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Technical, Economical and Environmental Aspects of Hybrid Renewable Energy Systems

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الجوانب التقنية والاقتصادية والبيئية لأنظمة الطاقة المتجددة الهجينة

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Abstract:

The world is witnessing a shift from the traditional fossil fuel-based generation system to a future with a larger share of clean renewable generation. Hybrid energy systems are connected with wind power, photovoltaic energy, fuel cells, biomass energy, geothermal energy, and tidal energy to generate electricity to meet energy demand at various scales and connect it to the main grid or microgrids, thereby reducing dependence on fossil fuels, which in turn reduces air emissions and mitigates environmental damage. The hybrid system is considered a better option for building modern electrical grids due to its economic, environmental, and social benefits. An overview of various distributed generation technologies has been presented. This research provides a comprehensive review of the energy, economic, environmental, and technical analysis of these sources, as well as the possibility of integrating different renewable energy sources to form a hybrid system.

Keywords: Hybrid renewable energy system; PV solar energy; Wind energy; Biomass energy; Marine energy; Geothermal energy; Hydropower energy.

الملخص
يشهد العالم تحولاً من نظام التوليد التقليدي القائم على الوقود الأحفوري إلى مستقبل يتمتع بحصة أكبر من التوليد النظيف والمتجدد. وترتبط أنظمة الطاقة الهجينة بطاقة الرياح، والطاقة الكهروضوئية، وخلايا الوقود، وطاقة الكتلة الحيوية، والطاقة الحرارية الجوفية، وطاقة المد والجزر لتوليد الكهرباء وتلبية الطلب على الطاقة بمقاييس متنوعة، وربطها بالشبكة الرئيسية أو الشبكات الصغيرة، مما يقلل من الاعتماد على الوقود الأحفوري، وهو ما يؤدي بدوره إلى تقليل الانبعاثات وتلطيف الأضرار البيئية. وتُعد الأنظمة الهجينة خياراً أفضل لبناء الشبكات الكهربائية الحديثة نظراً لفوائدها الاقتصادية والبيئية والاجتماعية. وقد تم تقديم نظرة عامة على مختلف تقنيات التوليد الهجين. ويقدم هذا البحث مراجعة شاملة للتحليل الطاقي والاقتصادي والبيئي والفني لهذه المصادر، بالإضافة إلى إمكانية دمج مصادر الطاقة المتجددة المختلفة لتشكيل أنظمة هجينة فعالة.

الكلمات المفتاحية: نظام الطاقة المتجددة الهجين، الطاقة الشمسية الكهروضوئية، طاقة الرياح، طاقة الكتلة الحيوية، الطاقة البحرية، الطاقة الحرارية الأرضية، طاقة الطاقة الكهرومائية.

Introduction

Worldwide total energy consumption reached an all-time high of 592 exajoules (EJ) in 2024, a 2% increase from 2023, driven by record global electricity demand which surged by 4.3% to over 30,000 TWh. More than 80% of electricity and thermal energy is generated by firing fossil-fuels in conventional power plants, such as coal, oil, and natural gas, putting the energy industry in the first place in terms of emissions among all other human activities. The energy-related CO2 emissions reach 37.6 Gt in 2024. Driven by concerns about climate change and global warming, the global installed capacity of renewable energy grew by 50% in 2024. In the end of 2024, the global installed capacities of renewables such as solar, wind, hydropower, geothermal, marine, biogas, etc reached about 4,448.1 GW, from them 1,600 GW for PV solar energy systems, 1,021 GW for wind energy, about 96.8 GW electricity from biomass energy, the geothermal energy reached 16,873 MWe, and hydropower capacity stood at nearly 1,450 GW at the end of 2024. This growth in the RE market reflects a global shift towards renewable and sustainable energy technologies [1]. High concentration of greenhouse gases (GHG) leads to global warming, it is expected that at the end of this century, the world's temperature will be increased up to 3–6°C. To address all the challenges such as, climate change and energy crises, renewable energy resources (RERs) are crucial for supplying clean and sustainable energy [2-8].

There are several types of renewable energy resources, such as solar, wind, biomass, geothermal, tidal, and wave energy. In all of that solar and wind energy are ubiquitous, economically feasible in many places around the world and environmentally friendly. The common drawback of solar and wind system is their random nature and they rely on the climatic condition [9]. So, for increasing the availability and reliability of the produced electrical energy, a hybridization of two or more energy systems (such as: photovoltaic solar system (PV), wind turbines (WT) and Diesel generator (DG) integrated with a storage system such as battery (B) and/or fuel cell (FC)) are recently preferred. Fig. 1 displays all possible way to create HRESs from renewable energy sources (RE) in connection with storage systems; in addition to, diesel generator (DG) and thermal generator (GT).

The hybrid renewable energy systems (HRESs) may be one of the potential alternatives of fired-depleted fossil-fuel energy facilities. The HRESs could be grid-connected or off-grid [10]. The grid-connected mode is cheaper and more flexible, such that no needs to a storage system, any mismatch with electrical load can be exchanged with the public grid. In contrast, the off-grid mode, the storage system is essential to store the excess energy produced and then reuse it when needed.

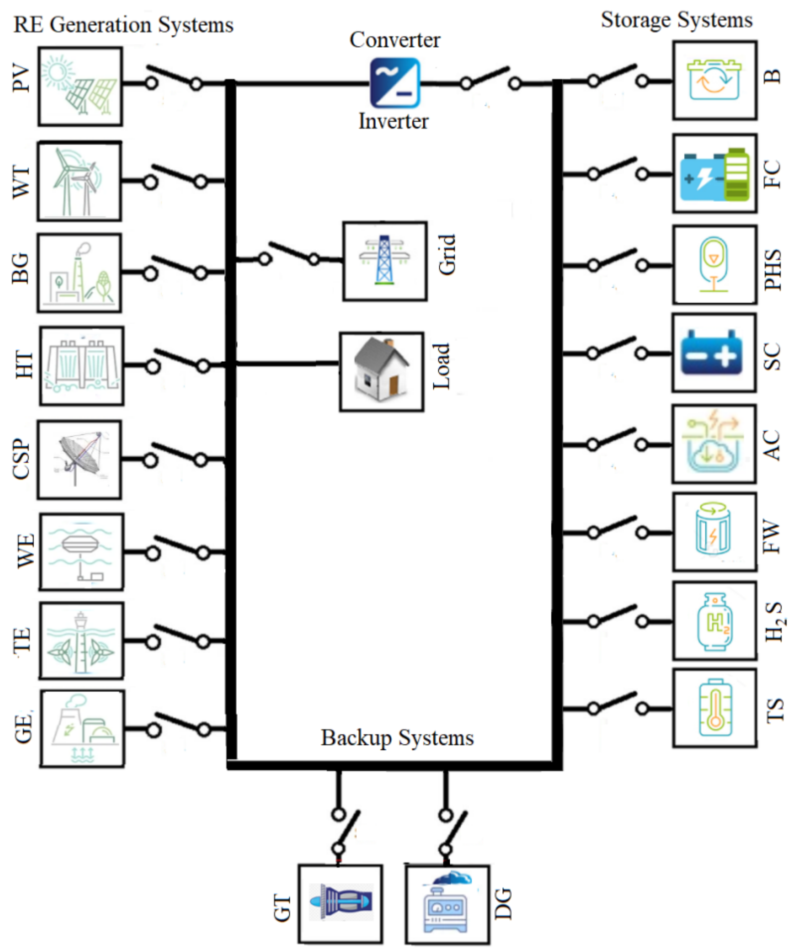

Figure 1: A Block diagram of possible typical hybrid systems.

Elmnifi et al. [11] presents a model for integrating solar and wind energy with Pumped Hydro Energy Storage (PHES) specifically for the city of Derna, Libya, to enhance the city's energy sustainability by leveraging its high potential for renewable resources and addressing challenges in its current fossil-fuel-dependent power sector. The study reviews the technologies, costs, and benefits of these combined systems, highlighting their importance in stabilizing energy supply and supporting energy infrastructure development, especially in post-conflict and reconstruction scenarios. Aqila, et al. [12] proposed a hybrid renewable energy system that incorporates solar thermal, biomass, and geothermal energy. The results show that the proposed hybrid system is capable of meeting residential heat demand, with an initial capital cost of approximately $3,027 and the levelized cost of energy (LCOE) of $0.054/kWh. Furthermore, the system contributed to a reduction of 425 kg CO_2 emissions annually. Several researches [13-65] successfully demonstrate the effectiveness of integrating pumped hydroelectric storage with hybrid PV/Wind systems to enhance renewable energy utilization and grid stability. Through comprehensive dynamic analysis and advanced sizing optimization techniques, optimal configurations were identified that maximize energy efficiency while minimizing costs. The case study highlights that incorporating pumped hydro storage significantly improves system reliability and flexibility, particularly in balancing intermittent renewable sources. The findings provide valuable insights for designing sustainable and economically viable hybrid renewable energy systems, paving the way for more resilient and efficient energy infrastructures in future applications.

Alkatsaprakakis and Voumvoulakis demonstrated the ability of hybrid systems to meet the entire demand for electricity in a small island with less than 3,000 inhabitants in Greece. The HRES is a combination of wind turbine and pumped storage hydroelectric (WT/PHS). Four wind turbines with a capacity of 3 MW each and a pumped storage hydroelectric (PHS) that designed to cover a maximum of 860 MWh or 16 days

of average consumption in the island. At times of low demand, the hydroelectric facility would pump seawater to an upper reservoir of more than 1.1 million m^3, placed at an altitude of 332 m. Four Pelton type turbines with a combined capacity of 8.74 MW and 12 centrifugal pumps of 10.28 MW in total were installed to charge/discharge the upper reservoir in order to produce power when wind is weak [66].
Another model that embodies the ability of HRESs to meet large electrical load of large communities; Jenin is a city locates on the northernmost of the West Bank – State of Palestine, with 314,866 inhabitants lives on an area of 37.3 km^2. The annual electrical energy consumption is 240.7 GWh. The proposed HRES consisting of a PV solar field with a capacity of 20MW, a wind farm with a capacity of 50MW, and a biomass system with a capacity of 40MW [15].
Fig. 2 illustrates a word cloud presentation of scientific papers that conducted HRESs and published by Elsevier journals during the years 2023-2024. Figure 2 indicates that the contribution of PV solar systems in hybrid energy systems is almost 100%, with wind energy around 72%, biomass energy about 34%, PHS energy approximately 12%, and negligible percentages not exceeding 1% for geothermal energy and marine energy.

Figure 2: A word cloud of the HRESs' combinations in scientific publications.

The rest of this paper is organized as follows: Section 2 describes the approach followed to achieve the research objectives, through which the governing equations for estimating the productivity of renewable energy systems, as well as the economic and environmental calculations, are presented. Section 3 illustrates the obtained results graphically, along with their discussion and analysis. The conclusions drawn from the research are included in Section 4. Finally, the study concludes with a list of references used throughout the research.

Material and methods

The followed approach in the present study is illustrated in the flowchart depicted in Figure 3. First, we prepare and process the climatic data which provided by SODA (https//www.soda-pro.com/web-services/radiation/helioclim-3-archives-for-free) to suit the study area. Global horizontal solar irradiation components ares processed to become global tilted solar irradiation, and wind speed is also adjusted to the hub height of the turbine. All these processes are carried out using solar radiation conversion models and wind speed conversion models based on the recommendations of local researchers [67-75].
The algorithm begins with importing data that include: meteorological, energetic, economic, environmental and technical data of the RHESs combination. The main energy and economic figures of the energy systems were determined by the aid of MSExcel or any other software such as SAM for solar and wind energies [76]. Then, the data obtained is subjected to the constraints and objective function/s in order to determine the optimum design size of the proposed HRES.

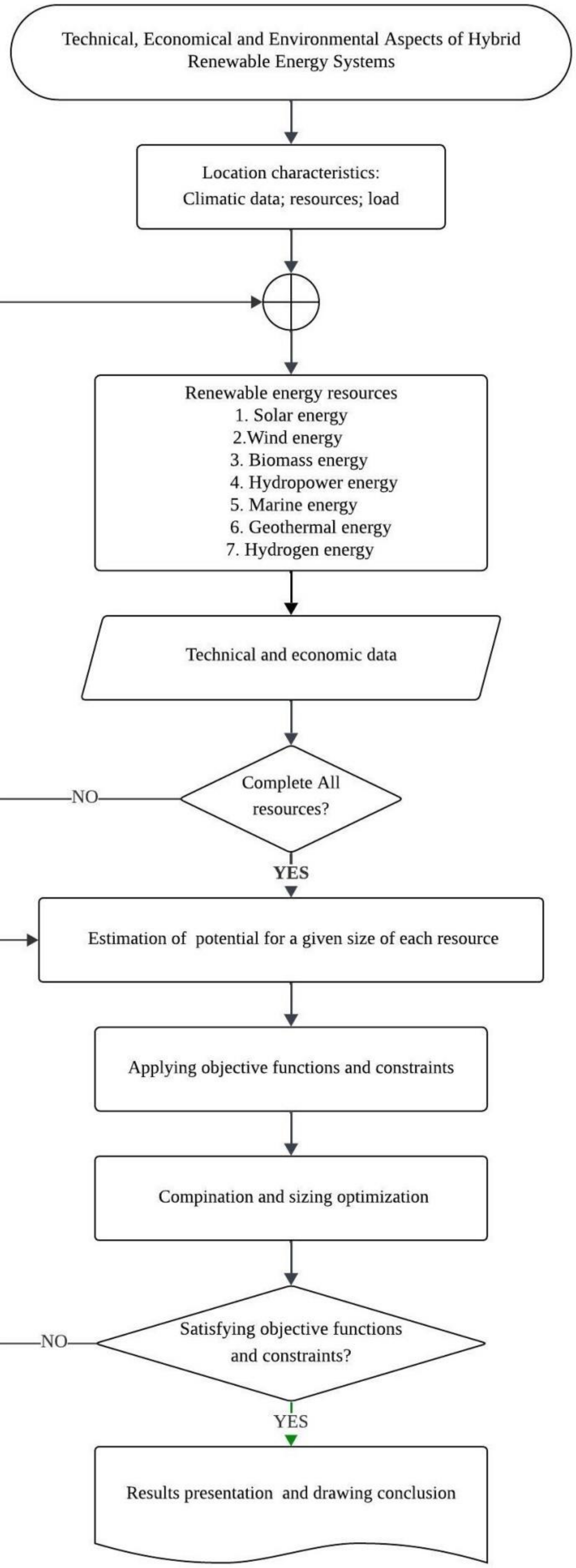

Figure 3: The approach to determine the optimal system of the HRES.

Potential Assessment of renewable energy resources

PV System

The energy produced by PV solar panel under a real climatic condition can be estimated as [77-79]:

$$E_{PV} = P_{STC}\left[1 + \beta_p(T_{cell} - T_{STC})\right]\frac{H_t}{H_{STC}} \tag{1}$$

Where: T_{STC} and T_{cell} are the cell's surface temperature at Standard Test Condition and under real operation conditions (°C), $\beta_p$is the power temperature coefficient (%/°C), and H_{STC} and H_t are the STC and real global solar irradiance incidents on the PV module surface. The challenge that researchers will face is to find an empirical equation to determine the cell surface temperature T_{cell} For example: $T_{cell} = T_\infty + 7.8 \times 10^{-2} H_t$ [80,81]. Table 1 presents characteristic of some commercial PV solar panels.

Table 1 Electrical characteristic related to the energy analysis of some commercial PV solar panels [82, 83]

Kinds Of solar module	Manufacturing Country	Technology	Efficiency %	Pmax (W)	Vmp (V)	Imp (A)	βp (%/°c)	βv (%/°c)	βI (%/°c)
Aleo solar S59Y310	Germany	M-Si	18.91	310	31.7	9.8	-0.396	-0.280	0.036
Canadian Solar Inc. SC3W-435	Canada	P-Si	20.05	435	40.1	10.8	-0.361	-0.270	0.039
SRS Energy SPT16	USA	T-F	15.00	16	4.5	3.5	-0.221	-0.410	0.084
Stion SN-115	USA	T-F	11.40	125	41.0	3.0	-0.400	-0.360	0.007
JA Solar JAM6 (k)-72-335/PR	GERMANY	M-Si	17.55	340	38.2	8.9	-0.377	-0.290	0.049

Wind Energy

The energy produced by a specific wind turbine can be estimated by [37, 84,85]:

$$E_W = \begin{cases} P_{rat} & V_{rat} \le V_{Z,t} \le V_{cut-off} \\ P_{rat}\left(\dfrac{V_{Z,t} - V_{cut-in}}{V_{rat} - V_{cut-in}}\right) & V_{cut-in} < V_{Z,t} < V_{rat} \\ 0 & V_{Z,t} \le V_{cut-in}\ OR\ V_{Z,t} > V_{cut-off} \end{cases} \tag{2}$$

Where: $P_{rat}$is the rated power of the wind turbine at rated wind speed V_{rat}, V_{cut-in} and $V_{cut-off}$ are the cut-in and cut-off wind speeds, and $V_{Z,t}$ is the wind speed at the wind turbine hub height (h_Z) and it is calculated from: $V_{Z,t} = V_{0,t}\left(\frac{h_Z}{h_0}\right)^{\propto}$, where, $V_{0,t}$ is the wind speed at a certain elevation (h_0) and α is the wind shear coefficient [86], and it could be taken as 1/5 or 1/7 [87]. Table 2 tabulates the technical characteristics of some wind turbines

Table 2 The most important technical characteristics of some wind turbines [88].

Type	Hub height, m	Rotor diameter, m	Cut-in wind Speed; m/s	Cut-off wind speed; m/s	Rated wind speed; m/s	Rated power; kW
Gamesa (2.0MW)	140	114	2.5	25	10	2000
Acciona (1.8MW)	80	77	3.5	25	14	1800
Enercon (2.5MW)	149	115	3	34	11	2500
Vestas (1.65MW)	108	82	2.5	32	12	1650
Gold wind (1.5MW)	100	82.3	3	30	12	1500
Nordex (1.0MW)	70	54	3.5	25	11	1000
Suzlon (3.3MW)	140	120	4	20	14	3300
GE wind (0.85MW)	60	45	3	25	14	850

Biomass energy

The annual CH_4 (Q_{CH_4}) that can be generated from fermentation of wastes can be estimated by [89]:

$$Q_{CH_4} = \sum_{i=1}^{n} MCF_i \times MW_i \times WCR_i \tag{3}$$

Where: MCF denotes to Methane conversion factor ($ton\ CH_4/ton\ waste$), MW states for the annual mass of wastes ($ton\ waste/year$), WCR represents the wastes collection rate. And the subscript i states for the type of the waste (Municipal solid -1; Agriculture-2; Livestock-3; Sewage-4). Table 3 and 4 presented the main agriculture and livestock residues, respectively. Then, the electrical energy generated by a power plant can be estimated by [90]:

$$P_{BG} = \dot{m}_{CH_4} \times LHV_{CH_4} \times \eta_{Gpp} \tag{4}$$

Where: P_{BG} states for the power of the plant (MW), $\dot{m}_{CH_4}$ represents CH_4 mass flow rate (kg/s), LHV_{CH_4} is the low heating value of the CH_4 (14.0 $kWh/kg\ CH_4$) and η_{Gpp} is the power plant efficiency (50%).

It is critical at this point to calculate the bioreactor's ability to digest waste and produce biogas. A review of the literature reveals that the digester capacity falls within very small ranges, despite the fact that the amount of methane produced varies depending on the type of waste. The volume of a digester required to digest wastes is as follows, [91-94]:

$$V_{Bio} = 0.221 \times (W_{AW} + W_{LW} + W_{MW} + W_{SW}) \tag{5}$$

Table 3 The main agriculture residues.

Crops (tons)	Residue/Product	**Vegetables (tons)**	Residue/Product
Barley	1.3	Melon	0.1
Wheat	1.8	Cantaloupe	0.1
Maize	2.3	Onion	0.1

Peanut	1.5	Garlic	0.3
Fruits (trees)	**Residue kg/tree**	Tomatoes	1.0
Date	4.7	Gherkin	1.0
Almond	4.7	Eggplants	0.5
Grape	4.7	Cucumber	0.5
Citrus	4.7	Lettuce	0.1
Olives	4.7	Cabbage	0.5
Apples	4.7	Cauliflower	0.5
Figs	4.7	Pepper	1.5
Others	4.7	Beet	0.4
		Kale	0.4
		Peas & Beans	1.4
		Carrot	0.6
		Potato	0.8
		Pumpkin	1.0
		Parsley	1.5
		Squash	0.5

Table 4 The main livestock residues.

Livestock type	Manure (kg/animal/year)	Collection rates	Volume of CH_4; (m^3 /kg manure)
Cows	936	40%	0.14
Goats	134.3	10%	0.1
Sheep	134.3	30%	0.1
Camel	720	10%	0.26
Horses	620.5	10%	0.26
Poultries	2.4	99%	0.27

Hydropower energy

The energy yield by a hydropower energy system is estimated as [95,96]:

$$P_{HES} = \rho \, g \, h \, Q \, \eta \quad (6)$$

Where: **E** is the reservoir capacity (W), **ρ** is the water density (1000kg/m³), **g**: Ground gravity (0.81 m/s²), **h** is the elevation difference between the upper and lower reservoirs (m), $\dot{Q}$ is the volumetric water flow rate from upper reservoir (m³/s) and **η** is the efficiency of the turbine and pump (75%).

Marine energy

The energy yield by a marine energy system is estimated as [97]:

$$P_{marine} = \frac{\rho_w g^2 T_e H_s^2 \eta_{wav} L}{64\pi} \quad (7)$$

Where: ρ_w is the sea water density, g is the gravity, and η_{wav} is the plant efficiency for length L (m); for the wave; T_e denotes its period and H_s is its height.

Geothermal energy

The energy yield from the hydro energy system is estimated as [89,99]:

$$P_{Geo} = \dot{m}_w[Cp_w(T_s - T_\infty) - T_\infty(s_s - s_\infty)]RF\,\eta \times 8760 \quad (8)$$

Where: $\dot{m}_w$ is water mass flow (kg/s) Cp_w is the specific heat of water at storage temperature T_s, T_∞ is the average ambient air temperatures (°C), s_s and s_∞ are the specific entropies at thermal ground-storage and ambient temperatures (J/kg/°C), respectively; RF is recovery factor ($RF = 0{,}1$) and η is the conversion system's efficiency (η =0.35)

3.7 Hydrogen energy

The capacity of the fuel cell P_{FC} (MW) is determined as [100-102]:

$$P_{FC}(t) = \left[\dot{m}_{H_2}(t) \times LHV_{H_2} \times \eta_{FC}\right]_{t=1\rightarrow 8760} \quad (9)$$

Where, $\dot{m}_{H_2}(t)$ is the H_2 productivity (ton/hr), LHV_{H_2} is the lower heating value of H_2 (33.33 $kWh/kg\ H_2$) and η_{FC} represents the fuel cell efficiency (60%).

Feasibility assessment of renewable energy resources

Environmental Aspects

Power plants that use fossil fuels produce almost all of the electricity in Libya. The CO_2 emission factor for the Libyan energy industry sector is estimated to be 983 kg CO_2/MWh [103]. The annual cost savings associated with CO_2 mitigation can be calculated, as shown in eqn. (12) [104].

$$C_{CO2} = EF_{CO2} \times G_{elec} \times f_{ren} \times \emptyset_{CO2} \quad (10)$$

Where EF_{CO2} is the CO2 emission factor [kg CO2/MWh], G_{elec} is the annual electrical power generated [MWh], f_{ren} is the renewable energy fraction coefficient, and $\emptyset_{CO2}$ denotes the CO_2 international price. The average carbon price has recently been set at least $70 per ton CO2 by the end of the decade (November 2022) to succeed the global climate goals at COP27 Sharm Elsheikh, Egypt [105]. The position of renewable energies is improved and they are given a fair chance to compete on the international energy market by including the environmental factor in economic calculations [106]. From the other side, the environmental impacts due to exploitation of renewables are documented in [107,108].

4.2. Economical Aspect

The LCOE is thought of as a tool to show how economically viable renewable energy systems are. The LCOE with the environmental impact cost is calculated by [109]:

$$LOCE = \frac{\sum_{i=1}^{N}\left[\frac{r(1+r)^{n_i}}{(1+r)^{n_i}-1}C_{cap,i} + C_{o\&m,i}\right]}{E_{RS}} \quad (11)$$

The capital costs ($) of CPS and biomass energy systems are indicated by the variables C_{dish} and C_{bm}, respectively. E_{Se} denotes the annual energy yields of the renewable systems (kWh/year), r denotes the discount rate, which is assumed to be 3.8%, and n denotes the plant's lifespan, which is assumed to be 30 years. The payback time money (PBTM) can then be calculated as follows [110]:

$$PBTM = \frac{\sum_{i=1}^{N}\frac{r(1+r)^{n_i}}{(1+r)^{n_i}-1}C_{cap,i}}{\sum_{i=1}^{N} I_i} \quad (12)$$

All economic parameters are tabulated in Table 5, for several types of renewable energy resources..

Table 5 System components associated expenditures.

Source	Capital; $/kW	O&M; $/kW/year	Lifespan, year
PV solar panel	500-880	17-30	25-30
Wind turbine	1200-1800	15-27	20-30
Geothermal	4500-6000	200-400	25-50
Biomass	1,600 - 5,600	10-65	15-25
Marine	2000-5000	15-60	8-10
Hydropower	1050-1300	50-70	50-100
Fuel cell	700-2000	20-25	40,000-80,000 hrs

Ecoenvironmental assessment of renewable energy systems

Involving the environmental damage cost in the economic analysis enhanced the competition position of renewables in the energy market. Accordingly please write the equation for LCOE as:

The Levelized Cost of Energy (LCOE) and the payback time money (PBTM). The cost of environmental damage produced by carbon dioxide (C_{CO2}) may be used to compute LCOE using the following equation [111]:

$$LLOCE = \frac{\sum_{i=1}^{N}\left[\frac{r(1+r)^{n_i}}{(1+r)^{n_i}-1}C_{cap,i} + C_{o\&m,i} - NC_{CO_2}\right]}{E_{RS}} \quad (13)$$

Where**:** NC_{CO_2} is the net CO2 emission cost.

$$NC_{CO_2} = (EF_{CO2} - LCEF_{CO2}) \times G_{elec} \times f_{ren} \times \emptyset_{CO2} \quad (14)$$

Where, $LCEF_{CO2}$ presents Life cycle CO_2 emission factor for each source of renewables. Table 4 presented the life cycle CO_2 emission factor for several energy generation technologies [112,113].

Table 6 CO2 emission factor (g GHG)⁄kWh for Various Alternatives of Electricity Generation.

Energy generation technologies	Life cycle CO_2 emission factor $g\ CO_2/kWh$	
	Rate	Average
Biomass energy	1000-100	350
Biogas energy	600-25	100
Solar thermal energy	150-15	40
Solar PV energy	200-20	60
Geothermal energy	80-10	25
Tidal energy	80-10	25
Wave energy	50-12	25
Hydropower energy	60-2	20
Offshore wind energy	70-5	15
Onshore wind energy	70-5	15
Nuclear energy	20-10	12
Thermal power generation energy	1500-800	800

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Technical assessment hybrid renewable energy systems

Sizing optimization

Any optimization process has controlled by objective functions and constraints**.** The objective function may be expressed as: "The LCOE is assumed as an essential key factor for evaluating the competitive capability of energy generation, so the corresponding sizes to the lowest total value of LCOE will be selected for the hybrid system."

While the constraints may be considered as: The proposed HRPS should meet the load requirements without any interruption. Therefore, the power supply reliability operational constraint (PSROC) was expressed in eqn. (16) [17]:

$$PSROC = \frac{\sum_{t=1}^{8760}[E_{Load}(t) - E_{Se}(t)]}{\sum_{t=1}^{8760}E_{Load}(t)} = 0 \quad (15)$$

$E_{se}(t)$ is the total of $E_{dish}(t)$ and $E_{bm}(t)$, which are the energy generated by the CPS and BG (HRPS) in GWh and t denotes the time, where $E_{Load}(t)$ denotes the electrical load in GWh. The value of PSROC suggests a trade-off between the proposed (HRPS) power supply's high reliability and security. A PSROC of 0.011% indicates that the load disruption over the course of a year will be no more than an hour. As a result, PSROC is taken into account as a constraint for the (HRPS) in the proposed sizing procedure. The range of PSROC is 0-1.0. The PSROC value of zero indicates that the HRPS is fully able to meet the load requirement, while a value of less than unity points to a sizing issue. The zero value, however, necessitates an expensive HRES.

Uncertainties of the results

The availability of data, the choice of model, the assumptions, and parameter estimations are the main sources of uncertainty. The output energy profile of the pertinent energy-conversion technologies (such as solar and wind) would be impacted, for instance, by variations in the supply of renewable energy. Another factor that creates uncertainty is the cost of renewable energy facilities. According to Nassar and Alsadi [114], the prices of solar instrumentation varied by 360%. The values presented in the references to the methane yields from residues and wastes, which are also thought to be sources of uncertainty, differed significantly as well [115,116]. The CO2 emission factor also varies significantly across references [117-121].

Conclusion

This paper provides a comprehensive review of various issues related to the modeling, analysis, and determination of the optimal size of hybrid systems associated with wind energy, photovoltaic solar energy, fuel cells, and others. Presentation of economic data such as capital costs of renewable energy system devices and operation and maintenance expenditures in a single article makes it easier for researchers to access important information to perform calculations quickly and with minimal effort. Also involving the CO2 social cost in the levelized cost of energy enhances the competitiveness of renewable and clean energies in the energy market, which is a new trend in the economics of renewable energies.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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