International Journal of Power and Energy Systems, Vol. 45, No. 10, 2025
An Open Access Paper

REVIEW OF RENEWABLE ENERGY HYBRID SYSTEMS FOR ALTERNATIVE SOLUTIONS

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Abstract

Hybrid renewable energy systems (HRESs), which combine a number of technologies, have proven to be highly effective at reducing challenge costs and resolving stability issues. To get over associated restrictions, it becomes sense to use hybrid energy producing systems with energy storage technology. Thus, the installation of HRES is highlighted in this research as a sustainable and effective way to meet energy needs, lower greenhouse gas emissions, and fight climate change. The many uses for renewable energy (RE) sources, modelling and simulation methods, environmental and economic analysis, and challenges in putting RE systems into practice are all covered in this article. In order to attain energy security, advance sustainable development, and create a cleaner energy infrastructure for the future, the paper highlights the shift to RE and discusses Lebanon's experience establishing sustainable RE systems as well as the difficulties it faces.

Key Words

Hybrid renewable energy system (HRES), energy storage systems (ESSs), modelling and simulation, energy infrastructure, challenges, Lebanon's case

1. Introduction

Renewable energies have emerged as a viable solution to meet the long-term energy requirements of a variety of sectors, including industrial, residential, transportation, and public utilities, in light of the anticipated depletion of non-RE and the associated harmful emissions. In the present day, renewable resources are used to protect the environment and lower the cost of generation for thermal power plants [1]. It is anticipated that the carbon dioxide quantity in the atmosphere will rise, potentially reaching a 59% level by 2030 [2]. Consequently, it is imperative to identify alternative energy solutions.

The utilisation of renewable energy (RE) is especially critical in numerous countries, including India [3], Iran [4], and others [5], that have rural areas that are remote from the primary electricity grid.

In addition to that, it is extremely expensive to continuously deliver energy to these places which makes it quite difficult for individuals to obtain affordable electricity. In recent decades, scientists have created several methods to produce energy efficiently [6]. The solution was to establish local stations to produce electricity through RES, such as wind, solar, biomass, hydrogen, water, and geothermal [7]–[9] in a way that they are completely independent of the main network or connected to it.

The selection of any RE source varies according to various factors, including the nature of the land, the climate in the region throughout the year, the amount of energy the region needs, the cost, *etc.* There are many criterions that could influence the cost of the project, and in many cases more than one source is used therefore it is called hybrid RE system (HRES) [10].

Therefore, understanding every aspect that influences the system performance and carefully sizing every component are necessary for an accurate system design [11] because one of the difficulties in developing RE systems is creating ones with minimal negative socioeconomic and environmental effects, and in many cases more than one source is used, cogeneration is integrated with wind and solar energy by Sontag and Lange [12]. Trillat Berdal *et al.* [13] combine thermal solar collectors with a ground-coupled heating system to satisfy an individual home's needs for hot water and heating. Additionally, Lee *et al.* [14] studied a combined renewable system that included a gas-powered boiler, an electric chiller, an underground source heat pump, solar photovoltaic and solar-powered water heating.

Energy storage systems (ESSs) may be incorporated into HRESs. The advantages of operating microgrids can be enhanced by the ESS, which can replace diesel-powered generators and provide end users with emergency power. Battery ESSs (BESSs) can fulfill the needs of end users for a diverse range of services, such as energy and power

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(DOI: 10.2316/J.2025.203-0572)

consumption, reliable service provisioning, and service delivery reliability, as per [15]. Numerous articles have reviewed HRESs and their complementarity with other energy sources in the field of research [16]. Photovoltaic (PV), wind, hydro, geothermal, tidal, and biomass are all compared by Elavarasan [17]. It concentrates on solar energy and highlights how important RES are to meeting the world's energy needs and reducing greenhouse gas emissions. Article [18] provides a thorough examination of RE sources, including solar, hydro, wind, bioenergy, geothermal, and hydrogen, emphasising the challenges and constraints associated with energy conversion efficiency, economy, and technology. The Ministry of New and Renewable Energy (MNRE) reports that the implemented RER-based generating capacity in India presently accounts for 18.8% of the total capacity in operation, with a projected increase to 40% by 2030 [19].

This review [20] investigates a variety of concepts associated with the integrated energy management system, which includes the supply and demand side response types and power system structures in which it functions.

This work offers a comprehensive examination of hybrid electric systems, which encompasses three subtitles: Energy Infrastructure, ESS, and DC/AC Bus Configuration. It also models and simulates RE systems, considering their distinctive challenges, policy frameworks, and Lebanon's progress in the implementation of a RE system. Ultimately, it concludes with a discussion.

Lebanon could serve as a case study for the implementation of these systems, as it has a plethora of RES, including the sun, wind, and rivers. Unfortunately, there are numerous obstacles, such as the availability of investments, security, and social stability, among others.

2. Hybrid Renewable Electric Systems

A hybrid system is characterised by the integration of multiple renewable and non-RE sources. Previous research, including that conducted Luna-Rubio *et al.* [21], focused on the integration of RE sources, including wind turbines (WT) and PV energy. Before discussing the economic benefits of hybrid systems, this study offers useful data regarding their cost-effectiveness compared to a lone source energy system (solar or wind). A system that exclusively utilises RE sources is referred to as an off-grid system [4], [22], [23]. Conversely, an on-grid system is one that includes the conventional sector [24]–[27].

Figure 1 presents the energy sources and their output current flow type. The type of output current varies in renewable sources, as wind, hydro, and tidal produce alternating current electricity, while solar and fuel cells produce DC electricity.

When it comes to RE, it is mainly affected by the weather and climate exhibit remarkable temporal and spatial variability. A frequently suggested solution for the imbalance between supply and demand created by RE generation is to combine multiple energy sources into one power plant (solar with solar, wind, or hydro). The complementary nature of RE sources is an essential element for the working of hybrid energy sources. Nevertheless, temporal

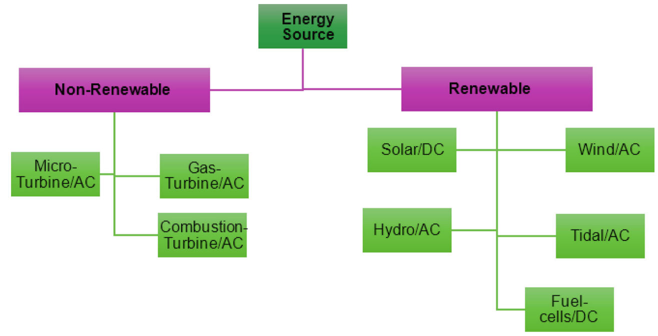

Figure 1. Distribution of energy sources.

complementarity and spatial distribution together can raise the system's overall reliability.

It is possible to see spatial complementarity between one or more energy source types. It is a situation in which energy resources cooperate with one another throughout a certain area. Regarding the temporal complementarity, it can be seen between two or more energy sources in the same area. For example, consider the wind and solar energy available throughout the year in Europe. During the autumn and winter, the former is abundant, while during the spring and summer, the latter is abundant. Berger *et al.* [28] explained in their manuscript that limited wind energy can be produced in a balanced manner on a regional scale by taking advantage of the diversity of wind patterns in the region. (In their case study, the first region is Western Europe and the other one is Southern Greenland.) In this research, it has been proven that transcontinental power generation can reduce the decline in wind energy production, supporting the need to assess the possible advantages of intercontinental electrical connections.

2.1 DC/AC Bus Configuration

A hybrid system includes energy sources, such as alternative currents/direct currents (AC/DC) and power electronic converters to transform current types into suitable ones for the load. While there are other types of DC/DC converters, the most commonly used forms are buck, boost, and buck/boost converters. The hybrid system configurations are: AC-coupled, DC-coupled, and AC/DC combination-coupled (hybrid-coupled) [29]. The use will determine which particular arrangement is applied. For example, DC linked systems, which comprise DC loads and DC sources, have the primary benefit of not necessary system synchronisation, making them appropriate for DC microgrid applications. Power frequency AC coupled systems and high frequency AC coupled systems can be used for AC microgrid applications and defense, respectively. Power frequency AC-coupled systems have either AC loads or sources, simplifying system protection, whereas high frequency AC-coupled systems have high frequency loads and AC sources operating at separate frequencies, leading to great system efficiency [30]. In comparison to prior configurations, hybrid coupled systems offer greater flexibility and the maximum efficiency because sources can be either AC or DC and the same for loads.

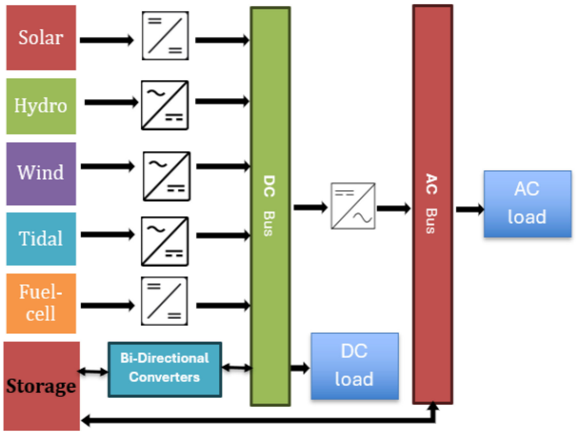

Figure 2. Basic components of some hybrid systems.

Figure 2 presents the principal elements of the hybrid system, which consist of the loads, energy storage devices, AC/DC power electronic converters, and energy sources. Inverters convert energy from renewable sources like WT or hydro turbines from DC to AC. An AC bus then distributes the converted AC power to loads, providing electricity for various purposes. In [31], an RE generator (wind/solar) was connected to a DC bus, and the battery bank and supercapacitor were linked to the DC or AC bus in parallel for charging or discharging energy.

2.2 ESS

Integration of storage systems into the system is necessary to enhance the reliability and productivity of hybrid systems [31], [32], where during periods of high energy production, ESS enable the effective absorption and usage of excess energy provided by RE. When demand is at its highest or RE sources are not actively producing energy, this stored energy can be dispersed, providing a stable and reliable supply of power. To handle the load, a backup system was required. Other issues in which ESSs have been important are [33], [34]:

- Allowing large RES penetration level,
- Enhancing operating reserve,
- Controlling of frequency,
- Improving the ability of transmission lines to transmit power,
- Lowering variations in voltage,
- Enhancing the power quality and reliability,
- Power smoothing.

There are several storage technologies with widely varying technical specifications and operational characteristics that are based on storage principles like chemical, mechanical, electrical, and thermal energy [33], [35] (Fig. 3), that are offered with a wide variety of technical and practical specifications. There is a short-, mid-, and long-term need for energy storage. Currently, when combined with added operational features, incorporating ESS technologies through the hybrid ESS (HESS) approach can be highly beneficial. The main advantages of HESS, to name a few [34], [36]:

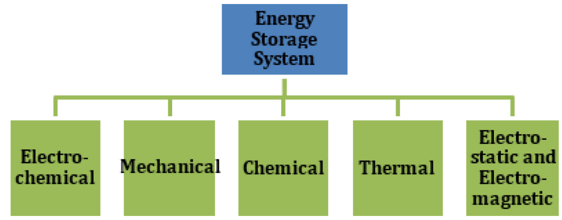

Figure 3. Energy storage systems.

- A reduction in the total cost of investment when in place of a single storage system,
- Enhancing the system's overall revenue,
- An improvement in system efficiency overall,
- Increased duration of system lifetime and storage.

Using ESS with unique properties like high energy density with low power density may cause power control issues due to their slower response times. By including a short-storage system, such as supercapacitors, the primary storage system's operating conditions are improved, extending its useful life and enabling it to meet power requirements at the same time [33], as example, particularly, lithium-ion batteries are essential to a large number of HESS applications. They are useful for storage as "high energy" or "high power."

In [31], a study was conducted on combining a chemical storage system (batteries) and an electrical storage system (supercapacitors). As a result, batteries remain longer and the energy storage has both high power and energy density.

2.3 Energy Infrastructure

Infrastructure influences HRES by facilitating grid integration, energy storage, remote monitoring and control, hybrid system integration, resource assessment, and site selection. Balancing supply and demand reduce the need for expensive infrastructure modifications. Therefore, in HRESs, improvements in energy storage have a direct bearing on the efficiency and scalability of energy infrastructure. According to the International Energy Agency, we will require $44 trillion in new energy supply infrastructure by 2040 [37], and we need to spend $45 billion annually to meet UN Sustainable Development Goal 7 and ensure access to cost-effective, durable modern energy services, it aims to guarantee that everyone has access to reliable, and cost-effective energy services; and this demonstrates how important it is to create financial support and strategy for meet targets for sustainable energy and manage global energy challenges successfully.

3. Modelling and Simulation of RES

Different RES must be integrated with one another to meet sustainable load needs under variable natural conditions. Furthermore, it is necessary to demonstrate the modelling of the different parts of this isolated or connected to grid system.

Many papers describe modelling and simulation of RES. For example, the paper of Siksnelyte-Butkiene *et al.* [26] reviews case studies, modelling techniques, control

Table 1
Hybrid Systems Analysis

Article	HS Component	Application Area	Electrical Load Details	Sizing Approach	HRES Outputs
[22]	Wind–Solar	Tunisia	2-KW	NSGA-II algorithm	$P_{pv} = 3200$ W $P_{wt} = 1029.34$ W
[41]	Wind–Solar–Biomass	–	173.65 MWh_{elec} (domestic users)	Multi-variable optimisation	102.8 $\mathrm{MWh}_{\mathrm{elec}}$
[42]	Wind–Hydro	Rwanda	The proposed PV-hydro hybrid system takes into account the 24-hour load requirement of 500 families in Mutobo village, two healthcare facilities, and three schools in the Musanze industrial zone.	P- and O-MPPT	$P_{hydro} = 200$ KW
[43]	Solar–Wind–Biomass	Jordan, the Karak governorate	The daily load requirement was 13 kWh when the load peaked at 3 kW	HOMER pro	28.2% is imported from the grid, and 71.8% is produced by wind.
[44]	Biogas	Nsukka Community (88 villages)	–	GOA and HOMER Pro	0% unmet load
[45]	Solar–Hydro–Biomass	Perugia, Central Italy	The energy covered by RES is up to 78% of the total demand	HOMER	Total RES energy generation is 33.2 GWh/year
[46]	Solar–Wind–Hydro	Papoon village - Sistan and Baluchestan - Iran	–	EO (equilibrium optimiser)	Total RES energy generation is 228.207 MWh

and management strategies, reliability studies, and optimal design methods for HRES's, it further provide an review and analysis of multiple-criteria decision-making (MCDM) methods and their advantages and disadvantages for evaluating technologies in households. The heat pumps and mathematical models of PV-thermal (PVT) solar arrays developed in the MATLAB environment were then linked to TRNSYS through the specialised Type 155 interface (intended for PV array simulation). Emmi *et al.* [23] used computer simulations to investigate different system configurations in accordance with a mathematical model developed to evaluate the hybrid solar collectors' thermal and electrical capabilities. In study of Talaat *et al.* [38], MATLAB/Simulink was employed in order to create simulation models of the hybrid energy system comprising fuel cells, solar energy, and wave energy. This study integrated three RE sources (fuel cells, solar energy, and wave energy) into a hybrid energy system. A controller was developed to integrate these sources and regulate the flow of energy through using buck-boost technology. The outcomes demonstrated that, with a 98% efficiency rate. In [39], in the first, a predetermined daily load profile and a mix of several commercially available PV modules were used to optimise a wind–PV hybrid system. The findings demonstrated that a system with a reduced cost may be achieved by matching the given load with a mix of different module ratings. In the second scenario, the ideal size of a wind–PV hybrid system under randomly fluctuating load was determined using a genetic algorithm (GA) approach. Another example, regardless of the monthly energy demand patterns, Nfah *et al.* [40] presented a novel approach that can be employed for PV hybrid systems sizing.

Table 1 presents the electrical load in some locations and the output of renewable energies from HRES, with an annual production of 102.8 MWhel [41], the multi-source energy apparatus can meet 59.3% of the home customers' electric load, while 43.5% is supplied to the grid. In particular, the percentages of the total electric energy generation that come from the wind and solar subsystems are 10.5% and 41.0%, respectively. Abdelkader *et al.* [22] conducted a cost analysis comparing three scenarios: a system featuring only a WT, another with both a WT and a PV generator, and a third incorporating a WT, PV generator, and storage system hybrid. The best case is the third one (Getting the most reliable solution at the lowest cost) that here results regarding output energies are shown in Table 1. In this study [42], the 500 houses in Mutobo Village, two medical facilities, three educational institutions, and estimates of load for the Musanze Industrial Zone were all considered by suggested PV–hydro hybrid system, where the PV array serves as the system's power source and is connected to a 200 kW micro hydro-power to meet the needs of a close to local load in Mutobo. Al Afif *et al.* [43] presented a case applied in Jordan, Karak specifically, where 28.2% of the electricity is obtained from the grid and 71.8% is produced by wind. Araoye *et al.* [43] presented four different hybrid renewable power system (HRES) designs that compared using the Grasshopper optimisation algorithm (GOA) and HOMER Pro software. Comparing configuration 4 (biogas/diesel) to HOMER and GOA, it is the best choice with empty unmet load at $0.01783/kWh of COE. The results showed that compared to HOMER-based solutions, the GOA-based HRES is more cost-effective because to its higher biogas and PV saturation. The results of [45] demonstrate that at 0.067 €/kWh, the lowest levelised cost (LC) of energy, is achieved while producing a significant annual production of sustainable energy (33.2 GWh). Furthermore, RE sources provide for up to 78% of the community's energy needs, saving 13,452 tons of CO_2 emissions annually.

The analysis of hybrid systems informs the efficient sizing of components to optimise overall system performance and to minimise investment and running costs is a critical issue in HRESs. HRES sizing and optimisation have been the subject of numerous research [4], [22]. For example, Rajaee *et al.* [4] applied an economic and environmental analysis on RE system of solar, wind, and battery, where the studied factors are the energy cost (EC), net present cost (NPC), the cost of energy for the optimal configuration, and CO_2 emissions. Sawle *et al.* [3] found in his study as results 0.2899$ as COE and 12,436 kg/year as emission. As Table 2 shows, the article [47] prepared by Tao Ma *et al.*, where a solar/wind system is studied, COE ($0.0943/kWh) is less than cited in [3]. Other economic studies like article of Abdelkader *et al.* [22] have minimum loss of power supply probability (LPSP) founded (5%), and the total cost of electricity is equal to $ 23856; while in [48], the permitted limitation is met by the LPSP of 0.049. It indicates that there won't be any load interruptions for more than 4.29 h, and the cost for the second HRPS was $741039.85, according to the results. Other economic factors are studied like that of Mertens [49] such as curtailment loss, capacity factor of façade panels, and inverter sizing for facade panels. According to the study, a baseload combination of wind and solar energy that has wind energy is 1.7 times more than PV energy provides a monthly supply profile that is nearly level and closely aligned with the demand profile. This configuration allows for 100% coverage of the energy demand with only 6% curtailment loss. Additionally, it is shown that vertical or facade solar PV panels can provide a better match with energy demand, with facade panels producing approximately 72% of the yield of standard slope panels and allowing for smaller inverter sizes without significant energy loss.

Another analysis factor applied is the technical factor, such as in articles [50] and [51]; in [51], the total harmonic distortion (THD) ratios are determined using appropriate values that correspond with Global regulations like IEEE 519-1992 and IEC 61000 and has a value of 0.69% at the output of inverter. While the article of Slusarewicz and Cohan [49] has the firm capacity as a studied factor, with wind and solar combined providing the maximum levels of firm capacity at a threshold of 87.5%. Al Afif *et al.* [42] studied economic (NPC, LC) and environmental (CO_2 emission) factors, where the annual CO_2 emissions are 220 tons, which is 53% less than a grid-alone system, the LC is 0.024 USD/kWh and the NPC is 298,359 USD. According to a recent study [46], the suggested system's estimated LCOE is 0.93 $/kWh, and for every kWh of power produced, it is predicted to emit 0.11 kg of CO_2.

4. Challenges in Implementing RE Systems

4.1 Challenges

Businesses, governments, and non-governmental organisations regularly provide money and support for the implementation of RE technologies. To enhance RE policy, economics, and production in both established and developing regions, governments have set environmental, energy, and development goals at distinct phases on a local, regional, and global level [55]. Most underdeveloped nations primarily depend on hydropower due to its low cost and high efficiency, but those with abundant RE sources are gradually shifting to more sustainable practices [56]. The development of RE markets, industries, and regulations also encounters various complex obstacles. The fossil fuel (FF) reserve, which diverts the focus of key authorities and society from concerns about the significance of RE, is one of the major obstacles to RE adoption. Because FFs and nuclear energy have more advanced technology than RE, many governments are more prepared to provide subsidies for FF development, which is mostly still in the developmental stages from a market, policy, and technical standpoint [57]. During periods of increased political instability, the demand for RE stocks as investment opportunities is growing, indicating their ability to improve energy independence [58]. According to the findings of [59], instability in politics limits the development of innovative RE solutions, especially in nations with strong bases in RE technology.

The developing nations lack RE policy implementation and methods to balance the price differential between FFs and RE. The developing nations lack the necessary experience to manage the potentially severe environmental problems that could arise when RE power facilities fail due to external financial or environmental shocks [60], [61]. Therefore, even in developing nations with abundant RE resources, FFs remain the main energy source for producing power. Conversely, nations with a high GDP per capita and a strong commitment to energy sustainability typically have the resources and capacity to conduct research and develop RE [62]. Only advanced nations are willing to invest in and take up the expense of developing and researching RE sources at this early stage of development. The majority of nations, including India, have impose some required purchases by power sector companies, known as renewable purchase obligations (RPOs), in order to gradually transition their power sectors, piece by piece, to RE sources [63]. Furthermore, industrialised nations frequently lead by establishing new rules, while developing nations modify existing ones and improve them by adding new laws [60]. However, the goal of applying RE is

Table 2
Summary of Outputs of Studied Factors in HRES

Article	Renewable Source(s)	Analysis	Studied Factor(s)	Output
[3]	Solar–Wind	Economics Environmental	• COE • Emission	• The COE is 0.2899, and the annual emissions are 12,436 kg.
[4]	Solar–Wind	Economic Environmental	• EC - NPC -$COE_{optimal}$ • CO2 emission	• This unit has an energy cost of 0.274 $/kWh and M$ 5.83 as net present cost, respectively. • The energy cost for the ideal configuration has been estimated to be between 0.255 and 0.285 $/kWh. • The hybrid energy unit prevents 1000 tons of CO2 emissions yearly (by comparing to the Iranian electrical system and the global standard for natural gas-fired plants)
[22]	Wind–Solar	Economics	• TCE ($) - LPSP (%)	• The total cost of electricity is $23856. • LPSP=5%
[43]	Solar–Wind	Economics Environmental	• NPC, LC • CO_2 emission	• The net present and levelised costs are $298,359 and 0.024 $/kWh, respectively. • 53% less CO2 is produced annually (220 tons) than with a grid-only system.
[44]	Biogas	Economic	• COE	• COE= $0.01783 / kWh
[45]	Solar–Hydro–Biomass	Economical Environmental	• LC • CO_2 emission	• According to the results, 33.2 GWh of RES energy are produced annually at 0.067 €/kWh which is the smallest LC of Energy. Furthermore, this avoids 13,452 kg of CO2 emissions per year.
[46]	Solar–Wind–Hydro	Economical Environmental	• LCOE • CO_2 emission	• The LCOE of the suggested system is $0.93 per kWh. For every kWh of power generated; it is expected that the suggested system will emit 0.11 kilogram of CO2.
[47]	Solar–Wind	Economics	• Cost of energy • LPSP • Simple payback time	• COE=$0.0943/kWh. • LPSP= 0.3%. • SPB= 20 years.
[48]	Solar–Wind	Economics	• Cost ($) and LPSP	• Cost ($) = 741039.85; and • LPSP = 0.049 % • (These results are for the second case study)
[49]	Solar–Wind	Economic	• Curtailment loss • Capacity factor of façade panels • Inverter sizing for facade panels	• Curtailment loss with 100% coverage: Approximately 6%. Curtailment loss with 75% coverage: Approximately 1%. • Capacity factor of facade panels compared to standard slope panels: Approximately 1.5 times higher capacity factor. • Inverter sizing for facade panels: Inverter power can be reduced by approximately 50% without significant energy loss.
[50]	Solar–Wind	Technical	• Firm capacity	• At a threshold of 87.5%, the incorporation of wind and solar power produced the highest firm capacity.
[51]	Solar–Wind	Technical	• THDv	• THD of voltage is 0.69%.
[52]	Solar–Wind	Environmental	• Return Level of duration of no power output for PV	• The return levels decrease to 20%–50% when the PV and wind power are combined.
[53]	Solar–Hydrogen	Economic	• Self-sufficiency ratio	• The SSR, determined by calculating the PV yield and monitoring electricity usage, is 26%.
[54]	Solar	Environmental	• Energy capacity	• According to the data, in India, over 74% of solar power projects were built on landcover types that are valuable for agriculture or the preservation of natural ecosystems.

Figure 4. Challenges in implementing RE systems.

to improve the lives of remote and rural communities and eradicate the harmful environmental effects of FF consumption. Figure 4 shows different challenges face while implementing RE systems.

4.2 Lebanon's Case

The country's electricity industry accounts for more than 53% of Lebanon's greenhouse gas emissions [64], while imported FFs remain supply 98% of the nation's energy needs [65]. The ultimate decision institution is the Council of Ministers (CoM), which is headed by the prime minister and consists of ministries representing the nation's major political parties [66]. Power failures are common occurrences due to insufficient energy infrastructure and supply. In 2018, the "Electricité de Liban" (EDL) utility met only over 47% of the electricity demand. According to World Bank estimates, the power shortfall is roughly 1 GW, which equates to daily cuts of Valley of Bekaa up to 17 h and 3 h in Beirut. Everyday power outages undermine the social contract. Recovery is impossible without a 24-h energy supply, and long-term success hinges on the availability of RE sources. The situation worsens due to the fact that refugees from the Syrian civil war constitute 25% of Lebanon's population, surpassing that of any other nation in the world. This did not include the 57 formally accepted as Palestinian refugees [67]. It is certain that this number will significantly increase, specifically in 2024. Since 2019, Lebanon has experienced an economic crisis marked by the collapse of the currency and various banking and economic sectors, which significantly affected the electricity sector. This crisis has prompted institutions and individuals to seek alternative solutions, primarily the solar energy implementation as a RES. This crisis has reinforced the need for distributed RE sources as a feasible solution, offering benefits to the economy, environment, energy security, and resilience.

5. Conclusion

The document highlights the importance of moving towards RE systems to confront the difficulties posed by the deterioration of non-RE sources and the harmful emissions associated with their use. The paper presented the structure of the system that includes: DC/AC Bus Configuration, ESS, and Energy Infrastructure, also it presents the complementarity in renewable sources and their types (temporal and spatial).

Modelling and simulation of RES is essential to integrating different RE sources to meet sustainable load requirements under different natural conditions. Better planning, forecasting, and decision-making are made possible by this method, leading to a more dependable and effective RE infrastructure that can meet demand for electricity while having a minimal effect on the environment.

The paper also highlights the challenges and opportunities connected with implementing RE systems, particularly in regions such as Lebanon where there is a high dependence on imported FFs for energy supply, and implementing of RE is strongly related to political stability.

In conclusion, the paper highlights how important it is to make the transition to RE sources in order to accomplish energy security, reduce climate change's consequences and support sustainable development, since there is widespread agreement that energy is essential for all economic activities, including driving innovation and new industries, as well as for information and communication technology and new industries. This is reflected in UN Sustainable Development Goal 9 and UNDP, 2019b.

References

[1] K. Majumdar, P.K. Roy, and S. Banerjee, Framework of hybrid renewable energy with conventional power generation scheduling using novel metaheuristic optimization algorithm, *International Journal of Power and Energy Systems*, *42*(10), 2022, 1–11.

[2] . *IRENA's Energy Transition Support to Strengthen Climate Action*, IRENA's Energy, International Renewable Energy Agency, Abu Dhabi, UAE, 2021.

[3] Y. Sawle, S.C. Gupta, and A.K. Bohre, Review of hybrid renewable energy systems with comparative analysis of off-grid hybrid system, *Renewable and Sustainable Energy Reviews*, *81*, 2018, 2217–2235.

[4] F. Rajaee, M.A. Vaziri Rad, K. Aliyon, A. Kasaeian, and O. Mahian, Techno-economic evaluation of an organic rankine cycle-based multi-source energy system for 100%-renewable power supply: A rural case study, *Sustainable Cities and Society*, *89*, 2023, 104290.

[5] D. Silva Herran and T. Nakata, Design of decentralized energy systems for rural electrification in developing countries considering regional disparity, *Applied Energy*, *91*(1), 2012, 130–145.

[6] Y.-W. Chong, W. Ismail, K. Ko, and C.-Y. Lee, Energy harvesting for wearable devices: A review, *IEEE Sensors Journal*, *19*(20), 2019, 9047–9062.

[7] N.A. Ludin, N.I. Mustafa, M.M. Hanafiah, M.A. Ibrahim, M. Asri Mat Teridi, S. Sepeai, A. Zaharim, and K. Sopian, Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review, *Renewable and Sustainable Energy Reviews*, *96*, 2018, 11–28.

[8] W.G. Santika, M. Anisuzzaman, P.A. Bahri, G.M. Shafiullah, G.V. Rupf, and T. Urmee, From goals to joules: A quantitative approach of interlinkages between energy and the sustainable development goals, *Energy Research & Social Science*, *50*, 2019, 201–214.

[9] W. Mao, S. Yang, and X. Gao, Modelling and optimization of green energy systems based on complementary integration of renewable energy, 1-9., *International Journal of Power and Energy Systems*, *44*(10), 2024, 0524.

[10] G. Notton, M. Muselli, and A. Louche, Autonomous hybrid photovoltaic power plant using a back-up generator: A case study in a Mediterranean island, *Renewable Energy*, *7*(4), 1996, 371–391.

[11] H. Borhanazad, S. Mekhilef, V. G. Ganapathy, M. Modiri-Delshad, and A. Mirtaheri, Optimization of micro-grid system using MOPSO, *Renewable Energy*, *71*, 2014, 295–306.

[12] R. Sontag and A. Lange, Cost effectiveness of decentralized energy supply systems taking solar and wind utilization plants into account, *Renewable Energy*, *28*(12), 2003, 1865–1880.

[13] V. Trillat Berdal, B. Souyri, and G. Fraisse, Experimental study of a ground-coupled heat pump combined with thermal solar collectors, *Energy and Buildings*, *38*, 2006, 1477–1484.

[14] K.-H. Lee, D.-W. Lee, N.-C. Baek, H.-M. Kwon, and C.-J. Lee, Preliminary determination of optimal size for renewable energy resources in buildings using RETScreen, *Energy*, *47*(1), 2012, 83–96.

[15] L.A. Wong, V.K. Ramachandaramurthy, P. Taylor, J.B. Ekanayake, S.L. Walker, and S. Padmanaban, Review on the optimal placement, sizing and control of an energy storage system in the distribution network, *Journal of Energy Storage*, *21*, 2019, 489–504.

[16] J. Jurasz, F.A. Canales, A. Kies, M. Guezgouz, and A. Beluco, A review on the complementarity of renewable energy sources: Concept, metrics, application and future research directions, *Solar Energy*, *195*, 2020, 703–724.

[17] R.M. Elavarasan, The motivation for renewable energy and its comparison with other energy sources: A review, *European Journal of Sustainable Development Research*, *3*(1), 2019, 1–19.

[18] T.-Z. Ang, M. Salem, M. Kamarol, H.S. Das, M.A. Nazari, and N. Prabaharan, A comprehensive study of renewable energy sources: Classifications, challenges and suggestions, *Energy Strategy Reviews*, *43*, 2022, 100939.

[19] *Power Sector: Executive Summary for the Month of Jun, 2017*. Central Electricity Authority New Delhi, June 2017.

[20] T. Falope, L. Lao, D. Hanak, and D. Huo, Hybrid energy system integration and management for solar energy: A review, *Energy Conversion and Management: X*, *21*, 2024, 100527.

[21] R LunaRubio, M TrejoPerea, D Vargas Vázquez, and G.J RíosMoreno, Optimal sizing of renewable hybrids energy systems: A review of methodologies, *Solar Energy*, *86*, 2012, 1077–1088.

[22] A. Abdelkader, A. Rabeh, D. Mohamed Ali, and J. Mohamed, Multi-objective genetic algorithm based sizing optimization of a stand-alone wind/PV power supply system with enhanced battery/supercapacitor hybrid energy storage, *Energy*, *163*, 2018, 351–363.

[23] G. Emmi, A. Zarrella, and M. De Carli, A heat pump coupled with photovoltaic thermal hybrid solar collectors: A case study of a multi-source energy system, *Energy Conversion and Management*, *151*, 2017, 386–399.

[24] M. Zaibi, H. Cherif, Gérard. Champenois, B. Sareni, X. Roboam, and J. Belhadj, Sizing methodology based on design of experiments for freshwater and electricity production from multi-source renewable energy systems, *Desalination*, *446*, 2018, 94–103.

[25] E.S. Barbieri, Y.J. Dai, M. Morini, M. Pinelli, P.R. Spina, P. Sun, and R.Z. Wang, Optimal sizing of a multi-source energy plant for power heat and cooling generation, *Applied Thermal Engineering*, *71*(2), 2014, 736–750.

[26] Siksnelyte-Butkiene, E.K. Zavadskas, and D. Streimikiene, Multi-criteria decision-making (MCDM) for the assessment of renewable energy technologies in a household: A review, *Energies*, *13*(5), 2020, 1164.

[27] V. Tavares Nascimento, J.R. Martinez-Bolaños, M.E. Morales Udaeta, A.L. Veiga Gimenes, V.B. Riboldi, and T. Ji, Energy storage system design in the light of multisource solution from a viability analysis, *Designs*, *6*(2), 2022, 38.

[28] M. Berger, D. Radu, R. Fonteneau, R. Henry, M. Glavic, X. Fettweis, M. Le Du, P. Panciatici, L. Balea, and D. Ernst, Critical time windows for renewable resource complementarity assessment, *Energy*, *198*, 2020, 117308.

[29] T Haque and M.T Iqbal, *A Comparison of AC and DC Coupled Remote Hybrid Power systems*, Memorial University of Newfoundland, St. John's, NL, 2020.

[30] K. Shivarama Krishna and K. S. Kumar, A review on hybrid renewable energy systems, *Renewable and Sustainable Energy Reviews*, *52*, 2015, 907–916.

[31] T Ma, H Yang, and L Lu, Development of hybrid battery supercapacitor energy storage for remote area renewable energy systems, *Applied Energy*, *153*, 2015, 56–62.

[32] M.T. Arif, A.M.T Oo, A.B.M.S. Ali, and M.F. Islam, Significance of storage and feasibility analysis of renewable energy with storage system, Presented at the Power and Energy Systems, ACTA Press, 2010.

[33] T. Bocklisch, Hybrid energy storage systems for renewable energy applications, *Energy Procedia*, *73*, 2015, 103–111.

[34] Y. Yang, S. Bremner, C. Menictas, and M. Kay, Modelling and optimal energy management for battery energy storage systems in renewable energy systems: A review, *Renewable and Sustainable Energy Reviews*, *167*, 2022, 112671.

[35] C. Acar, A comprehensive evaluation of energy storage options for better sustainability, *International Journal of Energy Research*, *42*(12), 2018, 3732–3746.

[36] Z. Lu, J. Yu, L. Sun, Y. Xiong, B. Yang, R. Yin, and L. Wang, Capacity optimisation configuration of hybrid energy storage system considering primary frequency regulation output of wind farm, 1-11., *International Journal of Power and Energy Systems*, *44*(10), 2024, 0529.

[37] G Bridge, B Özkaynak, and E Turhan, Energy infrastructure and the fate of the nation: Introduction to special issue, *Energy Research & Social Science*, 41, 2018, 1–11.

[38] M. Talaat, A. Elgarhy, M.H. Elkholy, and M.A. Farahat, Integration of fuel cells into an off-grid hybrid system using wave and solar energy, *International Journal of Electrical Power & Energy Systems*, *130*, 2021, 106939.

[39] M.S.R. Tito, T.T. Lie, and T. Anderson, Sizing optimization of wind-photovoltaic hybrid energy systems under transient load, *International Journal of Power and Energy Systems*, *4*(33), 2013.

[40] E.M. Nfah, H. Jeanmart, and P.M.T. Heteu, Sizing of photovoltaic hybrid power systems for remote villages, Presented at the Power and Energy Systems, ACTA Press, 2010.
A. Algieri, P. Morrone, D. Perrone, S. Bova, and T. Castiglione, Analysis of multi-source energy system for small-scale domestic applications Integration of biodiesel, solar and wind energy, *Energy Reports*, *6*, 2020, 652–659.

[41] E. Niringiyimana, S. WanQuan, and G. Dushimimana, Feasibility study of a hybrid PV/Hydro system for remote area electrification in Rwanda, *Journal of Renewable Energy*, *2022*, 2022, 1–11.

[42] R. Al Afif, Y. Ayed, and O.N. Maaitah, Feasibility and optimal sizing analysis of hybrid renewable energy systems: A case study of al-Karak, Jordan, *Renewable Energy*, *204*, 2023, 229–249.

[43] T.O. Araoye, E.C. Ashigwuike, M.J. Mbunwe, O.I. Bakinson, and T.I. Ozue, Techno-economic modeling and optimal sizing of autonomous hybrid microgrid renewable energy system for rural electrification sustainability using HOMER and grasshopper optimization algorithm, *Renewable Energy*, *229*, 2024, 120712.

[44] E. Gul, G. Baldinelli, P. Bartocci, T. Shamim, P. Domenighini, F. Cotana, J. Wang, F. Fantozzi, and F. Bianchi, Transition toward net zero emissions - integration and optimization of renewable energy sources: Solar, hydro, and biomass with the local grid station in central Italy, *Renewable Energy*, *207*, 2023, 672–686.

[45] S. Ghandehariun, A.M. Ghandehariun, and N. Bahrami Ziabari, Complementary assessment and design optimization of a hybrid renewable energy system integrated with open-loop pumped hydro energy storage, *Renewable Energy*, *227*, 2024, 120557.

[46] T. Ma and M.S. Javed, Integrated sizing of hybrid PV-wind-battery system for remote island considering the saturation of each renewable energy resource, *Energy Conversion and Management*, *182*, 2019, 178–190.

[47] A.Y. Hatata, G. Osman, and M.M. Aladl, An optimization method for sizing a solar/wind/battery hybrid power system based on the artificial immune system, *Sustainable Energy Technologies and Assessments*, *27*, 2018, 83–93.

[48] S. Mertens, Design of wind and solar energy supply, to match energy demand, *Cleaner Engineering and Technology*, *6*, 2022, 100402.

[49] J.H. Slusarewicz and D.S. Cohan, Assessing solar and wind complementarity in Texas, *Renewables: Wind, Water, and Solar*, *5*(1), 2018.

[50] E. Kabalci, Design and analysis of a hybrid renewable energy plant with solar and wind power, *Energy Conversion and Management*, *72*, 2013, 51–59.

[51] G Ren, J Wan, J Liu, and D Yu, Spatial and temporal assessments of complementarity for renewable energy resources in China, *Energy*, *177*, 2019, 262–275.

[52] T.S. Le, T.N. Nguyen, D.K. Bui, and T.D. Ngo, Optimal sizing of renewable energy storage: A techno-economic analysis of hydrogen, battery and hybrid systems considering degradation and seasonal storage, *Applied Energy*, *336*, 2023, 120817.

[53] A. Ortiz, D. Negandhi, SR. Mysorekar, SK. Nagaraju, J. Kiesecker, C. Robinson, P. Bhatia, A. Khurana, J. Wang, and F. Oviedo, J.L. Ferres, An artificial intelligence dataset for solar energy locations in India, *Scientific Data*, *9*(1), 2022, 497.

[54] P. Bayer, L. Dolan, and J. Urpelainen, Global patterns of renewable energy innovation, *Energy for Sustainable Development*, *17*, 2013, 288–295.

[55] *Medium-Term Renewable Energy Market Report 2013*, IEA, Paris, 2013. https://www.iea.org/reports/medium-term-renewable-energy-market-report-2013, Licence: CC BY 4.0.

[56] S. Hostettler, A. Gadgil, and E. Hazboun (Eds.), *Sustainable Access to Energy in the Global South*. (Cham: Springer, 2015) 3–9,.

[57] P. Igeland, L. Schroeder, M. Yahya, Y. Okhrin, and G.S. Uddin, The energy transition: The behavior of renewable energy stock during the times of energy security uncertainty, *Renewable Energy*, *221*, 2024, 119746.

[58] J.Z. Wang, G.F. Feng, and C.P. Chang, How does political instability affect renewable energy innovation? *Renewable Energy*, *230*, 2024, 120800.

[59] L.V. Kochtcheeva, Renewable energy: Global challenges, https://www.e-ir.info/2016/05/27/renewable-energy-global-challenges,(May 2016).

[60] U.T. Umoh and I.J. Ekpoh, Renewable energy resources barriers in Africa, Presented at the Power and Energy Systems, ACTA Press, 2008.

[61] S. Müller, A. Brown, and S. Ölz, *Renewable energy: Policy considerations for deploying renewables*, OECD/IEA, Paris, November 2011.

[62] P. Mundra, A. Arya, and S.K. Gawre, Assessing the impact of renewable purchase obligation on Indian power sector, *International Journal of Power and Energy Systems*, *40*(4), 2020, 208– 212.

[63] *Lebanon: Derisking Renewable Energy Investment*, United Nations Development Programme, New York, NY and Beirut, December 2017.

[64] IEA Statistics © OECD/IEA, https://www.iea.org/data-and-statistics, (2014).

[65] World Bank, https://documents1.worldbank.org/curated/en/235831562864951356/text/Concept-Project-Information-Document-PID-Lebanon-Electricity-Transmission-Project-P170769.txt, (2019)

[66] UNRWA, https://www.unrwa.org/where-we-work/lebanon, (2014).

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