. Indeed, the fumes from diesel generators have raised the rate of air pollution and intensified numerous respiratory illnesses in the country because of environmental deficiencies. It also incurs a greater amount while subsidizing energy and fuel usage; hence, the state financial plan has a more significant cost.

As the Lebanese state provides less energy, people's power bills become more costly. In other words, as the public division of electricity is weaker, it opens more space for the private division of electricity, having suppliers, importers, and allotment. Although Lebanon's dual problem has been significantly analyzed and chartered, the total amount of money spent amid the process is high and neglects the ecological effects of backup generators. According to L'Orient Today, Lebanon has spent around $10 billions of diesel fuel for generators since 2010. Within this period, the government spent $16.8 billion was set aside to purchase gasoline for EDL. Ultimately, even though generators produce only about 33% of the entire energy produced in the country, they represented 40% of Lebanon's sum money spent in fuel for power productions.

The high energy consumption rate in Lebanon portends a significant jeopardy to the insufficient powers generating capability, thus there is an urgent need to fix it. Contrary to the energy mix that is not currently capable of fulfilling the surging demands requirements, Lebanon is mandated to look for alternative energy sources and make efforts to reduce energy usage. There is, therefore, an urgent need to recognize and take rapid actions to lessen the present usage and guarantee an optimal increase in resources of energy. By doing so, Lebanon intends to minimize the gap in power supplies, reduce the energy-saving approaches, cut down on high energy dependency, and meet global durability objectives through energy saving. These strategies are indispensable in diminishing global energy differences around the globe, reducing environmental footmarks, and assuring a clean future.

1.5. The UN SDG 2030 Resolutions

The United Nations Sustainable Development Goals symbolize a universal call for the elimination of poverty, the preservation of the globe, and the promotion of universal peace and prosperity for all people by 2030. Seventeen integrated goals are a comprehensive approach to aligning humanity for a more sustainable future. The SDGs were supported by all United Nations member states in 2015.

The objectives are based on the UN and governments' extensive efforts on these issues, especially the United Nations Department of Economic and Social Affairs. In the past, these entities have made several efforts in recent decades. These UN entities recommended that the necessity to address poverty and other deprivations should be met at the same time. Hence, by applying specific steps, we can improve health and education, reduce inequality, promote economic growth, fight climate change, and safeguard oceans and forests.

Figure 3: Sustainable development goals

The following are the 17 SDGs:

1. No Poverty: Limit poverty in every aspect globally.

2. Zero Hunger: End hunger, attain food security and enhanced nutrition, and foster agricultural sustainability.
3. Good Health and Well-Being: Guarantee wellness and favor well-being for all the generations.
4. Quality Education: Verify an equitable and inclusive educational environment and encourage enduring learning opportunities for everybody.
5. Gender Equality: Attain the state of so-called gender equality and encourage all females, regardless of age, by providing them with the necessary resources and opportunities.
6. Clean Water and Sanitation: Maintain accessibility and sustainable management of water and sanitation for everyone.
7. Affordable and Clean Energy: Guarantee universal access to cost-effective, dependable, renewable, and contemporary energy sources.
8. Decent Work and Economic Growth: Support sustained, inclusive, sustainable economic expansion, full and profitable employment, and decent work for all.
9. Industry, Innovation, and Infrastructure: Construct resilient facilities, advertise inclusive and sustainable industrialization and foster innovation.
10. Reduced Inequality: Minimize income inequality within and among countries.
11. Sustainable Cities and Communities: Ensure cities and households are equitable, secure, adaptable, and sustainable.
12. Responsible Consumption and Production: Ensure sustainable consumption and production patterns.

13. Climate Action: Implement immediate measures to mitigate climate change and its consequences by enacting regulations on emissions and fostering advancements in renewable energy sources.
14. Life Below Water: Protecting and wisely employing the oceans, seas, and marine resources for sustainable development.
15. Life on Land: Safeguard, revitalize, and foster equitable utilization of terrestrial ecosystems; oversee forests sustainably; battle desertification; prevent and reverse land degradation; and hinder biodiversity loss.
16. Peace and Justice: Strong institutions aim to foster peaceful and inclusive communities, provide access to justice for everyone, and establish effective, responsible, and inclusive organizations at all levels, promoting sustainable development.
17. Partnerships for the Goals: Enhance the methods of conducting and renewing the Global Partnership for Sustainable Development.

CHAPTER 2

METHODOLOGY

2.1. Addressing the Problem

The 2015 UN initiative of implementing the 2030 SDGs has been a critical milestone in ensuring that the impacts of climate change are combated, and other environmental degradation challenges minimized to guarantee a sustainable future for humanity. Indeed, the use of alternative green technologies is a desirable solution. The initiative aims to minimize GHG emissions, combat global warming effects, and promote energy security by applying alternative and sustainable energy sources. Additionally, the new and established green technologies also provide employment opportunities, boost the economy, and improve public health. The technologies will help the global community in achieving sustainability, equity, and resilience while achieving the 2030 SDG objective.

To reach Lebanon’s 2030 SDG target it is imperative to acquire 30% of energy consumption from renewable resources. This will involve the exploitation of the three scenarios of energy mixing based on the country's economic status. The optimum renewable share, which is 30%, is surpassed among two of the scenarios, “optimistic” and “moderate”. This method allows for practical decisions, which not only handles Lebanon’s current energy demands but contribute significantly to ecologically conscious energy futures aligning with the SDGs 2030.

The primary aim of this thesis is to provide a detailed analysis of Lebanon’s power demand and its predicted growth, which will serve as the basis for attaining the optimum solution of the energy mix. The study will ensure that such a solution is economically viable through economic feasibility analysis. The approach, by extension, implicitly saves costs, reduces power consumption, enhances efficiency of energy uses, and reduces CO_2 and other GHG emissions. In essence, the study strives to grant Lebanon a more efficient, sustainable, and environmentally friendly energy system. Hence, the primary issues that this thesis will address:

1. Assessing Lebanon's power demand and its anticipated growth.
2. Applying energy conservation with optimum energy mix solution.
3. Identifying the possible economic implications.
4. Economic feasibility study of the energy mix scenarios.

2.2. Research Execution

The project implementation approach consists of four distinct stages, each crucial to determining the most effective combination of energy scenarios to meet Lebanon's 2030 SDG target.

- Step 1: Data Collection and Analysis: This includes collecting data on energy use in GWh, recording the total capacity of RE generation, calculating T&D costs, checking power demand, gathering the trend of electricity generation and the actual generation of electricity, and finding the percentage of electricity generated using produced renewable energy.
- Step 2: Developing Energy Scenarios: The three scenarios should be developed using MATLAB, reflecting a particular view of the SDGs. The first scenario will be optimistic, reflecting the maximum achievable economic recovery. The second scenario will be merely realistic, based on current presupposes. The third

scenario, which should be pessimistic, will give a warning perspective. The first and second scenarios should be optimized to align with the UNSDGs by 2030. Additionally, the economic feasibility should be presented in a detailed manner, and all presented costs should evaluate each adopted scenario.

- Step 3: Scenarios’ Evaluation: In other words, after the scenarios have been developed, a detailed study should be performed. In addition, different economic recovery levels will be evaluated, including capital costs, operation and maintenance expenses, and fuel costs. Moreover, renewable energy market prices will be provided to select the scenario that can offer the optimum solution by 2030.
- Step 4: Economic Feasibility: This step involves conducting an economic feasibility study using extrapolation model data. The study will check the necessity of installing RE systems, such as PV panels, wind turbines, and hydropower.

2.3. Projections and Optimization Using MATLAB

2.3.1. MATLAB Forecasting

The specially developed MATLAB code is utilized to assess and predict the development of RE sources, such as wind, PV (both centralized and distributed), concentrated solar power, and hydropower, from 2018 to 2030. This research relies on historical data available since the year 2018 to project patterns in energy capacity and output up to the year 2030, using a quantitative methodology to forecast future expansion.

Methodology Summary:

1. Data Preparation: The initial step is collecting the existing data for each RE source. These updates are used in scenarios and document the current growth of each energy source in the chosen period leading to the future.
2. Graphical Representation: In the next step, results obtained in the previous stage are shown in graphs, where the historical trend of capacity and generation of each RE source alongside others are shown. This stage is important for recognizing the patterns of development and the specific changes or common trends in each era.
3. Trend forecasting involves using polynomial fitting, specifically a linear regression model, to predict future trends by analyzing previous data. A linear regression model analyzes previous data and derives the coefficients that yield the linear equation closely describing the past trend. It is then used to predict future trends in capacity and generation power for the period 2026-2030.
4. Forecast Visualization: The analysis also includes visualizing these predictions, comparing previous data that has been adjusted to align with expected future patterns. This is used to check the accuracy of the model and establish a clear visual perspective-making projection on the increase for each one of the RE sources.

2.3.2. MATLAB Optimization

In this step, the comprehensive analysis and optimal implementation of multiple RE sources, namely, the energy carried by wind and PV in centralized and distributed models, CSP, and hydroelectric power, from 2025 to 2030. The process involves checking the economic viability of every energy source, assessing its cost against the alternative, pre-defined expenditures, and establishing the most favorable proportions of energy generation that correspond to the financial and operational constraints set in advance.

1. Allocation of the Costs of the Constraints: The analysis starts by allocating the per unit costs to each RE source, which accurately represent their respective economic requirements and are essential for comprehending the financial commitment needed for any technology and act as a basis for optimization.
2. Analytical Framework: An advanced linear programming model is used to navigate the limitations of energy planning. The model includes the minimum and maximum capacities for every RE source, ensuring that the solution is not only reasonable from a financial aspect but also feasible for practical and environmental reasons. The capacities are adjusted using the division factors, which imply the normalization of the factor data to ensure meaningful comparison and incorporation of every source into the plan.
3. Process of Optimization: The primary aspect of the method is the optimization process, which systematically explores all the possible energy shares from each source for every year, aiming to reduce the total cost while

complying with the constraints and, hence, distinguishing the most economically efficient energy composition for every year.

4. Projection and Estimation of Future Demand and Maximum Output: The critical aspect of the model is the projection of the energy shares and the available capacity in the next two years of 2030; the division factors are then used to generate the optimal layout of energy distribution, altering varying portions of the final year with the strategic goals, such as the percentage of RE shares.
5. Presentation of Results: The process is concluded by a comprehensive presentation and analysis of the results, which show the ideal annual distribution of shares, capacities, and overall expenses for each renewable energy source.

CHAPTER 3
OPTIMIZATION OF ADOPTED SCENARIOS

3.1. Descriptions

The yearly progression of renewable energy capacity and generation is presented on a timeline extending from 2018 until the year 2030. This is established by incorporating three scenarios (optimistic, moderate, and pessimistic) that represent different macroeconomic situations. The base year for all predictions and scenarios is 2018, selected to ensure the data’s applicability and availability. To achieve the highest possible installed capacity of renewable energy under the most optimistic circumstances, it is necessary to execute key policy adjustments and reforms for each scenario. These measures are crucial for effectively implementing the proposed renewable energy capacity. Indeed, to overcome the problems the country faces, these measures are essential.

3.1.1. The Optimistic Scenario

First, the success of the “optimistic” scenario is based on the revival of the country’s economy. It is determined by the outcome of the presidential election and the formation of a new administration with great international support. Second, the prompt implementation of the fiscal reforms and their sector-specific concentration is very important, especially in the power industry. The market triggers are the abundance of international capital and the financial community’s monetary assistance. Since CEDRE funds have already been committed and IFIs are eagerly investing in ecologically clean formats, it is hoped that this assistance and fund distribution will remove the socioeconomic issues and tackle the problem of the country's financial re-establishment. With the reforms effectively implemented and the economic situation improved, the private sector's confidence is restored, and the credit-rating agencies are improving Lebanon's credit rating upward.

3.1.2. The Moderate Scenario

In the "moderate" scenario, the country's economy is improving due to the formation of a revolutionary, accountable administrative and financial assistance from overseas sources. At the same time, key policymakers are on the brink of providing important changes to the entire economy and some industries, specifically the dynamics of the electricity sector. Nevertheless, these changes have been experiencing delays, representing the substantial dimensions of the obstacles. Funding from overseas sources and the financial community have deferred the transformation of money due to the postponed execution of administrative reforms. The Lebanese government addresses the issue and enacts the reforms to start funding the CEDRE money, but there are missed opportunities because of delays. As money and financial capacity expand, cash flow to and from the county improves. The socioeconomic crisis slacks in Lebanon while its fiscal health improves. The successful reforms and financial stability revive the private sector, with the credit ratings shifting Lebanon from unsteady to stable. Renewable energy projects are enthusiastic under the given directions as the International Financial

Institutions take interest in granting sustainable projects. The technologies available are expected to do well, but there might be early delays.

3.1.3. The Pessimistic Scenario

The scenario termed "pessimistic" contemplates a prolonged poor performance of the country's economy, which is not meeting expected growth benchmarks. Two other issues contribute to this economic crisis: the prolonged delays in electing an activist government committed to genuine reform and transparency and the inadequacy of international support resulting in additional macroeconomic and fiscal complexities. A particularly alarming symptom of this is the absence of effective reform and transparency in critical areas, severely affecting the energy sector. Vital CEDRE funds have become inaccessible due to such lengthy delays and the stagnation of needed reforms, meaning Lebanon misses important development opportunities. The government's incapacity to receive necessary fuel for thermal power stations has exacerbated the socioeconomic deterioration. Lebanon's credit has been downgraded by credit-rating organizations. As a result, private sector investors have grown increasingly cautious. The "Hawa Akkar" project to construct a wind farm has been halted in the near term. Nevertheless, it is essential to understand that not all international organizations have withdrawn their aid. Several financial institutions are prepared to invest in suitable fields, such as environmental initiatives. Thus, it can be assumed that the Lebanese cooperation model with multilateral organizations is showing promise.

3.2. Existing Data

3.2.1. Optimistic Scenario

Table 1 presents the data for the past seven years for all types of renewable energy sources in Lebanon, as obtained from the Lebanese Center for Energy Conservation (LCEC) for all three scenarios.

Table 1: Energy sources over the past seven years used in the optimistic scenario.

Years	Wind Energy (GWh)	PV Centralized Energy (GWh)	PV Distributed Energy (GWh)	CSP Energy (GWh)	Hydropower Energy (GWh)
2018	0	0	85	0	347
2019	0	0	112	0	347
2020	0	0	133	0	347
2021	0	0	309	0	347
2022	0	0	1262	0	347
2023	0	26	1924	0	347
2024	0	287	2145	0	347

The analysis of Table 1 in the context of Lebanon's progress in the growth of renewable energy makes it possible to acquire valuable insights. The absence of wind and CSP energy production in Lebanon in the observed period across the reported years indicated the country's limited investment in these sources or their use. Expectedly, financing restrictions, technical obstacles, or legislative barriers significantly limited the numerous efforts to promote their use. The growth in the production of PV energy is a positive tendency in Lebanon, which suggests the development of centralized and distributed solar energy utilization. While the country's centralized production of PV energy was 170 GWh in 2017, the forecast suggested reaching 3205 GWh by 2024. The high leap in the distributed energy production of PV energy from 85 GWh in 2018 to 2145 GWh in 2024, with personal actions contributing to its usage, illustrated the country's efforts to use rooftop power and small-scale solar generating to meet its requirement, especially in cities and remote locations. Such development corresponds with Lebanon's goals, relying on national strategies to promote renewable energy use and reduce fossil fuel dependency. The steady 347 GWh hydro-energy production in the observed period was stable and consistent since the 70s, verifying this renewable source's reliability. As is the case with solar energy, hydro contributes a minimal proportion of the country's energy while being necessary to supply consistent and stable power, particularly during varied energy requirements.

3.2.2. Moderate Scenario

Table 2: Energy sources over the past seven years used in the moderate scenario.

Years	**Wind Energy (GWh)**	**PV Centralized Energy (GWh)**	**PV Distributed Energy (GWh)**	**CSP Energy (GWh)**	**Hydropower Energy (GWh)**
2018	**0**	**0**	**85**	**0**	**347**
2019	**0**	**0**	**112**	**0**	**347**
2020	**0**	**0**	**133**	**0**	**347**
2021	**0**	**0**	**309**	**0**	**347**
2022	**0**	**0**	**1262**	**0**	**347**
2023	**0**	**0**	**1924**	**0**	**347**
2024	**0**	**182**	**2215**	**0**	**347**

Examining the data related to energy production for the moderate scenario, as presented in Table 2, shows a substantial increase in PV-distributed energy from 85 GWh in 2018 to 2,215 GWh in 2024. Therefore, it shows a rapid increase throughout this period. Wind, CSP, and centralized PV energy were not produced in chosen years or have a minimal amount. Hydro-energy is consistently stable and is produced around 347 GWh annually. Based on the presented information, Lebanon's energy economy is focused primarily on. It has PV-distributed energy and hydro-energy and has made nearly no progress in wind and CPS renewable, sustainable resources for these years.

3.2.3. Pessimistic Scenario

Table 3: Energy sources over the past seven years used in the pessimistic scenario.

Years	Wind Energy (GWh)	PV Centralized Energy (GWh)	PV Distributed Energy (GWh)	CSP Energy (GWh)	Hydropower Energy (GWh)
2018	**0**	**0**	**85**	**0**	**347**
2019	**0**	**0**	**112**	**0**	**347**
2020	**0**	**0**	**133**	**0**	**347**
2021	**0**	**0**	**309**	**0**	**347**
2022	**0**	**0**	**1262**	**0**	**347**
2023	**0**	**0**	**1924**	**0**	**347**
2024	**0**	**182**	**2073**	**0**	**347**

Table 3 shows a substantial increase in PV distributed energy generation from 85 GWh in 2018 to 2,073 GWh in 2024, demonstrating strong development in distributed PV installation during those years. As previously explained, centralized PV will change drastically over 2024 and evaluate to 182 GWh. Wind energy generation will remain zero for every year, so this creates an assumption that there was no advance in wind energy production. The Hawa Akkar project was suspended due to the economic situation and the Lebanese Lira losing value. This is the case for CSP, which includes little to no investment or process in the concentrated solar power technology. However, hydropower has a constant value of 347 GWh every year. This information leads to the fact that there was a strong focus on PV, especially in distributed installation. Still, there was no advancement in Wind and CSP in Lebanon's energy segment.

3.3. Projections

The next step is to project the RE availability until 2030 for all three scenarios.

3.3.1. Optimistic Scenario

The next step is to project the RE availability until 2030 for all three scenarios.

Table 4: Optimistic projections of RE sources

Years	Wind Energy (GWh)	PV Centralized Energy (GWh)	PV Distributed Energy (GWh)	CSP Energy (GWh)	Hydropower Energy (GWh)
2025	615	460	2475	345	563
2026	615	460	2971	345	628
2027	615	981	3465	345	692
2028	2247	981	3960	1035	757
2029	2247	1503	4454	1035	822
2030	2247	1503	4950	1035	887

Analyzing historical trends and projections for wind energy in Lebanon from 2018 to 2030 reveals setbacks and advancements in full-scale energy production recovery in the country. The first aspect to consider is the 2018-2025 period when the current wind production level is low and drastically below 200 GWh. Currency variance leads to the country's incapability to engage in the establishment of new wind farms, as can be seen from the financial analysis. However, the recovery that will stabilize the currency and secure the influx of investments aimed at green energy will increase the energy produced to 615 GWh by 2025. The overarching projections for future development show that the production will continue growing by 2028 to approximately 2,247 GWh and stay stable until the end of 2030. This highlights the issues connected to currency variance, which is an aspect of green power investments. This situation renders the costs high and increases uncertainty among investors. Despite this, Lebanon established the goal of recovering production, which indicates an aspiration for increasing self-sufficiency in energy generation. At the same time, the ambitious environmental goals also illustrate the probability of high wind energy production rates, and the influx of refugees is associated with an increasing need. Lebanon's NREAP utilizes bidding and auctions to ensure wind production goals. The analysis of the Akkar projects also illustrates the systematic increase in Lebanon's northern region, which signifies the country's strategic dedication even to the problematic areas and the existing limitations in development.

The historical trend for a centralized PV installation in Lebanon from 2018 to 2025 is the industry's development phase leading to production growth. The table above shows that production was not reported from 2018 to 2022. It shows that the development of the photovoltaic industry in Lebanon has been a significant challenge with total instability, economic constraints with the Syrian refugee crisis, and the effects of the COVID-19 pandemic. However, production increased afterward, leveraging Lebanon's solar radiation sources, estimated to be in the range from 1,520 to 2,148 $kWh/_{m^2/year}$. In 2023, production started at the rate of 15 MW and resulted in 26 GWh generated. This was followed by an increase in generation to 287 GWh in 2024, probably because of energy support and investment initiatives to revive the economy. Future estimates project an increased source of capacity and production. For example, in 2025, production will be 460 GWh from a capacity of 265 MW. The increased growth in the capacity and generation is supported by large solar projects, policy initiatives to promote renewable energy and reduced costs of solar equipment. The country has large land resources to accommodate PV installations on a large scale. International renewable energy national agency (IRENA) outlines how Lebanon had more than 5558 $kWh/_{m^2/year}$ of untapped solar radiation potential, enough to accommodate Beirut River solar snake (BRSS) and other project initiatives. BRSS generated a lot of interest, which shows that investors have confidence in the amount of investment put in place. It is from Lebanon's national initiative to realize 150 MW of solar power by 2020 and 300 MW by 2030 to reduce GHG emissions, meet environmental obligations, and lay a firm foundation for investment funds.

As evidenced by the historical trend for distributed PV installations between 2018 and 2030, capacity and production are set to increase with the various initiatives in Lebanon's energy sector. The capacity started to increase from 56 MW in 2018, generating 85 GWh, which advanced to 92 MW and 133 GWh by 2020 despite the COVID-19 restrictions efforts. By the end of 2022, the records indicate a rapid increase of 869 MW and 1262 GWh. Besides, the Lebanese Center for Energy Conservation facilitated private sector appearances by allocating $350 million in investments in new solar systems, reaching a maximum capacity of 250 MW. Therefore, when combined with existing plants, the capacity increased. The strategies are evident in the growth plans to achieve about 1300 MW and 2145 GWh even in 2024. Thus, despite various obstacles, the country has established the paradigms of how energy usage meets the growing demands. the power generation projections are slated to increase drastically from a 1500 MW record in 2025 to 3000 MW by 2030. Therefore, electricity production rises significantly and correlates to currency regimen alignment strategies such as the NEEREA fund procedures. Therefore, the country used decentralized PV systems in the aftermath of the Beirut port explosion, which demonstrated the relevance of these systems in meeting the economic and environmental goals. It enhances energy resilience and minimizes vulnerabilities to social disruptions. Despite the high technological costs, distributed PV installations are extensive, facilitated by measures such as net metering, which promotes the growth initiative of solar energy.

The historical trend analysis from 2018 to 2030 shows the road Lebanon passed concerning CSP development. In the first period, absent progress was explained as the less competitive option to improve the electricity deficit. While 2018-2024 did not bring any CSP, as it remained limited due to multiple reasons, and no developments were registered out any of the years, a radical change took place in 2025. It marked the year that introduced a 100 MW capacity generating 345 GWh and was the beginning of CSP in the future. Despite the challenges of the refugee crisis, the COVID-19 pandemic, the port explosion in Beirut, and the currency in Lebanon, investment in advanced technologies after 2024 still predicts economic recovery and successful aid and investment. Regarding the environmental framework agreement, despite the obstacles, Lebanon has more than enough solar radiation to achieve the accomplishment. Moreover, the committed energy is expected to help lower carbon emissions, addressing the rising need for energy to accommodate refugees while ensuring the focus is on environmentally and ecologically sustainable energy solutions. Such integration affirms societal alignment compatible with CSP's involvement in Lebanon's electricity in 2030.

The analysis of Lebanon's historical trends from 2018 to 2030 presents its actions to improve its hydropower sector. In the first six years, between 2018 and 2024, the capacity and production of existing facilities remained at 286 MW and 347 GWh, respectively, indicating a lack of development. These outcomes can be attributed to various factors, such as the expansive pull exerted on Lebanon's infrastructure due to Syrian refugee migratory trends and the varying currency exchange rates, which influenced project funding. However, from 2025, Lebanon's growth-oriented path is evident in both aspects presented. By 2030, the country is projected to have a capacity of 536 MW, with generation set at 887 GWh. This indicates that Lebanon has shown effort and capacity for improvement in the energy mix. The country plans to have an additional 25 facilities to achieve this goal. Despite the challenges faced, Lebanon realizes the economic feasibility of hydropower to cushion the country, given the explosion at Beirut's port and the financial crises. The proposed addition in 2030 aims to increase existing capacity to 601 MW. The Ministry of Energy and Water prioritizes hydropower as a reliable and affordable energy source. Similarly, Lebanon's environmental objective is to move from the run of the river to determine hydroelectric generation. This strategy targets the optimal use of water resources with low environmental costs. Finally, the social expectations relate to energy stress and countering the social-economic impacts of blackouts.

3.3.2. Moderate Scenario Projection

Table 5: Moderate projections of sources

Years	Wind Energy (GWh)	PV Centralized Energy (GWh)	PV Distributed Energy (GWh)	CSP Energy (GWh)	Hydropower Energy (GWh)
2025	**0**	**182**	**2506**	**0**	**347**
2026	**615**	**182**	**2797**	**0**	**347**
2027	**615**	**704**	**3087**	**345**	**347**
2028	**615**	**704**	**3378**	**345**	**563**
2029	**615**	**704**	**3669**	**345**	**563**
2030	**2247**	**1225**	**3960**	**345**	**563**

Lebanon faced challenges and local currency volatility between 2018 and 2024, which impeded wind energy development. As the Lebanese pound depreciated, investing in capital projects such as wind farms made it economically hard. However, a significant change happened in 2025, with the development of a 226 MW capacity, which produced 615 GWh of electricity, a critical factor in attempting to diversify the energy mix. The incoming project aligned with restructuring the currency and attracting foreign investment through renewable energy. The subsequent period, 2025-2030, marked a growth curve in wind capacity, which required an evaluation of the projects in this period. The capacity growth to 826 MW and 2,247 GWh by 2028 stabilized through 2030. It reflects Lebanon’s real-world situation and the utilization of wind energy, meaning it represents the progressive development of Lebanon’s conditions. The wind capacity growth trajectory indicates a stable and progressive development in Lebanon. The accurate projection reflects the determination to reduce limitations. These are reflected in the instability of the currency, which portrays a negative perspective of importing technology or capital to investors. Lebanon can commission a wind capacity of over 826 MW, but the NREAP projects are optimally achieved considering their existence at that time. Refugees as a source of growth challenges the ability to develop sustainable practices with job opportunities to maintain stability. The NREAP provides a strategic renewable energy procurement plan through the auction, coupled with the price drop/kWh, to show the market trend. However, the fact that LCEC focuses on the Akkar region is a strategic approach to facing fuel dependency.

Between 2018 and 2025, Lebanon's centralized PV installations remained dormant, which replicated the infancy of the country's energy infrastructure. The outbreak of the COVID-19 pandemic and the Beirut Port explosions in 2021 should have dissuaded investments in energy technologies, not least of all because the economic issues were intensified by instability and the Syrian refugee situation. Nevertheless, there was a positive dynamic in 2023 when PV capacity amounted to 105 MW, producing 182 GWh, hinting at attempts to capitalize on Lebanon's solar irradiance levels. It can be assumed that the country achieved this output because of post-crisis restorative and re-development investments. Based on the forecasts between 2025 and 2030, centralized PV capacity and production were expected to grow. Capacity was projected to be equal to 405 MW, and the output equaled 704 GWh by 2025, which indicated that an expansion of large-scale projects took place. Lebanon's potential in solar energy extraction is growing due to various policy-making measures and the drop in solar technology, which is forecasted to result in 705 MW capacity and production at 1,225 GWh by 2030. As such, solar energy became a feasible energy mix component. Implementing affordable procurement policies, like engineering, procurement, and construction (EPC) contracts and power purchase agreements (PPAs), facilitated large-scale projects such as BRSS and EOI for three PV farms. PV fields also reduced energy risks and gained public acceptance and investor trust, providing work opportunities and economic growth. The solar photovoltaic sector considerably expanded due to auction processes and charging practices, reducing prices and integrating solar energy into Lebanon’s energy mix.

Between 2018 and 2022, there was a notable interest in distributed PV in Lebanon, with capacities steadily rising from 56.2 MW to 869 MW. This slow expansion portrayed the increasing recognition of solar energy as an appropriate energy option amidst the country’s economic and social difficulties. Nonetheless, the 2023 data highlights a different attitude towards distributed PV with instituted capacities amounting to 1,166 MW. Despite issuing the respective capacity, the COVID-19 outbreak posed new challenges regarding disrupting supply chains and postponing installations due to health, safety, and economic reasons. Yet, the sector’s resilience became evident due to its decentralized nature, ensured the possibility of some smaller-scale installations to progress despite the suspension of significant projects. Furthermore, the continual devaluation of the Lebanese Pound has negatively impacted the costs and finance of PV projects, given that dollar-denominated expenses surged, requiring the project to be additionally financially taxing locally. Regarding migration, the initiative of NEEREA in providing low-interest loans was critical in preserving the pace of capacity installation in the distributed PV sector. Thus, during the 2025–2030-time frame, the distributed PV sector could increase and cover up to 2,400 MW regarding the projected capacities by the end. The expected data draws a modest picture of sector growth with ongoing economic recovery and elimination of currency fluctuation that would provide a desirable environment for renewable energy sources.

Nevertheless, despite the recent data and the country's economic state, financial tools like NEEREA loans have assisted in ensuring the sector's continuation and provided the resilient distributed PV as another opportunity to give the country inclined energy sources.

Similarly, between 2018 and 2022, Lebanon registered no CSP progress or production, indicating seeking economically viable solutions or early-stage evaluation of market potentials and technology in renewable energy. The factor that comes out predominantly is the lack of CSP advancements towards 2025, an implication of challenges encountered, such as costs, shortage of expertise, limited technology providers, and the country's economic problems associated with the refugee crisis and the COVID-19 pandemic. However, the government is halfway into implementing the technology by 2025, with promising developments by 2028, when Lebanon will achieve 100 MW capacity and a conservative 345 GWh production capacity by 2030. This development indicates a post-pandemic struggle by Lebanon to explore multiple types of energy sources and a sign of recovery and diversification. Lebanon has had an economic crisis characterized by currency deterioration in recent years; therefore, the advent of CSP technology suggests a waiting policy strategy awaiting a stable financial environment or seeking affordable solutions. On the other hand, its eventual inclusion as part of Lebanon's energy sources achieves environmental sustainability and stability, reducing reliance on expensive and volatile fuel markets and the dependency on humanitarian aid tied to energy The concept of late integration could suggest a strategic policy shift that sought to invest in profitable technologies or use those that cost, less, such as PVs and wind power, before investing in CSP.

Lebanon’s hydropower sector attained a 286 MW capacity and 347 GWh of renewable energy generation from 2018 to 2022. The industry does not register any change in capacity and production during the periods, highlighting the significance of the existing hydroelectric infrastructure. Thus, the hydro unit has always provided an alternative for energy sourcing during economic turmoil and the Syrian refugee influx into Lebanon. Hydropower development stagnates between 2023 and 2025. There was no change in its capacity, citing the challenges faced due to the COVID-19 situation and the Beirut port explosion. However, with a projected 386 MW capacity and 563 GWh of power generation between 2025 and 2030, the two options may present growth and upgrading opportunities. Hydropower flourishes amidst Lebanon’s uncontrollable economy and the pound currency’s fluctuations. The reliable and affordable energy source diminishes the impacts of the fluctuations in Lebanon’s limited generation capacity. The constant generation supports Lebanon’s quest for dependable energy and reduces the sector’s carbon footprint. A stable hydropower system contributes to energy security and social gains. Uncertain times, such as the refugee situation and the pandemic, require constant energy to meet resident needs. Despite no capacity growth until 2028, the focused energy generation depicted supports Lebanon’s commitment to sustainable energy.

3.3.3. Pessimistic Scenario

Table 6: Pessimistic projections of sources

Years	Wind Energy (GWh)	PV Centralized Energy (GWh)	PV Distributed Energy (GWh)	CSP Energy (GWh)	Hydropower Energy (GWh)
2025	**0**	**182**	**2223**	**0**	**347**
2026	**615**	**182**	**2372**	**0**	**347**
2027	**615**	**182**	**2522**	**0**	**347**
2028	**615**	**182**	**2671**	**0**	**347**
2029	**615**	**182**	**2821**	**0**	**347**
2030	**615**	**704**	**2970**	**0**	**347**

Wind energy had no capacity or production in Lebanon between 2018 and 2024, suggesting a lack of wind energy projects during the period marred by exacerbating challenges due to instability, the Syrian refugee' crisis, and the COVID-19 pandemic. The absence of wind energy production demonstrates the challenges that come with the depreciation of the local currency that makes investment in infrastructure such as wind farms to be too costly. However, a notable change occurred in 2025 when a 226 MW capacity was available that produced 615 GWh, indicating that Lebanon has embarked on actions to diversify its energy sources and rely on alternative energy. The mile means policy and economic reforms that were part of restoring the value of the Lebanese currency and attracting investments particularly in the alternative energy industry. Between 2025 and beyond, the wind capacity is expected to be maintained at 226 MW with a production of 615 GWh. However, the future years signify that the projection and goal for this period focused on piloting and establishing the wind projects before considering expansion. In this case, wind energy projects would be at an assessment phase beyond 2025 in Lebanon. Wind energy provides Lebanon with an opportunity for progress, job creation, and energy independence, which is critical during currency instability since foreign investment and economic performance are driven. Viable as a renewable source, wind energy will enable Lebanon to commit to lowering its carbon emissions, even on a small scale. Renewable, wind energy diversification would ensure that Lebanon is secure and resilient in energy consideration after the Beirut port explosion.

The historical trend analysis from 2018 to 2030 reveals Lebanon's evolving approach to PV capacity deployment. For instance, from 2018 to 2022, Lebanon did not place greater prominence on PV capacity due to other immediate energy solutions or as the PV sector was in the early stages of maturity. In 2023, a capacity of 105 MW, accounting for 182 GWh of PV, was established, representing initial pathways towards high solar energy production, with post-crisis support funding the experimental process. The subsequent period between 2023 and 2026 saw the retention of PV capacity constant at 105 MW and 182 GWh as an attempt to evaluate its performance and the grid integration. Moreover, capacity had reached 405 MW and 704 GWh by 2030, corresponding to improved conditions, technological benefits, and developmental support. In practice, implementing PV projects capitalizes on Lebanon's extremely high solar irradiance. It diversifies the energy politics, which follows the government's strategy for aligning energy to its economic status while using renewable energy to stimulate economic growth and reduce reliance on costly fuels. On the environmental level, developing the PV system contributes to the national and global objectives for sustainability through renewable energy practices in Lebanon, easing GHG production and fossil fuel dependency. In addition, on the social level, the PV provides opportunities for employment while ensuring a reliable and inexpensive energy source, critical in enhancing living standards after a crisis.

Lebanon's PV sector failed to produce from 2018 to 2022, which indicates its early development at the time and prioritization for immediate energy solutions during the country's massive economic and infrastructure challenges. Lebanon's large-scale solar power journey commenced in 2023, recording the start of its PV production at 105 MW capacity, which realized the generation of 182 GWh, most probably to reduce energy dependencies during a commitment to post-crisis recovery and stabilization. Between 2023 and 2026, the produced PV capacity stagnated at the same level of 105 MW, producing 182 GWh, which is likely to indicate a period of performance assessment and grid installation integration. In 2030, PV production will have grown to a capacity of 405 MW and output of 704 GWh, which indicates the solar infrastructure installation realization amidst better economic conditions, advanced solar technologies, and more international support. The implementation and expansion of PV projects in Lebanon involve realizing benefits at the strategic, environmental, and social levels. At a strategic level, Lebanon benefits from the economic advantages of harnessing solar irradiance for generation and energy diversification to cushion currency fluctuations and failure of energy sources. Environmental benefits are reflected through the country's commitment to global warming reduction and minimization of fossil fuel dependency. Socially, the deployment of PV projects creates job opportunities and enhances skill development and livelihood enhancement, which are crucial in post-crisis stability and recovery.

Between 2018 and 2025, Lebanon barely accounted for the development of CSP technology. High investment costs and technological complexity could have been the primary reasons for CSP to remain underestimated in the country compared to the more easily deployable PV or wind power. Moreover, one possible reason that CSP capacity does not just stand still between 2025 and 2030 is technical barriers, among others. The constant lack of growth in CSP capacity implies that policy prioritizes other fast-deploying, lower-cost energy forms. These goals can hardly be achieved in Lebanon in normal conditions, especially considering the recent economic challenges. The devaluation of the currency and the general fiscal instability could have driven substantial investment resources into wind power and PV. The lack of investment leads to capacity stagnating, with more dependence on renewable energy. The goal may still be met, as is the case with Lebanon. However, CSP can only be used when there is a stable economic environment and sufficient labor. Even though the investments in CSP local capacities stopped in 2030, it does not mean that Lebanon has essentially abandoned the plans.

From 2018 to 2025, Lebanon excessively utilized its already available hydroelectric structures to keep generating power despite the refugee crisis, political instability, the COVID-19 pandemic, and the blast at the Beirut port. There was no initiation of new hydropower projects during this period because the country was primarily focused on existing challenges and economic mediocrity. From 2025 to 2030, the power output remains the same, reinforcing the possibility that no new developments will be made in the hydroelectric infrastructure. It is deducible that Lebanon decided to exhaust previously available resources while considering potential sustainable energy or resource management or facing economic and logistical barriers to implementing new hydropower projects. Economically, the steady power output from hydropower promotes energy stability, eliminating the possible multiplication of new investments during economic shifts. Environmentally, hydropower helps Lebanon reduce its carbon emission burden and ensures a clean and renewable source that aligns with the grid and environmental compliances.

3.4. 2030 Target Optimization

3.4.1. Introduction to MATLAB Code

We focus on highlighting the optimal solution, particularly aligning with our target of attaining 30% of electricity from renewable energies by 2030. This scenario is shaped by examining the boundaries of both the "pessimistic" and "optimistic" scenarios. Thus, in pursuing an environmentally friendly future, we will prioritize the data spanning from 2025 to 2030. This MATLAB code represents a series of comprehensive analyses of changes in energy consumption that will lead to an environmentally friendly future. Overall, the code aims to determine the mix of all renewable energy sources that proves to be the most cost-effective and efficient. The scenario presented in the code comprises an optimization model that calculates wind, combined centralized and dispersed hydropower, and CSP from 2025 to 2030, inducing the optimal solution. By incorporating costs related to the capacity of each energy source and the variability of CSP sources, the code uses linear programming to determine the best possible combination of all energy sources' capacity for the years from 2018 to 2030. This optimization technique calculates the most cost-effective combination of renewable shares that add up to the total energy needed while achieving an aggregate target of 0.3. The latter means that renewable energy resources should consume 30% of the electricity by 2030, per the UN SDG target. The code determines the distribution of different sources, assuming dynamic capacity constraints to minimize costs throughout the years. This strategy perfectly fits the desired goal and showcases the commitment to engaging more and more sound energy solutions. The subsequent results from this MATLAB code, including the distribution of energy and minimal cost, will be utilized for strategic planning for a more sustainable future. It exemplifies how Lebanon can achieve its transition towards a sustainable renewable energy future.

3.4.2. Code Analysis

- The Objective Function for the Optimization is Defined as:

$$C = c_1x_1 + c_2x_2 + c_3x_3 + c_4x_4 + c_5x_5$$

This linear function aggregates the total cost of the energy mix, where variables x_1 to x_5 represent the electricity shares of each energy source.

- **Cost Definition**: Costs for each energy source are defined at the beginning. These costs are used in the objective function of the linear programming problem.
    1. Wind (c_1= 70,000): Represents the cost per energy produced for wind energy ($/GWh).
    2. PV Centralized (c_2 = 81,000): Cost per energy produced for centralized solar photovoltaic energy ($/GWh).

3. PV Distributed (c_3 = 45,000): Cost per energy produced for distributed solar photovoltaic energy ($/GWh).
4. Hydro (c_4 = 8,500): Cost per energy produced for hydroelectric energy ($/GWh).
5. CSP (c_5 = 390,000): Cost per energy produced for concentrated solar power ($/GWh).

- **Constraints:** Equality Constraint: The sum of the shares of all energy sources should be equal to 0.3 in 2030. This is expressed as: $x_1 + x_2 + x_3 + x_4 + x_5 = 0.3$
- **Bounds Normalization**: Each energy source has lower and upper bounds; for the minimum and maximum share of each energy source, respectively. These were obtained from the two scenarios introduced earlier: pessimistic and optimistic, and in each, upper one and lower one, and were defined per year 2018-2030. They were normalized by division with the total generation, including the losses of each year based on which the scale was adequate for the optimization algorithm.
- **Optimization Tool**: The code goes through all the combinations of lower limits for each year. For every combination, it sets up a programming problem to minimize the cost while satisfying capacity constraints (upper and lower limits) and a sum constraint (the total shares should add up to 0.3, which is the target set by the UN SDGs for 2030). The optimization uses the LINPROG function, which finds the energy shares that minimize costs.

- **Display of Results**: At the end of the function, the best combination of upper and lower bounds, the optimal energy shares, and the minimum cost are displayed.

3.4.3. Input Data

For the year 2025:

Upper Bounds (ub): Based on the "optimistic" scenario, calculated by dividing the forecasted power of each source by the total annual energy generated, including losses.

- **Wind:** $\frac{615}{17914}$, Wind power share of 615 (GWh) out of the total electricity generated including losses (GWh)
- **PVc:** $\frac{460}{17914}$
- **PVd:** $\frac{2475}{17914}$
- **CSP:** $\frac{345}{17914}$
- **Hydro:** $\frac{563}{17914}$

Lower Bounds (lb): Based on the "pessimistic" scenario, calculated similarly by dividing forecasted power of each energy source by the total annual energy generated including losses value.

- **Wind:** $\frac{0}{17914}$
- **PVc:** $\frac{182}{17914}$
- **PVd:** $\frac{2223}{17914}$

- **CSP:** $\frac{0}{17914}$
- **Hydro:** $\frac{347}{17914}$

Similar calculations were carried out for the other years till 2030, and the results are presented in table 7.

Table 7 represents the data related to the shares of various RE sources from 2025 to 2030. The shares are expressed as fractions of energy produced in the total electricity generated, including losses. These data can facilitate the determination of the optimal shares that minimize the costs associated with RE integration.

Table 7: Input data of optimized projections

Year	Bounds	Wind Share	PV Centralized Share	PV Distributed Share	CSP Share	Hydropower Share
2025	Upper	$\frac{615}{17914}$	$\frac{460}{17914}$	$\frac{2475}{17914}$	$\frac{345}{17914}$	$\frac{563}{17914}$
	Lower	$\frac{0}{17914}$	$\frac{182}{17914}$	$\frac{2223}{17914}$	$\frac{0}{17914}$	$\frac{347}{17914}$
2026	Upper	$\frac{615}{18088}$	$\frac{460}{18088}$	$\frac{2971}{18088}$	$\frac{345}{18088}$	$\frac{628}{18088}$
	Lower	$\frac{615}{18088}$	$\frac{182}{18088}$	$\frac{2372}{18088}$	$\frac{0}{18088}$	$\frac{347}{18088}$
2027	Upper	$\frac{615}{18375}$	$\frac{981}{18375}$	$\frac{3465}{18375}$	$\frac{345}{18375}$	$\frac{692}{18375}$
	Lower	$\frac{615}{18375}$	$\frac{182}{18375}$	$\frac{2522}{18375}$	$\frac{0}{18375}$	$\frac{347}{18375}$
2028	Upper	$\frac{2247}{19294}$	$\frac{981}{19294}$	$\frac{3960}{19294}$	$\frac{1035}{19294}$	$\frac{757}{19294}$
	Lower	$\frac{615}{19294}$	$\frac{182}{19294}$	$\frac{2671}{19294}$	$\frac{0}{19294}$	$\frac{347}{19294}$
2029	Upper	$\frac{2247}{20259}$	$\frac{1503}{20259}$	$\frac{4454}{20259}$	$\frac{1035}{20259}$	$\frac{822}{20259}$
	Lower	$\frac{615}{20259}$	$\frac{182}{20259}$	$\frac{2821}{20259}$	$\frac{0}{20259}$	$\frac{347}{20259}$

2030	**Upper**	$\frac{2247}{21272}$	$\frac{1503}{21272}$	$\frac{4950}{21272}$	$\frac{1035}{21272}$	$\frac{887}{21272}$
	Lower	$\frac{615}{21272}$	$\frac{704}{21272}$	$\frac{2970}{21272}$	$\frac{0}{21272}$	$\frac{347}{21272}$

3.5. Analysis of Optimal Shares

Table 8: Renewable energy progress in Lebanon: shares, SDGs, and benefits (2025-2030)

Years	RE Shares	SDGs	Benefits
2025	PV Distributed: 12.41% Hydro: 1.94%	SDG 7: Affordable and Clean Energy	- Access to reliable, modern, and affordable energy for all. – Less dependence on fossil fuels. - Improved energy security. - Economic expansion and job opportunities.
2026	Wind: 3.40% PV Centralized: 1% PV Distributed: 13% Hydro: 2%	SDG 13: Climate Action SDG 9: Industry, Innovation, and Infrastructure SDG 8: Decent Work and Economic Growth	- Diversified energy mix and reduced carbon emissions. – Use of advantageous wind conditions to boost sustainable industry and innovation. - Boosts local economies and fosters investment and employment expansion.
2027	Wind: 3.35% PV Distributed: 1% Hydro: 13.73%	SDG 7: Affordable and Clean Energy SDG 11: Sustainable Cities and Communities SDG 9: Industry, Innovation, and Infrastructure	- Access to affordable, dependable, sustainable, and modern energy services for all. - Improved energy security and resilience. - Fosters investment and promotes innovation and technical progress.
2028	Wind: 3.04% PV Distributed: 0.90% Hydro: 13.92%	SDG 7: Affordable and Clean Energy SDG 8: Decent Work and Economic Growth SDG 13: Climate Action	- Enhances sustainable energy access. – Less dependence on fossil fuels. - Economic growth and the creation of employment opportunities. - Mitigates climate change and reduces carbon emissions.
2029	Wind: 3.98% PV Centralized: 4.56% PV Distributed: 19.22% Hydro: 2.25%	SDG 7: Affordable and Clean Energy SDG 9: Industry, Innovation, and Infrastructure SDG 13: Climate Action	- Promoting affordable, dependable, and available energy services. - Stimulates the development of new ideas and technical progress. - Supports worldwide initiatives to combat climate change and foster sustainable development.

2030	Wind: 3.98% PV Centralized: 4.56% PV Distributed: 19.22% Hydro: 2.25%	SDG 7: Affordable and Clean Energy SDG 8: Decent Work and Economic Growth SDG 13: Climate Action SDG 11: Sustainable Cities and Communities SDG 12: Responsible Consumption and Production	- Reduces dependence on fossil fuels and shifts towards clean, sustainable energy sources. – Fosters energy availability and affordability. - Stimulates economic development and job creation.

3.5.1. Projection of Energy Production

- **For year 2025:**

1. Wind: $0 \times 17914 = 0\ GWh$
2. PV Centralized: $0.010160 \times 17914 = 182\ GWh$
3. PV Distributed: $0.124093 \times 17914 = 2223\ GWh$
4. Concentrated Solar Power: $0 \times 17914 = 0\ GWh$
5. Hydropower: $0.019370 \times 17914 = 347\ GWh$

A similar approach has been iterated until 2030; the results are presented in Table 9.

Table 9: Projection and optimization results for all RE sources

Year	Electricity Generated, including Losses (GWh)	Wind Energy (GWh)	PV Centralized Energy (GWh)	PV Distributed Energy (GWh)	CSP Energy (GWh)	Hydropower Energy (GWh)
2025	**17914**	**0**	**182**	**2223**	**0**	**347**
2026	**18088**	**615**	**182**	**2372**	**0**	**347**
2027	**18375**	**615**	**182**	**2522**	**0**	**347**
2028	**19294**	**615**	**182**	**2671**	**0**	**347**
2029	**20259**	**615**	**182**	**2821**	**0**	**347**
2030	**21272**	**820**	**938**	**3960**	**0**	**462**

The table shows RE electricity generation, including losses, in Lebanon in GWh for the years up to 2030. Wind energy production starting in 2026 will rise to 615 and will remain fixed at this level until 2030, when a major expansion in the wind generation capacity is planned, thus increasing the installed energy up to 820. However, centralized PV energy remains unchanged for the period mentioned and remains at 182 GWh production annually for 2026-2030, which implies no growth in centralized PV energy for Lebanon at that time. Distributed PV, however, grows at a low or moderate pace from 2372 GWh in 2026 up to 2821 GWh in 2029, possibly due to incentives or the reduction of the cost by the Lebanese government; however, CSP energy is shown as producing 0 annually, which may suggest no development in this technology for the given dates. The only RE source presented annually is hydropower, which, at 347 GWh, remains unchanged during the period mentioned. The statistics indicate potential barriers and opportunities in Lebanon’s RE landscape; however, more detailed analysis is required to understand compounding factors and develop appropriate strategies for the country’s future RE development.

3.5.2. Analysis of Optimized Capacities

LCEC’s projections include a massive rise in wind energy, from zero MW in 2025 to 2,247 MW in 2030. Still, the optimized capacities follow a cautious line of development, beginning from zero in 2025 and growing to 820 MW by 2030. When considering Lebanon’s economic, environmental, and social conditions and the 2030

SDGs target, the decision to expand in renewable energy originally began with a cost-effective strategy. The optimal wind energy capacity seems to be quite cautious compared to projections. This could be explained by some risks, including the uncertainty about the wind resources' availability, land scarcity, or difficulties in infrastructure development. The fact that Lebanon has excellent wind conditions due to its mountains and coastline does not reduce expenditures on utilization, and all risks previously discussed could occur. Therefore, the country's best reaction to such threats is expanding capacity by 2025-2030. Such mitigation is consistent with SDG Target 7, which involves reducing reliance on fossil fuels and supporting climate change fighting measures.

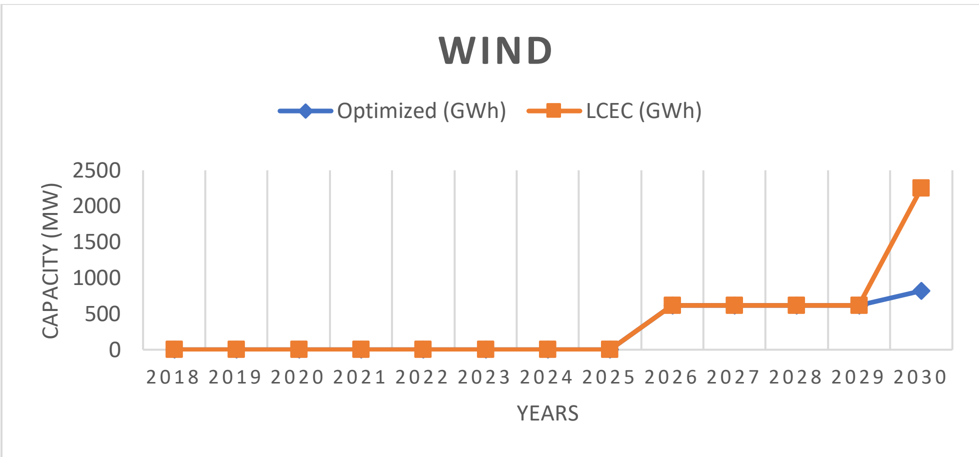

Figure 4: Wind energy projections

Source: Beirut Energy Week 2023

According to the official projections, the centralized PV capacity will increase significantly, from 182 MW in 2025 to 1225 MW in 2030. On the contrary, the optimized capacities begin at 182 MW in 2025, with steady growth to 704 MW in 2030.

As previously demonstrated, Lebanon values optimal resource utilization and cost-effectiveness when seeking sustainable energy and meeting the 2030 SDGs mark. The optimal capacities for the centralized PV systems also reflect insecure behavior. However, growth is constant over the summative period. Several constraints could influence this, including land availability, grid connection issues, and financial uncertainty. The country's high amounts of solar insolation make it attractive to pursue RE with PV, but it is necessary to optimize capacity to balance economic feasibility and energy. Lebanon can optimize its solar power potential while avoiding the dangers of high growth by gradually expanding its centralized PV to the projected 704 capacity. This is consistent with SDG 7, which calls for universal access to safe, efficient, and sustainable energy sources.

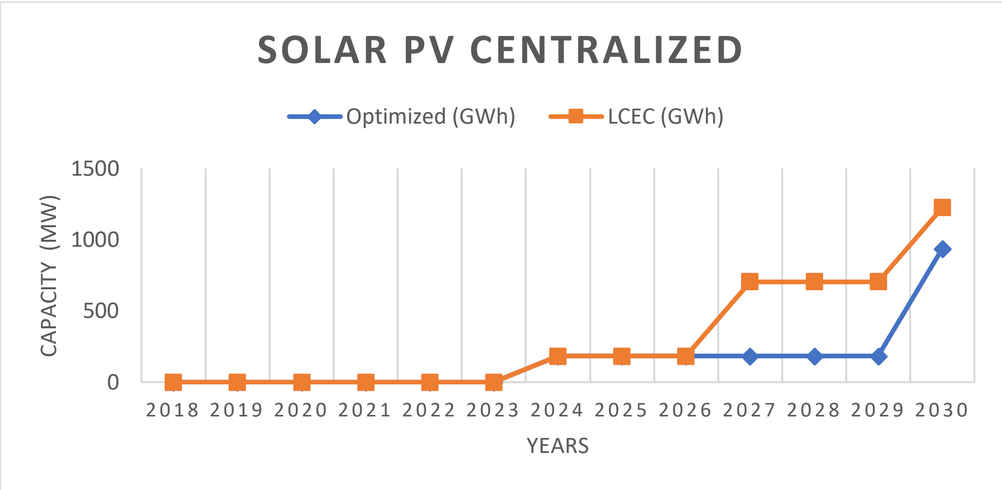

Figure 5: Centralized PV energy projections

The projections demonstrate the significant increase in the capacity of distributed PV, from 2506 MW in 2025 to 3960 MW in 2030; the optimized capacities show an additional, gradual rise starting from 2506 MW in 2025 to 3669 MW in 2030. Therefore, this opportunity to combine the economic efficiency and implementation of renewable sources is a timely strategy that would significantly contribute to Lebanon's socio-economic growth and the 2030 SDGs. Likewise, the pattern of gradual expansion of the optimum capacities for distributed PV systems is like the one that is expected according to the forecasts. This approach is wise and might be affected by multiple factors, including the availability of rooftop space, integration possibilities, and available incentives for distributed production. Due to their ability to enhance energy resilience and the autonomy of local populations, distributed PV systems play a unique role in the process of energy production decentralization. Therefore, Lebanon has developed an efficient and environmentally friendly approach that may help to prevent the challenges of energy access by addressing the issues of energy procurement. This union correlates with SDG 7 and SDG 11 because it enhances the use of clean energy and provides sustainable local communities.

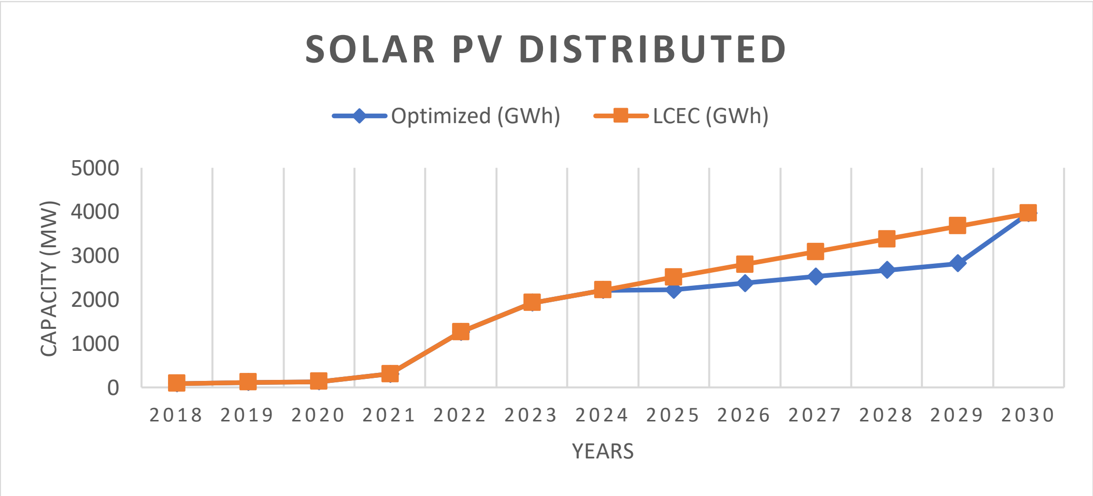

Figure 6: Distributed PV energy projections

Projections suggest that CSP capacity would increase at a moderate rate; the total capacity by 2030 is estimated to be 345 MW. In contrast, the optimized capacities consistently remained at zero throughout the assessed period, suggesting that it was in Lebanon's best interest to promote other forms of renewable energy over CSP. Such a choice aligns with the country's efforts in achieving sustainable energy targets and the related 2030 SDGs through cost-effective measures and available technology. Not including any capacity for CSP in the optimized outputs seems inconsistent with projections indicating a moderate growth from CSP to 2030. This may be due to uncertainties around the level of advancement in the technology itself, the falling cost competitiveness, or the limited area of land suitable for CSP installation. Overall, consistency with the SDGs is maintained in this choice since promoting renewable energy development is essential to address urgent socio-economic needs, while considering the cost and affordability of the technology.

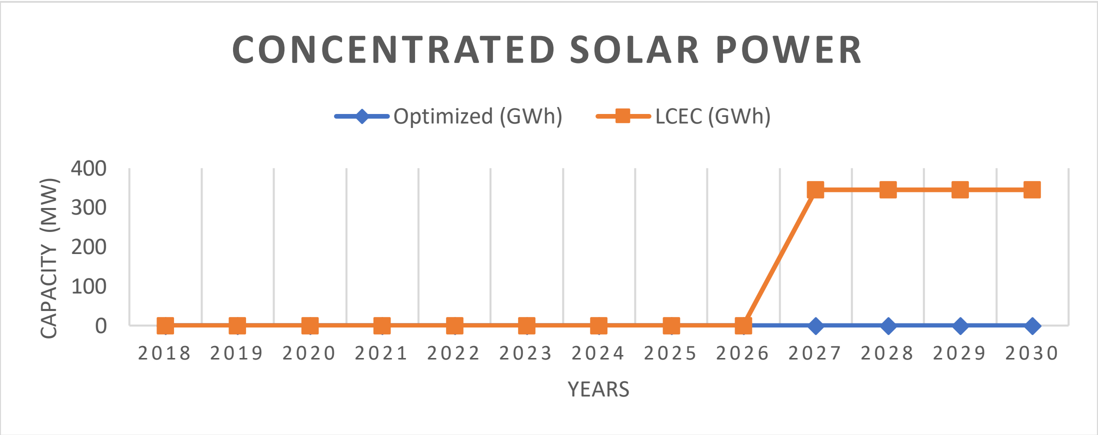

Figure 7: Distributed PV energy projections

The projections indicate a slight improvement in hydropower capacity, with an increase from 347 MW in 2025 to 563 MW by 2030. The optimal capacity is constant throughout interest, from the start and during at 347 MW. Lebanon's focus on maintaining the current hydroelectric systems to ensure a reliable electricity supply and reduce environmental damages supports the 2030 SDG objective. The optimal capacity associated with hydropower remains constant throughout interest, showing that the country does not have to develop significantly to maintain it. The role of environmental impact assessments, water resource management, and socio-economic issues can justify this approach. Hydropower is one of the most reliable forms of sustainable energy, but it may require a careful development framework to maintain its ecological suitability and equitable society. Lebanon can achieve energy security while minimizing the inherent negative environmental and social impacts by maintaining a stable capacity. This fact supports SDG 6 on clean water and sanitation and SDG 7 on sustainable water management and renewable energy use

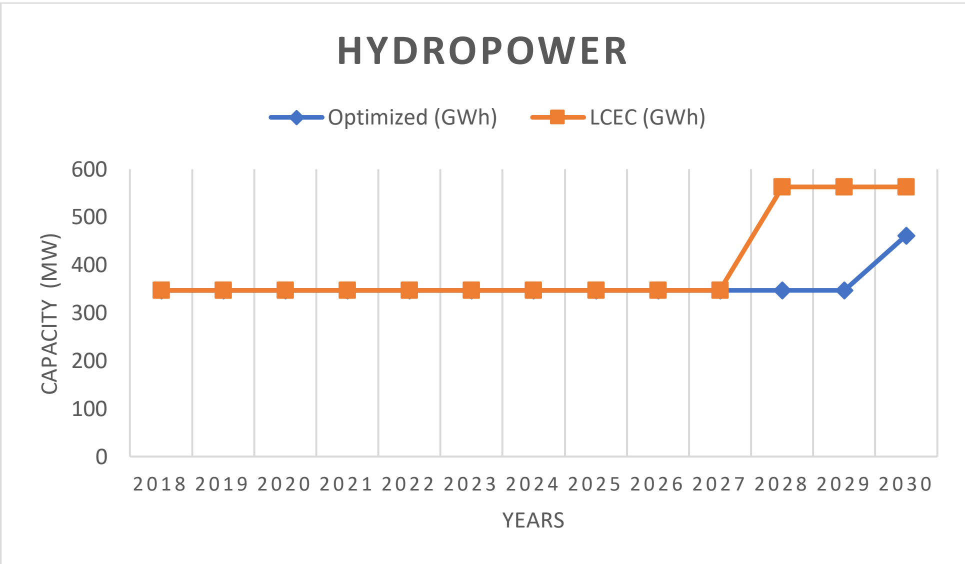

Figure 8: Hydropower energy projections

CHAPTER 4

FINAL RESULTS

4.1. Introduction

The main goal of comparing the capacities and costs of the optimized values with those offered by the LCEC projection scenario is to conduct economic feasibility of RE initiatives in Lebanon. Conducting the economic study of this comparison is aimed at evaluating the country's capacity to be directed toward a sustainable, cost-effective, and green future. The first phase of the comparison work is to compare the capacities of every RE source from 2018 to 2030 with the similar data described in the LCEC. Soon after, an analysis of the graphs and interpretations of the results will be analyzed to conclude based on the findings about the related differences and strategies. In phase two, a similar strategic approach will be made to compare the costs of the maximal values with the costs per project provided by the LCEC. This comparison will offer remarkable perspectives on how to use this information for policymakers, stakeholders, and related parties in the strategic path for Lebanon's future.

This linear function aggregates the total cost of the energy mix, where variables x_1 to x_5 represent the electricity shares of each energy sources and $c_1$to c_5 represent the cost per unit for each RE source. In essence, this equation will aggregate the costs associated with each RE source's consumption to determine the energy mix's overall minimum cost.

$$C = c_1x_1 + c_2x_2 + c_3x_3 + c_4x_4 + c_5x_5$$

The unit costs c_1 to c_5 for each of the RE sources are maintained constant across all the projection years.

1. Wind (c_1= 70,000): Represents the cost per unit for wind energy ($/GWh).
2. PV Centralized (c_2 = 81,000): Cost per unit for centralized solar photovoltaic energy ($/GWh).
3. PV Distributed (c_3 = 45,000): Cost per unit for distributed solar photovoltaic energy ($/GWh).
4. Hydro (c_4 = 8,500): Cost per unit for hydroelectric energy ($/GWh).
5. CSP (c_5 = 390,000): Cost per unit for concentrated solar power ($/GWh).

4.1.1. Levelized Cost of Energy of Optimized Energies

2025: $Cost = c_1(0) + c_2(0.010160) + c_3(0.124093) + c_4(0) + c_5(0.019370)$. The calculated minimum cost for this energy mix is 6,571$/GWh. Since the cost per unit is expressed in ($/GWh), it typically represents the Levelized Cost of Energy (LCOE). The LCOE is a measure that considers both the capital expenditure (CAPEX) and operational expenditure (OPEX) over the project's lifespan. Therefore, to determine the LCOE, we divide the electricity generated, including losses, by the sum of the energy produced. Where each cost per unit expressed in ($/GWh) is multiplied by the optimal share conducted for each source.

Minimum Cost = 6571 $/GWh

$$\text{LCOE} = \frac{6571}{2752} = \mathbf{0.238 \times 10^{-3}} \ (\boldsymbol{C/kWh})$$

Table 10: Levelized cost of optimized energies

Year	x_1	x_2	x_3	x_4	x_5	Minimum Cost ($/GWh)	LCOE (c/kWh)
2025	0	0.010160	0.124093	0	0.019370	6571	0.238×10^{-3}
2026	0.0340	0.010062	0.131137	0	0.019184	9259	0.263×10^{-3}
2027	0.033469	0.009905	0.137252	0	0.01884	9481	0.258×10^{-3}
2028	0.031875	0.009433	0.138437	0	0.017985	9377	0.245×10^{-3}
2029	0.030357	0.008984	0.139247	0	0.017128	9267	0.233×10^{-3}
2030	0.039797	0.045557	0.192192	0	0.022455	15315	0.247×10^{-3}

4.1.2. *Optimized Costs Vs. LCEC Costs*

The costs for both optimized and levelized cost of energy calculation models for each renewable energy source remain constant from 2018 to 2024, this implies that there is a stability or no variance in the cost-reduction strategies. This stability described above acts as control that is essential in examining how optimization has contributed to the declining energy cost in 2025.

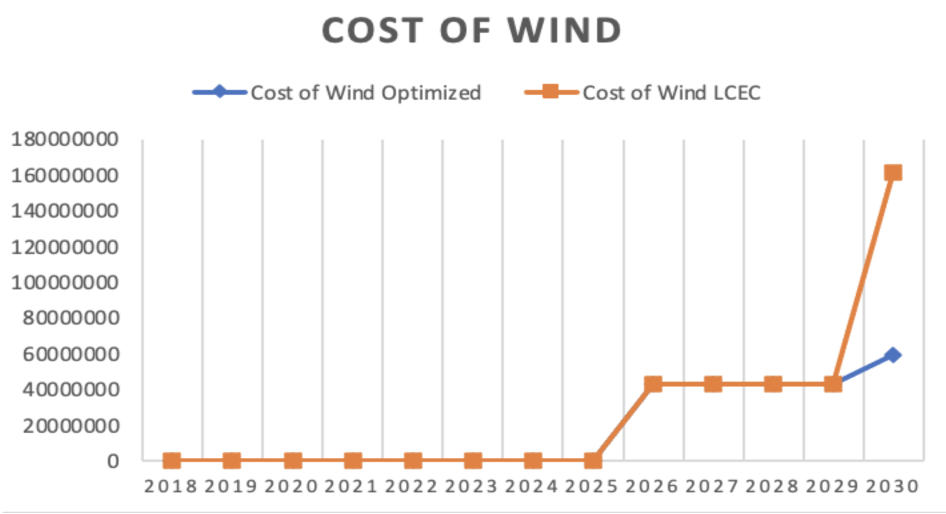

Figure 9: Wind power-cost comparison

- **Wind Energy (2025-2030):** Costs of optimal and LCEC are fixed for 2026 at 43,049,440 ($), 2027 at 43,049,501 ($), 2028 at 42,893,550 ($), and 2029 at 43,050,172 ($) with zero cost variations as savings. By 2030, the optimized cost reaches 59,259,324, much lower than the LCEC cost of 161,539,568 ($), contributing to substantial savings. Therefore, the total savings are 102,280,244 ($).

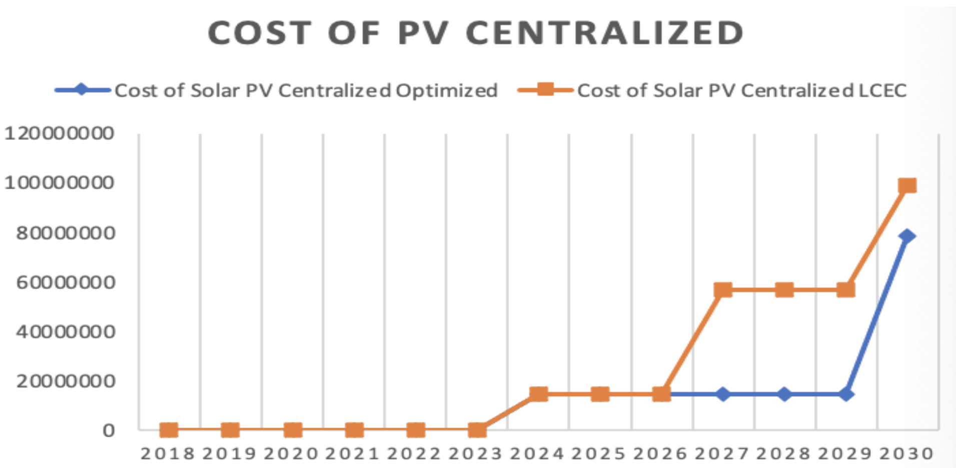

Figure 10: Centralized PV-cost comparison

- **PV Centralized (2025-2030):** The costs will remain unchanged until 2027. Starting in 2027, the optimized costs will be consistently lower than the LCEC costs. In 2027, the optimized costs will be 14,742,505 ($), compared to 57,017,625 ($) for LCEC. In 2028, the optimized costs will be 14,742,024 ($), compared to 57,013,770 ($) for LCEC. And in 2029, the optimized costs will be 14,742,555 ($), compared to 57,008,826 ($) for LCEC. The optimal cost in 2030 is 78,496,168 ($), lower than the LCEC cost of 99,212,608 ($). Hence, the savings exhibit progressive growth, starting at 42,275,271 ($) in 2027 and reaching a cumulative amount of 20,716,440 ($) by 2030.

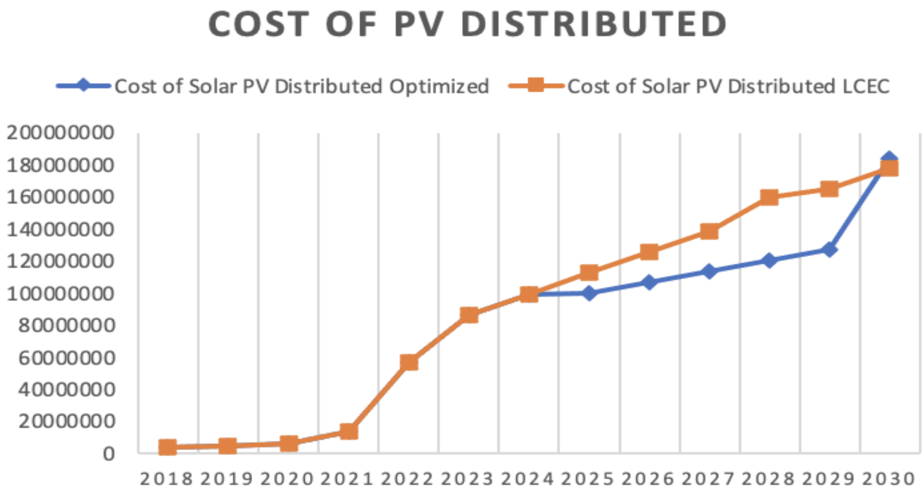

Figure 11: Distributed PV-cost comparison

- **PV Distributed (2025-2030):** By 2025, the optimized cost equals 100,035,090 ($), while the LCEC cost remains at 112,768,630 ($). The savings persist until 2029 since the optimized costs remain lower than the LCEC prices. By the year 2030, the costs of both will be the same. Therefore, the cumulative savings achieved between 2025 and 2029 is 129,046,613 ($).

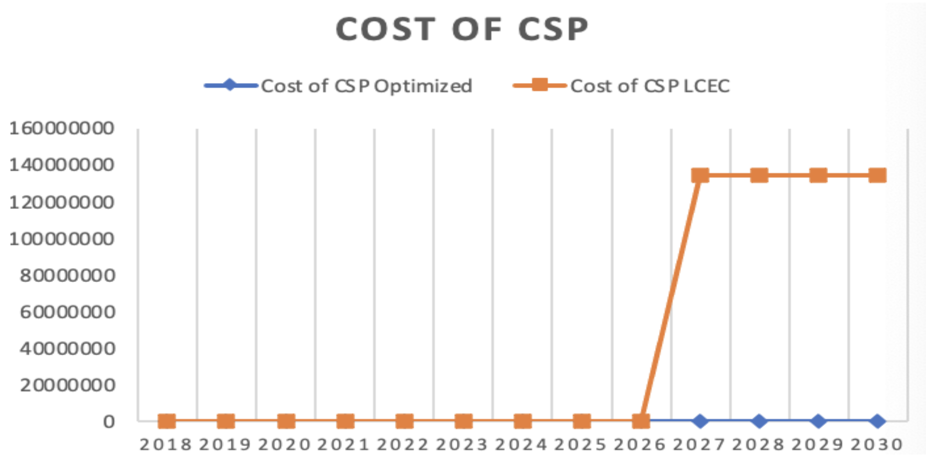

Figure 12: CSP-cost comparison

- **Concentrated Solar Power (2025-2030):** There will be no observed costs until 2027. Starting in 2027, substantial annual savings are amounting to 134,541,750 ($),134,537,062 ($), 134,540,019 ($), 134,545,400 ($) for each consecutive year. Until 2030. So, the cumulative savings achieved between 2027 and 2030 amount to 538,164,231($).

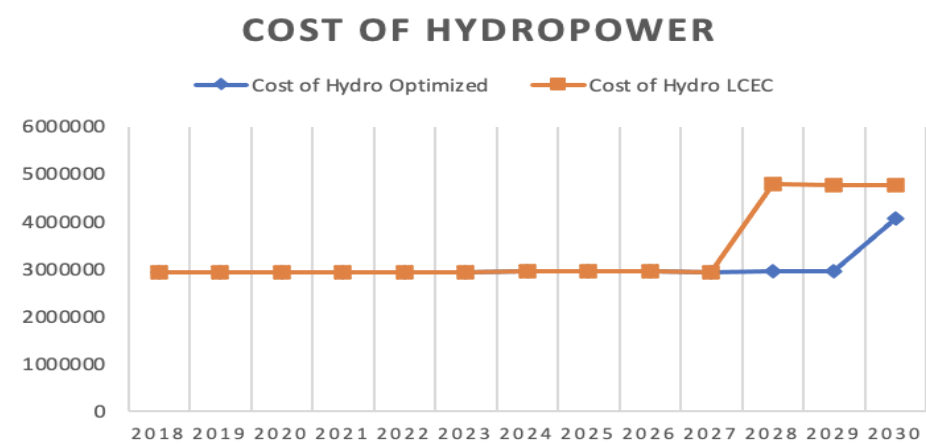

Figure 13: Hydropower-cost comparison

- **Hydropower (2025-2030):** The expenses remain unchanged until 2027. Starting in 2028, the optimized costs are cheaper than the LCEC prices. In 2028, the optimized expenses will amount to 29,495,22 ($), compared to 47,849,12 ($) for LCEC. In 2029, the optimized costs will be 29,494,67 ($), while the LCEC costs will be 47,811,24 ($). Finally, in 2030, the optimized expenses will be 40,601,33 ($), while the LCEC costs will be 47,649,28($). Hence, the cumulative savings achieved between the years 2028 and 2030 reach a sum of 43,718,42 ($).

Table 11: Total savings

Sources	**Wind**	**PV Centralized**	**PV Distributed**	**CSP**	**Hydropower**
Old Cost ($)	333,582,231	299,737,451	880,426,471	538,164,231	231,724,87
Optimized Cost ($)	231,301,987	152,207,723	751,379,858	0	188,006,45
Total Savings ($)	102,280,244	147,529,728	129,046,613	538,164,231	437,184,2

CHAPTER 5
CONCLUSION

In the contemporary context, there is a crucial need to focus on expanding renewable energy capacities beyond meeting set targets. The deployment of RE directly influences different social environments and the economic, environmental, and social well-being of the people. It is vital to understand that amidst the increased speed of global climate change, Lebanon should not only take its domestic obligation weight but also use international efforts to reduce emissions. Furthermore, the post-COVID-19 surge in energy demand has observed increased oil prices due to expanding needs in transportation, industry, and infrastructure, emphasizing the difficulty of meeting demand in the presence of limited low-cost petroleum reserves. Importantly, this factor leads to the increased production of CO2 and environmental risks. Thus, Lebanon has a perfect opportunity to use international support to transition to affordable cleaner energy. It will create an opportunity for improving the national plan on a long-term basis, introducing new technology and developments in renewable energy, such as PV and wind power, to enhance national energy infrastructure.

As such, this thesis has thoroughly investigated the deployment of wind, centralized PV, distributed PV, CSP, and hydropower energies in Lebanon. Its emphasis was placed on fitting the deployment of each renewable energy source sector based on economic feasibility, met by the methodological approach based on the optimization method, determining the optimal share for each. In addition, various energy scenarios aided the analysis by addressing the need for sustainable energy and meeting the UNSDG target demand to have 30 % of the end-use energy demand from renewables by

2030. In each, the capacities and power deployed by each renewable energy source, the costs of transmission and distribution, the demand for electricity, and the deployment of renewable energy sources used were the significant factors considered.

Further this study will include complete economic analyses that will consider the capital, operation and maintenance, and the current market prices of the selected renewable energy sources. These analyses will be essential to validate the viability of each scenario and determine if the projections are within the central aim of sustaining growth. Secondly, this research undertaking aims to offer critical insights that will allow key players such as policymakers, other stakeholders, and the parties involved in the shift to renewable energy in Lebanon. By undertaking quantitative comparison and analyzing data to escalate cuts in the period between 2018 and 2030, the study is ready to offer actionable knowledge and intelligence to ensure a transition to economically viable and environmentally sustainable energy.

Ultimately, within the range of vital guidelines designed to trigger massive investments in RE and propel sectoral development, there is a set of risk mitigation approaches that address a variety of dimensions, including legal, economic, social, financial, institutional, and regulatory ones. Yet, with the view of underpinning the global investment surge, a critical need arises to implement a workable long-term national strategy supported by the corresponding laws, norms, and rules with a suite of risk mitigation approaches. Suppose they are coupled with a robust risk mitigation framework. In that case, these measures are projected to produce a favorable investment climate and create a setting that enables the retrieval of substantial capital.

In essence, the transition to clean energy in Lebanon is crucial for the attainment of the 2030 SDGs. This study aspires to offer practical ideas that will enable the country to achieve these goals, prioritize economic feasibility, and prefer optimization of energy mixing approaches. The incorporation of RE projects is likely to lead to sustainable societal benefits and contribute to the country's wealth and power and stability.

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