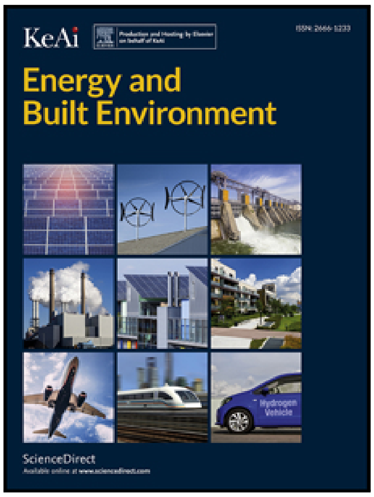
Journal Pre-proof



Multi-objective Optimization of Hybrid Energy Systems Based on Life Cycle Exergy and Economic Criteria

Mohammad Rezaei , Yadollah Saboohi , Gary Wang , Amirhossein Fathi

PII: S2666-1233(24)00043-6
DOI: https://doi.org/10.1016/j.enbenv.2024.03.009
Reference: ENBENV 318

To appear in: *Energy and Built Environment*

Received date: 5 August 2023
Revised date: 22 March 2024
Accepted date: 26 March 2024

Please cite this article as: Mohammad Rezaei , Yadollah Saboohi , Gary Wang , Amirhossein Fathi , Multi-objective Optimization of Hybrid Energy Systems Based on Life Cycle Exergy and Economic Criteria, *Energy and Built Environment* (2024), doi: https://doi.org/10.1016/j.enbenv.2024.03.009

Highlights

- Hybrid energy system was simulated and optimized in different configurations
- The renewable wind-solar-hydro system with water-heating module was assumed
- A multi-objective optimization was performed for a case study
- The levelized cost for standalone system is equal to 0.22 $/kWh
- The exergy cost ranges from 1.93 to 4.13 $/kWh in different scenarios

Multi-objective Optimization of Hybrid Energy Systems Based on Life Cycle Exergy and Economic Criteria

Mohammad Rezaei[1], Yadollah Saboohi [1], Gary Wang [2], and Amirhossein Fathi[3,*]

[1]*Department of Energy Engineering, Sharif University of Technology, Tehran, Iran*;
[2]*Engineering Science Department, Simon Fraser University, BC, Canada*
[3]*School of Mechanical Engineering, Shiraz university, Shiraz, Iran*

***** Correspondence: *afathi@shirazu.ac.ir*; Tel.: +98-713-3613-3444

Abstract

The present study aims to develop a novel optimal design of hybrid energy systems based on exergy and lifecycle concepts using genetic algorithms. The model consists of both stand-alone and on-grid options with scenarios for exchanging energy with the grid. The objectives include cost minimization or benefit maximization primarily, and lifecycle exergy efficiency, i.e., cost as the sustainability index secondarily. This research considers renewable sources such as solar, wind, hydropower, and hydrogen production and storage in addition to conventional diesel generators. The optimization was performed subject to weather conditions and solar radiation profiles, demand, and environmental or economic aspects. Also, the model contains various modules such as water-heating, waste energy utilization, as well as the options of power exchange with the distribution network and injection of hydrogen produced from excess renewable sources into the gas network. The application was demonstrated in a case study, where specific demands and the climate of Tehran were assumed. The case study considers four scenarios, including standalone, completely on-grid, on-grid with a non-backup generator, and on-grid without an energy sale option. The first optimal objective, the levelized unit cost of energy for the standalone system, is $0.22 per kWh. Moreover, the second optimal objective, the lifecycle exergy cost, ranges from 1.93 to 4.13 in different grid-connection states.

Keywords

Hybrid energy system, Life cycle Exergy, Optimization; Renewable energy, Sustainability.

Nomenclature

SI	sustainability index
ψ	exergy efficiency
P	thermo-ecological unit exergy consumption
E	unit exergy output of the system
P_B	power flow of electric storage system
P_{BU}	Backup power
P_{DL}	Dump load power
P_D	Demand power
SOC	battery state of charge
V_B	Battery voltage
V	Wind speed
V_{ci}	Cut-in speed of the wind turbine
V_{co}	Cut-out speed of the wind turbine
V_r	Rated speed of the wind turbine
P_r	Nominal power of the wind turbine
P_{module}	Photovoltaic module power
V_{OC}	the open-circuit voltage of the photovoltaic system
I_{sc}	the short-circuit current of the photovoltaic system
I_{sc0}	the short-circuit current of the photovoltaic system under standard conditions
T_{PV}	Photovoltaic Temperature
T_{air}	Ambient temperature
G	solar irradiance
G_0	solar irradiance at standard conditions
α	the exponent to consider the non-linear effects
β	dimensionless coefficient related to PV technology
δ	Exponent to observe temperature–voltage effects.
ρ	air density
Q	magnitude of the electron charge
K	Boltzmann constant
G	gravity constant (9.8 m/s^2)
Q	volumetric flow rate
Q_l	Loss of volumetric flow rate
H	head of flowing water
H_l	head loss of flowing water
K_{LFC}	life cycle exergy cost
LPSP	loss of power supply probability
Ex_{LFC}	Life cycle exergy consumption
Ex_{dir}	Direct life cycle exergy consumption
$Ex_{ind.}$	Indirect life cycle exergy consumption
K_{LFC}	life cycle exergy cost
ψ_{LFC}	life cycle exergy efficiency
AEP	annual energy production
AC	annual cost
ICC	initial capital cost

$C_{O\&M}$	operation and maintenance cost
R_{sell}	revenue generated by delivering electricity and/or hydrogen to the energy network
AEP	annual energy production
FCR	fixed charge rate
NPV	Net Present Value

1. Introduction

Renewable energy sources, as competitors with conventional types of primary energy carriers, are not economically strong alternatives to traditional fuels[1]. However, the utilization of renewable energy sources can be improved by increasing efficiency and reducing the degeneration of resources or greenhouse gas emissions. On the other hand, the unit energy costs of these energy sources have decreased drastically in recent years[2].

Indeed, hybrid energy systems are one of the most efficient applications of using renewable energy technologies. By integrating two or more energy conversion systems simultaneously, advantages of each energy source could be truly utilized. Also, economic losses and environmental consequences can be decreased in hybrid energy systems [3-5]. Furthermore, compensating the deficiencies of each energy source and enhance cost compatibility, reliability and accessibility to the required energy at any time is one of the other benefits [6-8].

One of the main issues on hybrid energy systems is design and sizing optimization. There are numerous researches about the issue in the literature [5, 9, 10]. They adopt various methods and algorithms such as genetic algorithm, particle swarm optimization, simulated annealing, and neural networks [11-13]. Furthermore, many different sizing codes as software tools such as HOMER have been developed and widely used in certain applications [14-16]. The aim of the present paper is to review and categorize different methodologies and approaches for optimizing hybrid system design and configuration. Therefore, this paper can be useful for researchers to review the recent trends of sizing optimization and sustainability assessments of integrated energy systems for small-scale and residential applications.

A number of studies have been published concerning the optimal design of hybrid energy systems[17-19]. Also, some researchers have studied and introduced different methods to assess and optimize the sustainability of energy supply systems [20-22]. Consequently, the literature has been reviewed in separate sections and categories.

1.1. Design Optimization Objectives

In the literature, various optimization criteria and objective functions have been reported for hybrid energy system design and sizing [5-7]. Many researches have focused on economic aspects, such as minimization of energy unit costs or maximization of total annual benefits [5, 12, 15]. Besides, some papers have applied extra objectives in addition to economic criteria [7, 13, 14]. These goals can be summarized in life cycle, environmental and emission objectives and limitations that include resource or geology prospects and the other physical or institutional constraints. A great majority of researches – about 90% of them, as reviewed in this paper - have adopted economic and cost objectives and constraints as main criteria.

Most of the studies regarding hybrid energy systems have assessed renewable energy sources, especially photovoltaics and wind turbines [5, 19]. The proposed hybrid system i.e. wind-PV, as the most conventional integrated system, has been studied in a considerable part of literature. In comparison to conventional studies, some research presents innovative solar hybrid units, commonly relying on electrolysis processes and renewable energies [23] and [24]. For instance, one study optimizes a unit integrating a parabolic trough collector, proton-exchange membrane electrolyzer, and fuel cell using Dowtherm™ A as the working fluid, showcasing cost-effective power generation during different demand periods [25]. Another unit combines a heliostat solar field, solid oxide electrolyzer cell (SOEC), and solid oxide fuel cell, with studies focusing on thermodynamic and economic aspects [26].

In contrast to hydrogen generation for storage systems or a product, certain studies concentrate on liquid air energy storage. An example involves the combination of liquid air energy storage with concentrated solar power technology [27], which can be utilized for water production or electricity generation [28]. The significance of energy storage has led to research efforts aimed at improving storage systems, considering different aspects such as Energy, Exergy, Environment, and Economic concepts [29].

The remaining researches have focused on the other renewable or fossil-based hybrid systems, such as diesel generators, combined cycles, hydro, biomass etc. Each of these technologies has its own advantages and drawbacks. However, the compensation of their disadvantages can be done in an integrated system. Hydropower is the most reliable renewable energy source beside biomass and biofuels. On the other hand, the costs of solar PV and wind turbine systems have decreased dramatically in these years [15, 19].

In addition, different methods of modeling have been applied in the literature in terms of the design and optimization of integrated energy systems. However, one of the main conventional optimization methods in this field is the genetic algorithm [9-11]. The researchers have utilized another popular algorithm, namely Particle Swarm Optimization (PSO) [12, 30, 31]. Also, neural networks, Linear Programming (LP), Simulated Annealing (SA), and software tools such as HOMER are other analytical tools considered in research works [8, 22, 32].

1.2. Sustainability Assessment Methods for Energy Systems

Sustainability of energy systems is an interdisciplinary phenomenon. In fact, there are limited conventional definitions and characteristics for energy sustainability. Energy sustainability can be divided into two most significant components. The first component is related to resource deficiency and renewability. Indeed, less consumption of natural sources such as mineral materials and fossil fuels by an energy system has more merits to reach sustainability goals. Moreover, the second element of energy sustainability, which represents the environmental aspect, can be described as a measure of nature's ability to absorb pollutants of any system [33].

However, the selection of the optimum system configuration according to multi-dimensional aspects is one of the novel approaches to identify the best system based on economic-environment aspect. Indeed, most researches have focused on multi-criteria analysis and decision-making methods to find and select the best system [20, 21]. The criteria studied are illustrated as follows:

I. Energy -or Exergy- Efficiency (%)
II. Unit (Levelized) Cost (currency unit/kWh)
III. Capital Cost (currency unit/kW)
IV. Unit Emission of Equivalent CO_2 (kg/kWh)
V. Unit Emission of NOx (kg/kWh)
VI. Unit Area per Capacity (m2/kW)
VII. Resource Consumptions

VIII. Availability indices

IX. Social indices

Table 1 shows variety of criteria in literature that have utilized method of multi-criteria analysis.

The point of each energy system (j) with ith index should be determined. In addition, the weight of each index in the objective function has to be defined. However, the weights are usually considered based on different scenarios and presumptions. Eq. 1 shows the total index for each system as a summation of different weighted indices of criteria for that system, in which w is the weight of ith index and q_{ij} is the score of jth system about ith criterion (index) [34, 35]:

$$Q_{(j)} = \sum_{i=1}^{n} w_{(i)} q_{ij} \tag{1}$$

Table 1. Different researches of sustainability assessment using multi-criteria methods

Index/Research	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
(Afgan et al , 2000) [34]	*	*	*	*	*		*		*
(Afgan et al , 2002) [35]	*	*	*	*		*			
(Afgan et al , 2008) [36]	*	*	*	*	*				
(Chatzimouratidis and Pilavachi, 2009) [37]	*	*	*	*			*	*	
(Evans et al, 2009) [38]	*	*		*		*	*	*	*
(Brent and Rogers, 2010) [39]	*	*		*			*	*	
(Stein, 2013) [40]	*	*	*	*			*	*	*

Another way to compare the sustainability of energy systems is to adopt exergy analysis. As exergy is the part of energy that is available to do work [33], the exergy concept can reflect the sustainability-related issues properly. Exergy-based methods comprise exergy analysis, energy analysis, thermo-economics, lifecycle exergy assessment, and extended exergy analysis, which can use exergy cost concepts. Thermo-economic and exergy cost methods have been applied in many cases for optimization of energy systems [33].

Two significant research works have utilized the method of advanced exergy for sustainability assessment and index definition. A research work was focused on wind-PV-hydrogen-geothermal renewable hybrid energy system where the sustainability index has been defined as a function of exergy efficiency [41].

Eq. 2 determines this index, where ψ is exergy efficiency of the system [41].

$$SI = \frac{1}{1-\psi} \tag{2}$$

In addition, as the second example, Frangopoulos defines the sustainability index as a thermo-ecological efficiency e.g. cost for a non-renewable energy system [42], in which ρ is the thermo-ecological unit exergy consumption and e is the unit exergy output of the system as shown in Eq.3 [42].

$$r = \frac{\rho}{e} \tag{3}$$

1.3. ADVANTAGES OF SUSTAINABILITY AND EXERGY BASED OPTIMIZATION

Although modelling of energy systems based on exergy is rather complex, there are merits in applying the concept of exergy. Exergy concept avails itself to monitoring depletion and consumption of resources, i.e. material and energy. As energy is conserved in a process or system, the exergy is destroyed in the process of conversion. Indeed, mechanical friction, heat transfer, chemical reactions and the other means of entropy generation are destructive phenomena [42].

Another advantage of utilizing exergy concept is the possibility of using an integrated objective in an optimization model. A multi-criteria model may result in definition of scenarios to weigh each criterion for a system configuration that inserts tact and undependable values for system selections based on diverse sustainability goals [16, 42].

As mentioned earlier, there are many conventional exergy-based methods for energy supply systems. Exergy analysis is a simple method to calculate and analyze exergy flows in a system [33]. Also, thermo-economic methods are analysis and optimization techniques based on imputing costs and values to exergy flows and minimizing exergy destruction and cost [42]. Furthermore, there are several lifecycle analysis methods based on exergy concept [43, 44] The first is ExLCA that proposed by Cornelissen (1997), which can be used together with LCA to determine the consumption and depletion of natural resources by measuring the lifecycle irreversibility, i.e., the exergy loss [43].

Another method is LCEA – Life Cycle Exergy Analysis – that introduced by Gong and Wall (1997, 2001), which separated renewable resources from non-renewable. Firstly, natural resources are classified as natural flows and stocks. Stocks are then divided into deposits (dead stocks) and funds (living stocks). Indeed, all flows during the life cycle of production, use and disposal are considered as exergy power over time [33, 43]. As for the simple life cycle analysis, the environmental charges are associated with a product or activity by recognition and quantifying used energy, materials and waste. Likewise, impacts on the environment from these energy and material uses and wastes should be assessed as well. However, the multidimensional approach of this method causes large problems in terms of comparing various substances and flows, and general judgements are difficult. This issue has been avoided if exergy was used as a common quantity, which has been done in Life Cycle Exergy Analysis (LCEA) [43].

The capabilities of different proposed methods are illustrated in Table 2. As can be seen, the lifecycle exergy analysis can be the best option for utilization of exergy concepts into power and heat supply technologies, while the other methods such as multi-criteria optimization have more issues. In other words, that is the one of limited methods, which can consider lifecycle of the systems and detailed exergy consumption of technologies.

Table. 2. Advantages and disadvantages of different methods in energy systems sustainability assessments [32, 33, 42]

	Life Cycle Exergy Analysis [43, 45]	**Exergetic Life Cycle Assessment [43, 44]**	**Exergy Analysis [46, 47]**	**Thermo-economic methods [48, 49]**	**Multi-criteria Analysis [20, 37, 40]**
Considering short and long term effects	+	+	-	+	+
Analysis the whole process from cradle-to-grave	+	+	-	-	-
Considering environmental concepts	+	+	-	-	+
Considering scarcity of non-renewable sources	-	-	-	-	+
Ability to compare	-	-	+	-	+

factors and indices					
Considering resource destruction and exergy concepts	+	+	+	+	-
Ability to be used in system sizing and design	+	-	+	+	-

Therefore, in this paper, the rule of sustainability for integrated energy systems of heat and electricity supply can be conveyed by means of a novel index, namely lifecycle exergy efficiency. Also, the heat and electricity supply system, e.g. cogeneration, considering comparison between renewable energies and fossil fuels has been presented, which has not been studied in this degree of comprehensiveness. Moreover, the functions of equations of costs and exergy consumptions have been built as well.

Consequently, the contribution of this research can be expressed in the following areas:

i. Introducing concepts such as exergy and life cycle analysis in the examination and optimization of hybrid systems.
ii. Development of a comprehensive model for simulating complex systems based on the method of determining optimal dimensions using the optimal performance point, taking into account appropriate objective functions.
iii. Development and application of the concept of partial stability and its indicators in small-scale household energy systems to expand and enhance the effective efficiency of these energy systems.
iv. Defining novel optimization objective functions that, in addition to addressing purely technical and economic issues, consider hierarchical levels and macro issues related to the sustainability of energy systems.
v. Comparing the results obtained from the addition of partial sustainability goals and indicators with conventional technical-economic objective functions in hybrid systems.

2. Materials and Methods

The developed tool contains optimization of supply, storage and backup system based on hourly dynamic simulation of an integrated system in a year. The model consists of heat and power sub-modules for two scenarios of on-grid and off-grid systems. In addition, two diverse options for energy exchange to the grid is considered. Indeed, hydrogen injection to the gas distribution network is assumed as an alternative to the delivery of electricity to the network. Also, the electrical grid and back-up generator are two options for compensating power loss at every hour. The comparison between alternatives is on costs of each option. Design and configuration of the hybrid electricity system is shown in Fig.1, which indicates PV and wind turbine as the representatives of AC and DC current supply systems.

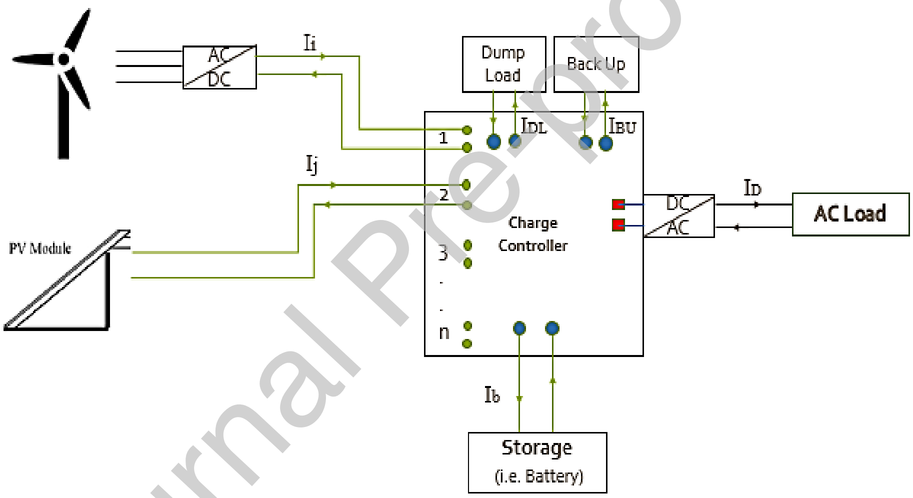


Fig. 1. Schematic diagram of a standalone integrated electrical supply system

The Hourly profile of temperature, wind speed, and energy demand are inputs of the model. Furthermore, geographic location of the region, i.e. latitude and longitude, monthly air clearness index, and the other constants are considered as input parameters. In addition, economic parameters such as the discount rate, system lifetime, and prices of energy buy and sale should be inserted.

The total power flow balance is shown as Eq.4, where the P_B is the power flow of electric storage system, and P_{BU} and P_{DL} are backup power and dump load respectively [14, 19]. SOC shows the battery state of charge and $\boldsymbol{V_B}$ is the battery voltage.

$$\sum_{i=1}^{n} \boldsymbol{P_i(t)} + \sum_{j=1}^{m} \boldsymbol{P_j\,(t)} + \boldsymbol{P_{BU}(t)} = \boldsymbol{P_D(t)} + \boldsymbol{P_{DL}(t)} + \boldsymbol{P_B(t)} \tag{4.a}$$

$$\boldsymbol{P_B(t_0)} = \sum \boldsymbol{P_i(t_0)} + \sum \boldsymbol{P_j(t_0)} - \boldsymbol{P_D(t_0)} \tag{4.b}$$

$$\boldsymbol{SOC(t)} = \boldsymbol{SOC(t-1)} + \frac{\boldsymbol{P_B(t_0)}}{\boldsymbol{V_B(\,t)}} \tag{4.c}$$

The considered types of hydro turbines are Pelton, Kaplan and Francis turbines. Also, vertical (VAWT) and horizontal axis turbines (HAWT) are assumed as two conventional wind turbine types. In addition, the mono-crystalline, poly-crystalline, Cd-Te and thin-film PV panels are included in the model. Sinus and square types of inverter are included in the technology vector. Furthermore, life cycle emission coefficients of different systems are also assumed as a part of costs for penalizing the GHG emissions.

2.1. Wind Turbine

The wind turbine performance equation is power curve with inputs of cut-in, rated and cut-out wind speeds, and also capacity of the turbine as Eq.5 [48, 49]. The subscripts ci, co, and r are cut-in, cut-out and rated speed or power illustrations, respectively.

$$P_w(t) = \begin{Bmatrix} P_r \dfrac{(V(t)^3 - V_{ci}{}^3)}{(V_r^3 - V_{ci}{}^3)} & if \quad V_{ci} \le V(t) \le V_r \\ P_r & if \quad V_r \le V(t) \le V_{co} \\ 0 & e,o,c \end{Bmatrix} \tag{5}$$

2.2. Photovoltaics

The five-parameter model was employed where the parameters are temperature and radiance factors, internal resistance, and standard factors of PV e.g. open circuit voltage and short circuit current. In the technical model, the module power and the panel temperature are formulated in Eq.6, which have been solved iteratively for the nonlinearities [50].

$$\boldsymbol{P}_{\text{module}} = \frac{\frac{\boldsymbol{Voc}}{\boldsymbol{n}_{\text{MPP}}\boldsymbol{KT}_{\text{PV}}/\boldsymbol{q}} - \boldsymbol{ln}\left(\frac{\boldsymbol{V}_{\text{oc}}}{\boldsymbol{n}_{\text{MPP}}\boldsymbol{KT}_{\text{PV}}/\boldsymbol{q}} + \mathbf{0.72}\right)}{\mathbf{1} + \frac{\boldsymbol{V}_{\text{oc}}}{\boldsymbol{n}_{\text{MPP}}\boldsymbol{KT}_{\text{PV}}/\boldsymbol{q}}}\left(\mathbf{1} - \frac{\boldsymbol{R_s}}{\boldsymbol{V}_{\text{oc}}/\boldsymbol{I}_{\text{sc}}}\right)\boldsymbol{I}_{\text{sco}}\left(\frac{\boldsymbol{I_c}}{\boldsymbol{G_0}}\right)^{\boldsymbol{\alpha}}\frac{\boldsymbol{V}_{\text{oco}}}{\mathbf{1} + \boldsymbol{\beta}\,\boldsymbol{log}\left(\frac{\boldsymbol{G_0}}{\boldsymbol{Ic}}\right)}\left(\frac{\boldsymbol{T_0}}{\boldsymbol{T}_{\text{PV}}}\right)^{\boldsymbol{\gamma}} \quad (6.a)$$

$$\boldsymbol{\alpha' A}\left(\boldsymbol{I_c} + \boldsymbol{\sigma}(\boldsymbol{\epsilon}_{\text{sky}}\boldsymbol{T}_{\text{sky}}^{\mathbf{4}} + \boldsymbol{\epsilon}_{\text{ground}}\boldsymbol{T}_{\text{ground}}^{\mathbf{4}} - \mathbf{2}\boldsymbol{\epsilon}_{\text{PV}}\boldsymbol{T}_{\text{PV}}^{\mathbf{4}})\right) = \mathbf{2}\boldsymbol{A}\left(\mathbf{1.31}(\boldsymbol{T}_{\text{PV}} - \boldsymbol{T}_{\text{air}})^{\frac{1}{3}} + \mathbf{0.5}\boldsymbol{V}_{\text{wind}}\right)(\boldsymbol{T}_{\text{PV}} - \boldsymbol{T}_{\text{air}}) + \boldsymbol{P}_{\text{module}} \quad (6.b)$$

In which V_{oc} is the open-circuit voltage, R is the resistance, G illustrates the radiation, T is the temperature and I_{sc} is the short-circuit current.

2.3. Hydro Turbine

Actually, the performance model of a specific hydro turbine requires mechanical and electrical efficiencies of turbine and generator and the nominal flow rate is an input parameter for the model.

The mechanical efficiency in hydro turbines depends on the ratio between the real and nominal flow rate [51]. The equation of output power of a hydro turbine is given in Eq.7 [51].

$$\boldsymbol{P(t) = \rho * g * (Q(t) - Q_l) * (H - H_l) * \eta_{mech}(t) * \eta_{elec}} \quad (7)$$

Where ρ is the air density, g is the gravity constant (9.8 m/s^2), Q shows the volumetric flow rate and H is the head of flowing water.

2.4. Battery

Among various models and formulations for batteries, the Copetti model was opted to simulate the utilization of the storage system [52]. Simplicity and accuracy of the model is acceptable for the simulation in comparison with the other equivalent-circuit models [51, 52].

2.5. Fossil-fuel Generator

The generator of the hybrid system can act either as a backup of electricity supply or as a main power supply device. In the first option, the power loss of supply and storage systems is compensated using backup generator. In the second case, a specific mass flow rate profile of a fuel is used to generate in addition to the other renewable energy systems. The performance curves and equation are extracted from relative researches. Moreover, the generator can be performed fixed or variable RPM [53].

2.6. Heat Supply System Configuration

The heat supply system consists of series modules that heat water from ambient temperature to the desired value. The heat loss from PV, diesel generator, or fuel cell, and different types of solar collectors are considered. Additionally, to achieve the desired temperature of 80 degrees Celsius, a boiler is included in the system. Fig. 2 illustrates the schematic formation of the water heating system.

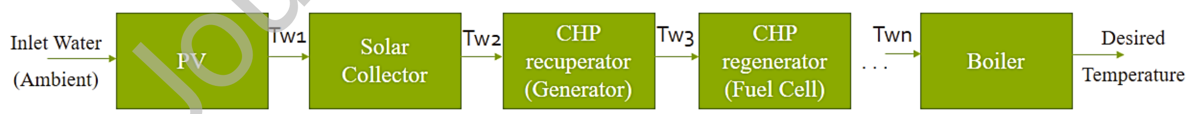


Fig. 2. Heating system flow diagram

2.7. Validation of the Simulation model

As the purpose of this research is to develop a model for **the** optimization of the size of hybrid energy systems, the simulation model validation is shortly pointed. Indeed, the validation was performed in a hybrid wind-solar lab in Sharif Energy Research Institute, in which the system includes wind and solar photovoltaics as the supply systems and batteries as a storage device. The horizontal axis wind turbine has been tested in a wind tunnel using a fan and filters to make wind. In addition, the solar photovoltaic panels are mounted in an outdoor place being insolated. Various tests were implemented for the hybrid system for **the** validation of the simulation model. Thereupon, total errors of the model were found to be less than 10% in all tests. Also, for the hybrid system for a few hours simulation, the relative difference between model and experimental results has been 6.2% for the sum of supplied power. Fig. 3 illustrates a system power output compared to the power calculated by the model with inputs of solar radiation at specific time and wind speed, which was set by the fan.

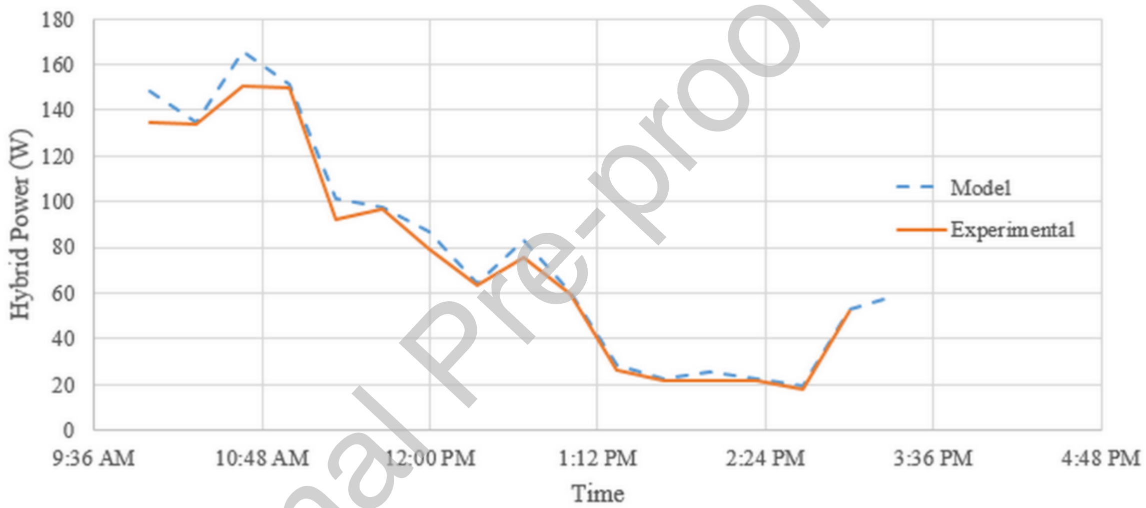


Fig. 3. Comparison between experimental and simulation results for hybrid system output power

3. Optimization Model

According to the proposed comparisons between different approaches to survey sustainability of an energy system, life cycle exergy is the optimal method to study technical systems regarding energy sustainability criteria. The main objective is to maximize this variable i.e. to minimize life cycle exergy cost for a hybrid energy system.

Moreover, the second objective is defined in a multi-objective formulation in the position of unit or levelized energy cost minimization. As life cycle emission cannot be properly modelled in the way of exergy consumption [7, 33], this phenomenon is assumed as a penalty cost in addition to levelized energy cost. This index explains the cost of one kWh of energy supplied by the whole system, and can be calculated in form of Eq. 11. Furthermore, the cost competition of different options can be considered by assuming the second objective function. The multi-objective function of the optimization problem is shown below in Eq.8, where K_{LFC} is the life cycle exergy cost, and LCOE is levelized i.e. unit cost of energy. The constraints of the model are desired loss of power supply probability, power and heat demand hourly profiles, and historical temperature, wind speed, solar radiation, and hydro flow rate profiles of the region.

$$\begin{aligned} &\boldsymbol{Min\ Z_1 = K_{LFC}} \quad \text{or} \quad \boldsymbol{Min\ Z_2 = LCOE} \\ &\boldsymbol{S.t.} \\ &\boldsymbol{Demand\ profiles} \\ &\boldsymbol{Ambient\ temperature\ profiles} \\ &\boldsymbol{Renewable\ energy\ flow\ profiles} \\ &\boldsymbol{LPSP \leq LPSP_{Desired}} \end{aligned} \tag{8}$$

Indeed, the optimization problem has 14 variables including size of wind turbine, PV, hydro turbine, solar collector (area), fuel cell and electrolyzer, hydrogen tank, number and capacity of batteries, and type of wind turbine, PV, hydro turbine, collector and batteries. In the case of energy sale to the grid, the revenue would be achieved **besides** costs of the system. Therefore, the net present value should be defined instead of levelized cost of energy for the second objective function. Table 3 illustrates the variables of **the** problem, which can be varied in the optimization process.

Table 3. Variables of the optimization problem

Variable	Description	Unit
X_1	Wind turbine size (capacity)	W
X_2	Wind turbine type (HAWT or VAWT)	-
X_3	Solar PV size (capacity)	W
X_4	Solar PV type	-
X_5	Hydro turbine size (capacity)	W
X_6	Hydro turbine type	-
X_7	Solar collector area	m^2
X_8	Solar collector type	-
X_9	Battery capacity (and/or numbers)	A.h

X_{10}	Battery type	
X_{11}	Diesel (gas) generator size (capacity)	W
X_{12}	Electrolyzer capacity	W
X_{13}	Fuel cell size (capacity)	W
X_{14}	Hydrogen storage volume capacity	m^3

3.2. Formulation of Life Cycle Exergy

Life cycle exergy consumption is derived to direct and indirect exergy. Direct exergy is the exergy of energy e.g. fuel consumption in operation periods of a device or system, and indirect exergy defined as sum of all exergy consumptions during construction and destruction. Therefore, the total life cycle exergy consumption of a system can be defined as Eq.9.

$$\boldsymbol{Ex_{LFC}} = \sum \boldsymbol{Ex_{dir}} + \sum \boldsymbol{Ex_{ind}}. \tag{9}$$

Where direct and indirect exergy are considered as below in Eq.10.

$$\dot{\boldsymbol{Ex}}_{\boldsymbol{dir(i)}} = \dot{\boldsymbol{m}}_{\boldsymbol{f}} * \boldsymbol{ex}_{\boldsymbol{f(i)}} + \dot{\boldsymbol{Ex}}_{\boldsymbol{dir(renewables)}} \tag{10}$$

Therefore, life cycle exergy cost can be defined as inverse of life cycle exergy efficiency as illustrated in Eq.11.

$$\boldsymbol{K_{LFC}} = \frac{\boldsymbol{1}}{\boldsymbol{\psi_{LFC}}} = \frac{\sum \dot{\boldsymbol{Ex}}_{\boldsymbol{LFC}}}{\sum \dot{\boldsymbol{Ex}}_{\boldsymbol{out}}} = \frac{\sum \dot{\boldsymbol{Ex}}_{\boldsymbol{dir}} + \sum \dot{\boldsymbol{Ex}}_{\boldsymbol{ind}}}{\boldsymbol{AEP}} \tag{11}$$

where K_{LFC} shows the life cycle exergy cost, which is the inverse of life cycle exergy efficiency. The AEP is annual energy production or sum of the total energy produced by the systems, which can be derived from the power and heat supply. The optimization variables can be utilized and computed in exergy consumption and AEP equations, which are based on simulation model. Indeed, the information and data for relations of indirect and direct exergy of different technologies are required for the equations, which should be included in the model. Also, economy of scale has an important role where the exergy consumptions are related to the system size [18].

3.3. Formulation of Energy Cost

Manufacturing, construction and installation of a system is summarized as initial capital cost. This parameter can be followed with operation and maintenance **costs** in the working period. The levelized unit cost of energy for the whole hybrid system can be illustrated as below in Eq. 12 [54].

$$\boldsymbol{LCOE = \frac{\sum AC}{AEP} = \frac{ICC * FCR}{AEP} + C_{O\&M}} \quad (12)$$

The term AC is the annual cost or sum of the operation, maintenance and discounted capital cost. For on-gird systems, delivering electricity or hydrogen to the network is assumed as a source of revenue. Therefore, the net present value maximization is considered to announce the economic objective function, which is indicated in Eq. 13.

$$\boldsymbol{NPV = -ICC - \frac{C_{O\&M}}{FCR} + \frac{R_{sell}}{FCR}} \quad (13)$$

where ICC, $C_{O\&M}$ and R_{sell} represent the initial capital cost, operation and maintenance cost and the revenue generated by delivering electricity and/or hydrogen to the energy network respectively. In addition, AEP is annual energy production, and FCR represents fixed charge rate, which is relies on the system age and discount rate.

The economy of scale should be applied for initial capital cost formulation as for exergy consumption rates. Results of literature review indicate that equations for cost and exergy consumption in Table 3, which are extracted by interpolation of the data, can be utilized for applying the economies of scale in the hybrid system modelling [19, 54, 55].

Table 3. Varying capital cost (ICC) in $ and Indirect Exergy in MJ per capacity (x) in [kW] or [Ah]

Technology (Device)	Initial Capital Cost ($[\frac{\$}{kW}]$ or $[\frac{\$}{Ah}]$)	Indirect Exergy Consumption ($[\frac{MJ}{kW}]$)	References
Wind Turbine (HAWT)	$3056\ x^{-0.53}$	$-1446 \ln(x) + 13267$	[6, 19, 55]
Solar PV Panel (Monocrystalline)	$1432\ x^{-0.141}$	$x^{-0.066}$	[46, 54, 55]

Hydro Turbine (Francis)	$5768\ x^{-0.2}$	$52910\ x^{-0.169}$	[32, 33, 56]
Battery (C10 lead-acid type C)	$5.5319\ e^{-0.003x\ [A.h]}$	-0.0015x + 20.33 [MJ/Ah]	[5, 51, 54]
Fuel cell (PEM)	$6693\ x^{-0.205}$	-0.1x+23.2	[41, 47, 55]
Generator (Diesel 3000 rpm)	$1213\ x^{-0.48}$	$0.4718x^2 - 36.63x + 3886.2$	[51, 53, 54]
Inverter (Sinus)	$2019\ x^{-0.31}$	310x-16	[18, 33, 51]
Solar Collector (Flat Plate)	$791\ x^{-0.081}$	$2238.7\ x^{-0.174}$	[6, 46, 51]

4. Case Study Results and Discussion

The sample case study of the optimization model is a hybrid energy system in the city of Tehran. **The** implemented exogenous parameters of the model are indicated in Table 4. Also, Fig. 4 shows the annual temperature, wind speed and hydro flow rate profiles in the region. The load profiles were extracted by studying researches in the literature by combining annual and weekly demand profiles [57]. Fig. 5 illustrates considered profiles of power and heat demand. The results are presented for various scenarios. The strategies are off-grid as a first case, full on-grid, on-grid with power purchase option, and non-backup systems. The simulation model results have been validated using a wind-solar laboratory in Sharif Energy Research Institute, which was a comprehensive verification and comparison of the model results to the experimental parameters.

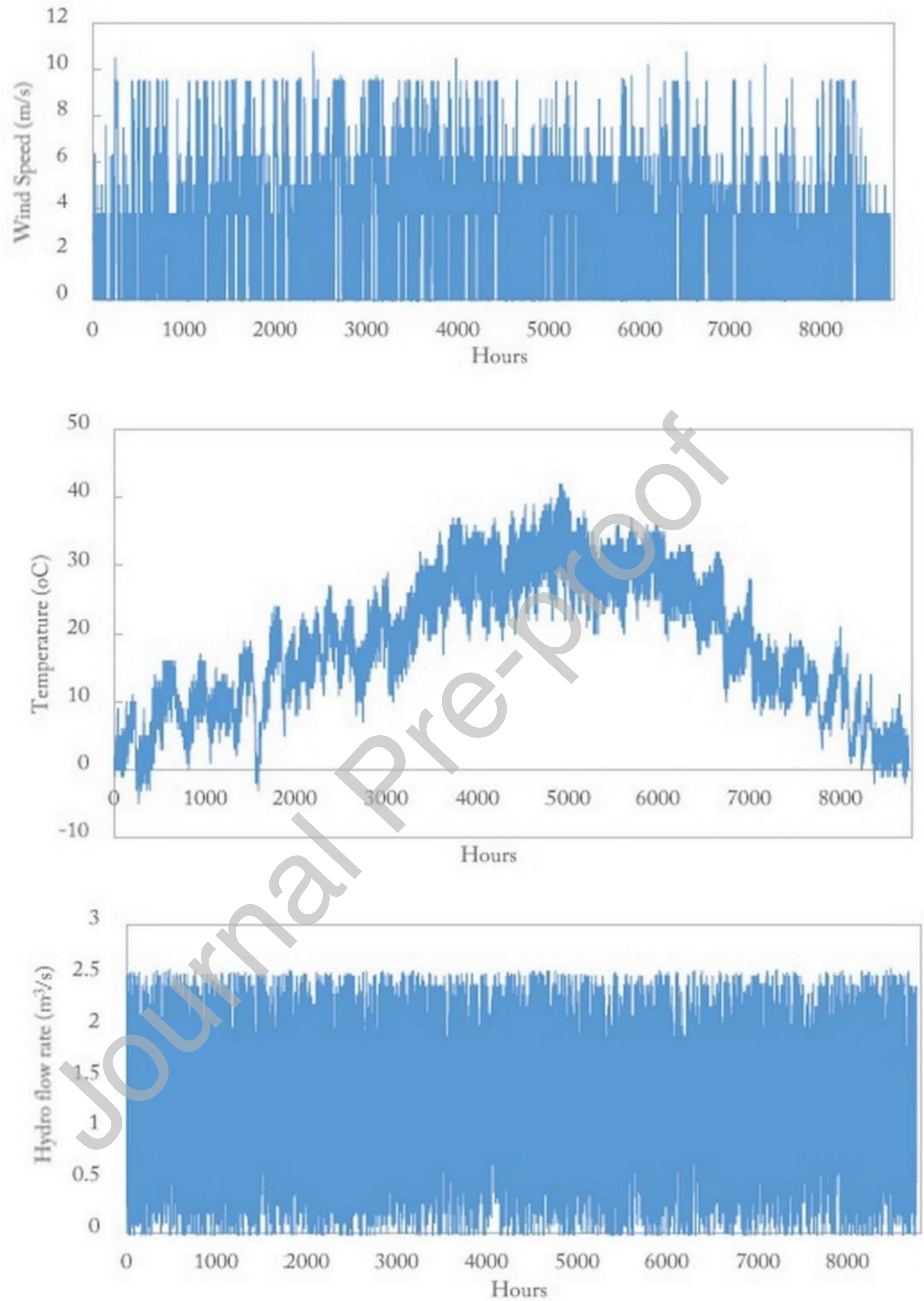
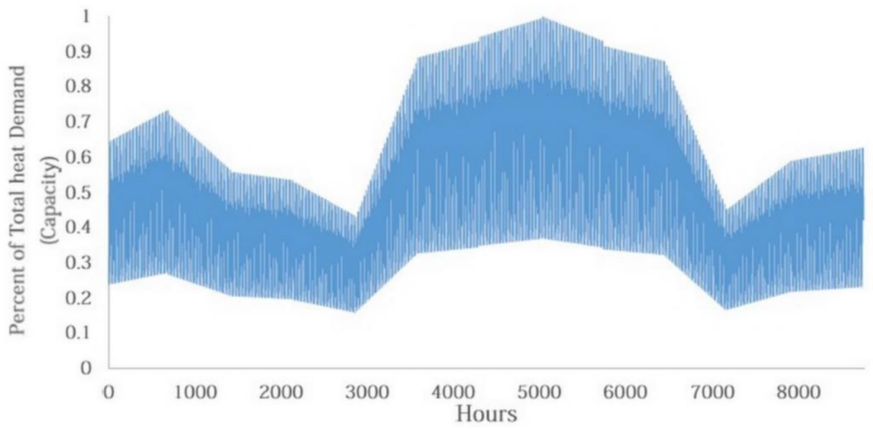


Fig. 4. Time-variable weather boundary conditions of case study in Tehran

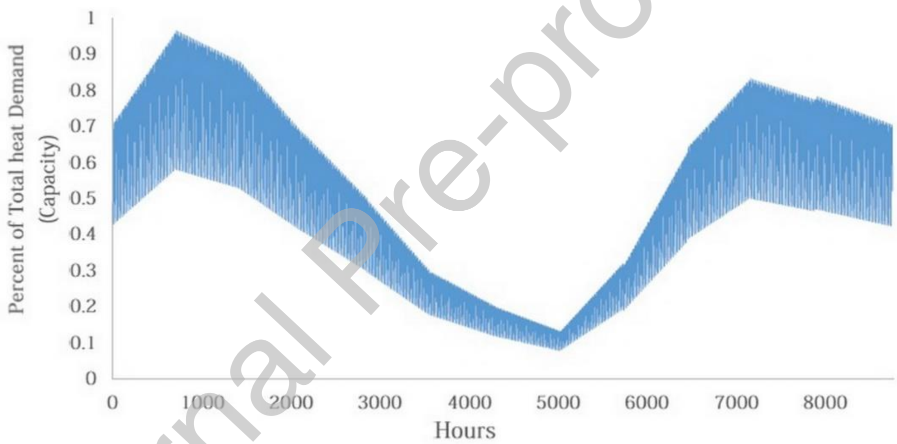
Table 4. Input parameters for the case study of optimization model

Input Parameter	Specification
Region	Tehran, Iran
Hydro turbine head	0.7 m
Battery voltage and capacity	200 Ah, 12V
Number of storage days	1 day
Generator type	Diesel, fixed rpm
Peak electrical demand	2000 W
Peak heat demand	1000W
Required water temperature	80 ^{o}C
Electricity Feed in tariff ($/kWh)	0.2
Electricity Purchase Price ($/kWh)	0.03
Hydrogen Feed-In Price ($/kg)	20
Natural Gas unit Price ($/m3)	0.05
Gasoil unit Price ($/kg)	0.1
CO_2 Carbon penalty ($/kg)	0.01

The input parameters listed in Table 4 are based on the configuration employed at Sharif Energy Research Institute and mirror the energy carrier tariffs prevalent in Iran during our study period. Nevertheless, it is imperative to highlight that the tariffs for energy carriers have undergone modifications owing to fluctuations in exchange rates.



(a)



(b)

Fig. 5. (a) Hourly power demand profile diagram, (b). Hourly heat demand profile diagram

The global optimization toolbox of MATLAB has been used to solve this problem. The parameters of the optimization method have been described in Table 5.

Table 5. Parameters of utilized genetic algorithm for the optimization

Parameter	Magnitude or type
Population size	35
Fitness scaling	Rank
Selection Function	Stochastic Uniform
Population type	Double vector
Number of generations	100

4.1. Off-grid system

For the first scenario, the standalone hybrid system is considered, which has generator as a power backup system. In this case, the results are obtained as Table 5 for 15% discount rate, 20 years of life and in the case of input parameters in Table 4. The optimization results are presented in three cases, which are single and multi-objective conditions. Since no exchange of energy with grid is possible, only levelized unit cost of energy shall be estimated, which is indicated in the Table 6. Also, the Pareto front of multi-objective problem with different iteration points are illustrated in Fig. 6.

Table 6. Output parameters and results of single-objective optimization for off-grid system

Output Parameter	Result for economic objective function (Levelized cost)	Result for exergy objective function (LCEx)
PV rated power (W) * Number, PV type	390*8, Polycrystalline	230*8, Cd-Te
Wind turbine rated power (W), turbine type	90, HAWT	430, HAWT
Hydro turbine rated power (W)	809	1209
Hydro turbine type	Pelton	Kaplan
Solar Collector Area (m2), collector type	3.5, Evacuated Tube	2.9, Flat-Plate
Number of batteries	24	25
Annual Electricity Production (kWh)	11238	11237

Annual Heat Production (kWh)	4336	4336
System Capacity Factor	25%	26%
Renewable Energy use Fraction (%)	94.50%	95.50%
Backup option (Generator, Fuel cell or Grid)	Generator	Generator
Annual Fuel (Boiler natural gas) Consumption (kg)	268.9	270.4
Annual Fuel (Gasoil Generator) Consumption (kg)	1197	1082
Annual / Life Cycle CO_2 production (kg)	1923	1890
Levelized cost of energy ($/kWh) [2nd obj.]	**0.22**	0.27
Life Cycle Exergy cost [1st obj.]	7.1	**4.13**
Levelized cost of electricity ($/kWh)	0.32	0.36
Levelized Cost of heat ($/kWh)	0.04	0.05

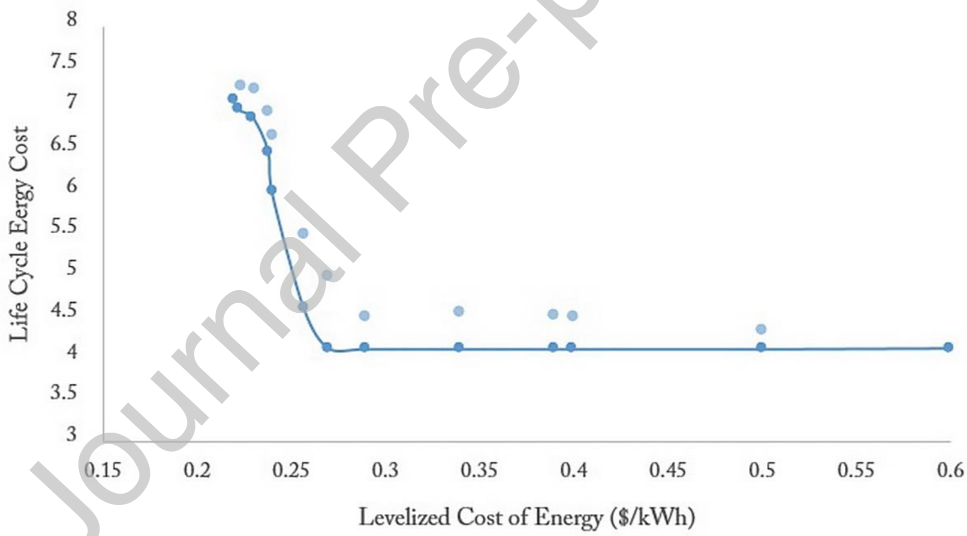


Fig. 6. Pareto front of two-objective optimization for off-grid hybrid system

4.2. On-grid without energy sell option

The second scenario states on a hybrid system regarding similar boundary conditions, but with the option of buying electricity from the grid as a competitor to backup diesel generator. In this situation, the results are listed in table 7. Indeed, the electricity purchase price has a significant role in changing the results. Actually, the presumed price in this paper is 0.03 $/kW h.

Table 7. Output parameters and results of single-objective optimization for on-grid with power purchase system

Output Parameter	Result for economic objective function (Levelized cost)	Result for exergy objective function (LCEx)
PV rated power (W) * Number, PV type	173*15, Polycrystalline	72*10, Monocrystalline
Wind turbine rated power (W), turbine type	496, HAWT	152, HAWT
Hydro turbine rated power (W), turbine type	397, Pelton	1808, Pelton
Output Parameter	**Result for economic objective function (Levelized cost)**	**Result for exergy objective function (LCEx)**
Solar Collector Area (m2), collector type	1.69, Evacuated Tube	2.43, Flat-plate
Electrolyzer Capacity (W)	0	0
Annual Electricity Production (kWh)	11056	10084
Annual Heat Production (kWh)	4336	4336
System Capacity Factor	28%	29%
Renewable Energy use Fraction (%)	0.78	0.74
Backup option (Generator, Fuel cell or Grid)	Grid	Grid
Annual Fuel (Boiler natural gas) Consumption (kg)	294	265
Annual / Life Cycle CO_2 production (kg)	1890	1850
Levelized cost of energy ($/kWh) [1st obj.]	**0.21**	0.24
Life Cycle Exergy cost [2nd obj.]	5.05	**3.3**
Levelized cost of electricity ($/kWh)	0.288	0.33

4.3. Total On-grid system

The next scenario for hybrid energy system configuration belongs to the on-grid system, which can transfer i.e. buy and sell energy to the grid. The proposed system has two options of power backup and two options of excess energy sale to the grid. The cases are electricity purchase beside diesel or fuel cell generator system, and electricity sell in competition with hydrogen injection to gas network for excess energy transfer. The model can determine the optimum point regarding exogenous parameters and the system power flow. Results of optimization in the case of an on-grid are shown in Fig. 7 and Table 8 for the same boundary conditions in Table 4. As can be seen, the net present value is the second objective function instead of unit cost of energy.

Table 8. Output parameters and results of single-objective optimization for on-grid system

Output Parameter	**Result for economic objective function (NPV)**	**Result for exergy objective function (LCEx)**
PV rated power (W) * Number, PV type	396*15, Polycrystalline	90*8, Cd-Te
Wind turbine rated power (W), turbine type	1450, HAWT	1152, HAWT
Hydro turbine rated power (W), turbine type	1445, Pelton	1214, Pelton
Solar Collector Area (m2), collector type	2.63, unglazed	0.7, unglazed
Electrolyzer Capacity (W)	1819	0
Hydrogen storage (kg)	6.835	0
Annual Electricity Production (kWh)	23129	10533
Annual Heat Production (kWh)	4348	4337
System Capacity Factor	29%	33.2%
Renewable Energy use Fraction (%)	93.8	79.7
Backup option (Generator, Fuel cell or Grid)	Grid	Grid
Delivery Option to the grid (Electricity or Hydrogen)	Hydrogen	Electricity
Annual Fuel (Boiler natural gas) Consumption (kg)	234	296

Annual / Life Cycle CO_2 production (kg)	3430	1723
Annual Sale Revenue ($)	11456	3650
NPV($) [1st obj.]	**53463**	33988
Life Cycle Exergy cost [2nd obj.]	3.76	**2.69**

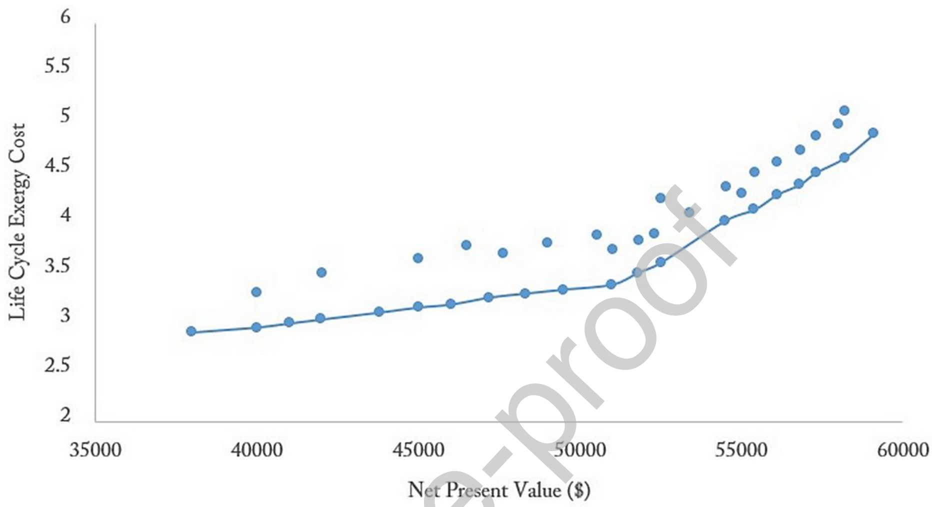


Fig. 7. Pareto front of two-objective optimization for on-grid hybrid system

4.4. On-grid system with non-backup generator

The last case for hybrid systems can be defined as a system with non-backup fossil-fuel generator operating in comparison with renewable energy supply technologies. The generator can produce electricity same as the other energy systems regarding a specific mass flow rate of the fuel. The exogenous conditions of the scenario are similar to previous situations. The results for a specific mass flow rate profile with average of 0.5 kilograms per hour and boundary conditions of table 4 can be shown in Table 9.

Table 9. (a) Output parameters and variables (b) results of optimum design

(a) Output parameters and variables

Output Parameter	Result for economic objective function (NPV)	Result for exergy objective function (LCEx)
PV rated power (W) * Number, PV Type	52*8, Poly-crystalline	64*15, Thin-film
Wind turbine rated power (W), WT Type	120, HAWT	552, HAWT
Hydro turbine rated power (W), turbine type	620, Pelton	1024, Kaplan
Output Parameter	**Result for economic objective function (NPV)**	**Result for exergy objective function (LCEx)**
Diesel Generator rated power (W)	2150	1608
Solar Collector Area (m2), collector type	2.65, Evacuated tube	1.82, Evacuated tube
Electrolyzer Capacity (W)	980	1578
Fuel Cell capacity (W)	0	1904
Hydrogen storage (kg)	1.67	2.88

(b) results of optimum design

Output result	Result for economic objective function (NPV)	Result for exergy objective function (LCEx)
Annual Electricity Production (kWh)	9094	10234
Annual Heat Production (kWh)	4435	4434
System Capacity Factor	24%	26%
Backup option (Generator, Fuel cell or Grid)	Grid	Fuel cell
Delivery Option to the grid (Electricity or Hydrogen)	Hydrogen	Hydrogen
Annual Fuel (Boiler natural gas) Consumption (kg)	284	245
Annual Fuel (Gasoil Generator) Consumption (kg)	3454	2182
Annual / Life Cycle CO_2 production (kg)	1989	1998

Annual Sale Revenue ($)	1254	2358
NPV($) [1st obj.]	**24409**	22087
Life Cycle Exergy cost [2nd obj.]	2.43	**1.93**

The optimal values of objective functions for the two different single objectives are categorized in Table 10.

Table 10 – Optimum value of single objective functions in the proposed scenarios

	Optimum 1st obj. function	Optimum 2nd obj. function
Scenario 1 (Off-grid)	0.22 $[\frac{\$}{kWh}]$	4.13
Scenario 2 (On-grid without energy sale)	0.21 $[\frac{\$}{kWh}]$	3.3
Scenario 3 (On-grid)	53463 [$]	2.69
Scenario 4 (On-grid with non-backup generator)	24409[$]	1.93

5. Sensitivity Analysis

An analysis was performed by changing the input parameters. Indeed, the threshold points have been determined, which an option such as diesel generator is preferred to another choice e.g. grid. These margins can be detected by a sensitivity analysis that redounds to variation of optimal results.

For on-grid system without power sale option, the marginal fuel and electricity prices were determined, in which grid power purchase or diesel generator options were chosen. These margins for the levelized energy cost objective function of optimization have been illustrated in

Fig. 8. There are two areas, in which each of the backup solutions was opted, since being more affordable.

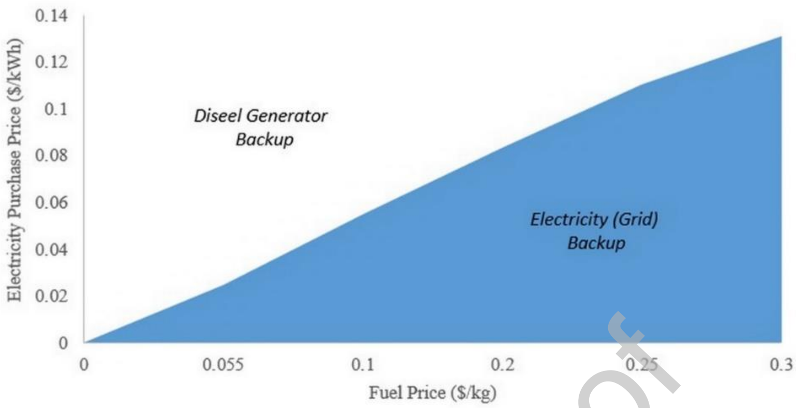


Fig. 8. Threshold optimal points of backup system selection for first objective i.e. levelized cost

Figure 8 depicts a sensitivity analysis on the electricity network price and the fuel cost. In cases where the electricity network price is higher than the fuel cost, factoring in the capital cost of the diesel generator, utilizing the diesel generator as a backup system demonstrates higher economic justification compared to supplying a portion of the demand through the network.

Also, for on-grid system, the marginal hydrogen and electricity prices that change optimum excess energy selling option were figured out. Fig. 9 illustrates the result of the proposed threshold points of choosing sale options for both objective functions as well.

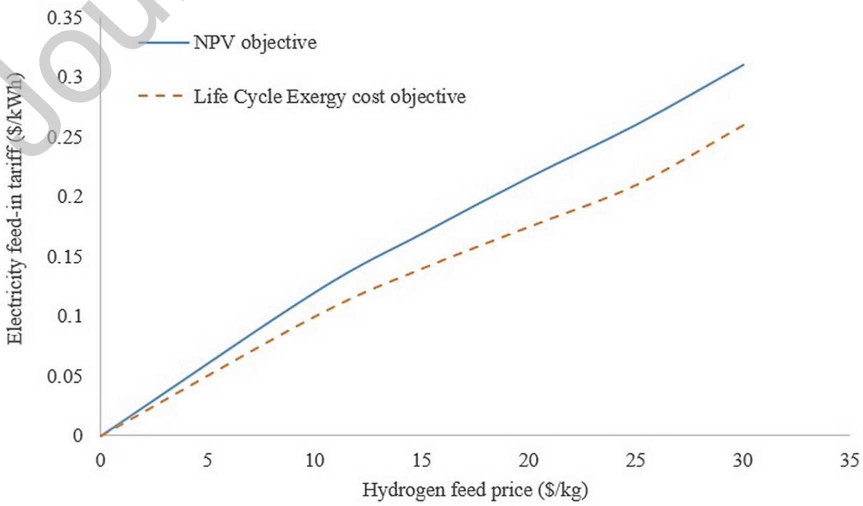


Fig. 9. Different optimal threshold points of energy sale alternative selection for two objective functions

Figure 9 investigates the variation in hydrogen prices and the tariff for selling electrical energy to the national grid in the context of appropriate utilization of surplus electrical energy based on objective functions: maximum net present value or minimum life cycle exergy cost.

The results show that, when selecting the maximum net present value as the objective function, the use of surplus electricity for hydrogen production, compared to selling surplus electricity to the national power grid, is recommended in higher tariff ranges than the electricity selling tariffs to the grid in terms of the minimum life cycle exergy cost objective function. This is because the use of electrolyzers and the hydrogen selling system, in terms of exergy and resource consumption, lowers the system's qualitative state. Consequently, if the objective function is to minimize the life cycle exergy cost, hydrogen sales are recommended in a smaller range of electricity selling tariffs to the grid

6. Conclusion

In the present paper, optimum sizing and configuration of hybrid power and heat supply systems were discussed. A comprehensive simulation model has been developed, which can consider either renewable or fossil fuel supply system in a micro scale and domestic demand. In addition, four scenarios have been assumed as back-up generator mode in off-grid, on-grid with power purchase, purchase and sale on-grid and non-backup mode of on-grid states.

For the on-grid condition, the optimum net present value i.e. first objective function was calculated equal to 53436 dollars. Also, the same objective function optimal magnitude for non-backup generator is decreased to 24409 dollars, because of increasing capital and operation costs and decreasing renewable system size and annual sale revenue. Moreover, for the off-grid system, the total cost increased because of batteries and limited backup options. In addition, the fuel cost was added to the system total cost. It was calculated that the batteries **contain** about 29% of total capital cost. However, the most probable scenario for the proposed case study is on-grid without energy sale option, because lack of selling infrastructure and pricing in most regions. Likewise, the most proper option can be on-grid, since it will be the most profitable scenario.

Also, the sensitivity analysis was performed by **varying** of input parameters such as gasoil fuel, hydrogen and electricity prices. The **results** claimed that there are threshold points or margins, which in energy purchase and sale options **selection, change with** varying energy carrier prices.

The main novelty of the proposed research is to implement new criteria based on lifecycle exergy for **the** optimal sustainability-based design of hybrid energy systems. Moreover, extracting cost and exergy consumption equations for different systems, and a comprehensive model for renewable and conventional energy carriers to provide both heat and electricity are the other contributions of the present work. For **the** improvement of the next researches, one can contribute more detailed cost and lifecycle exergy data and equations beside variety of different supply technologies. In addition, a time-variable model for equations of technologies, which can predict the trend and future of energy supply and storage systems cost and exergy consumption, will be a remarkable research objective.

The results of the present research and optimization model can be suitable for both macro and micro **decision-makers**. Actually, power officials can either make new or change policies mostly based on **lifecycle** exergy objective function. On the other hand, for domestic and residential applications, both objectives, especially economic optimization can result in a competitive hybrid system based on each specific region and demand.

References

[1]. Agency, I.E., *World Energy Outlook 2014*. 2014.

[2]. Eia, U., *Levelized cost and levelized avoided cost of new generation resources in the annual energy outlook 2016.* Washington DC, USA, 2016.

[3]. Seeling-Hochmuth, G., *Optimization of Hybrid Energy Systems Sizing and Operation Control*. 1998, University of Kassel.

[4]. Tina, G., S. Gagliano, and S. Raiti, *Hybrid solar/wind power system probabilistic modelling for long-term performance assessment.* Solar energy, 2006. **80**(5): p. 578-588.

[5]. Bilal, B.O., et al., *Optimal design of a hybrid solar–wind-battery system using the minimization of the annualized cost system and the minimization of the loss of power supply probability (LPSP).* Renewable Energy, 2010. **35**(10): p. 2388-2390.

[6]. Caballero, F., E. Sauma, and F. Yanine, *Business optimal design of a grid-connected hybrid PV (photovoltaic)-wind energy system without energy storage for an Easter Island's block.* Energy, 2013. **61**: p. 248-261.

[7]. Dufo-López, R., et al., *Multi-objective optimization minimizing cost and life cycle emissions of stand-alone PV–wind–diesel systems with batteries storage.* Applied Energy, 2011. **88**(11): p. 4033-4041.

[8]. Ekren, O. and B.Y. Ekren, *Size optimization of a PV/wind hybrid energy conversion system with battery storage using simulated annealing.* Applied energy, 2010. **87**(2): p. 592-598.

[9]. Ramoji, S.K. and B.J. Kumar, *Optimal economical sizing of a PV-wind hybrid energy system using genetic algorithm and teaching learning based optimization.* International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, 2014. **3**(2): p. 7352-7367.

[10]. Kanase-Patil, A., R. Saini, and M. Sharma, *Sizing of integrated renewable energy system based on load profiles and reliability index for the state of Uttarakhand in India.* Renewable Energy, 2011. **36**(11): p. 2809-2821.

[11]. Yang, H., et al., *Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm.* Solar energy, 2008. **82**(4): p. 354-367.

[12]. Hongxing, Y., Z. Wei, and L. Chengzhi, *Optimal design and techno-economic analysis of a hybrid solar-wind power generation system.* Applied energy, 2009. **86**(2): p. 163-169.

[13]. Cano, A., et al., *Optimal sizing of stand-alone hybrid systems based on PV/WT/FC by using several methodologies.* Journal of the energy institute, 2014. **87**(4): p. 330-340.

[14]. Shi, Z., R. Wang, and T. Zhang, *Multi-objective optimal design of hybrid renewable energy systems using preference-inspired coevolutionary approach.* Solar energy, 2015. **118**: p. 96-106.

[15]. Sharafi, M., T.Y. ElMekkawy, and E.L. Bibeau, *Optimal design of hybrid renewable energy systems in buildings with low to high renewable energy ratio.* Renewable Energy, 2015. **83**: p. 1026-1042.

[16]. Killinger, S., et al., *A regional optimisation of renewable energy supply from wind and photovoltaics with respect to three key energy-political objectives.* Energy, 2015. **84**: p. 563-574.

[17]. Madhlopa, A., et al., *Optimization of a PV–wind hybrid system under limited water resources.* Renewable and Sustainable Energy Reviews, 2015. **47**: p. 324-331.

[18]. Bazmi, A.A. and G. Zahedi, *Sustainable energy systems: Role of optimization modeling techniques in power generation and supply—A review.* Renewable and sustainable energy reviews, 2011. **15**(8): p. 3480-3500.

[19]. Sinha, S. and S. Chandel, *Review of recent trends in optimization techniques for solar photovoltaic–wind based hybrid energy systems.* Renewable and sustainable energy reviews, 2015. **50**: p. 755-769.

[20]. Erdinc, O. and M. Uzunoglu, *Optimum design of hybrid renewable energy systems: Overview of different approaches.* Renewable and Sustainable Energy Reviews, 2012. **16**(3): p. 1412-1425.

[21]. Afgan, N.H., M.G. Carvalho, and N.V. Hovanov, *Modeling of energy system sustainability index.* Thermal Science, 2005. **9**(2): p. 3-16.

[22]. Phillips, J., *Determining the sustainability of large-scale photovoltaic solar power plants.* Renewable and Sustainable Energy Reviews, 2013. **27**: p. 435-444.

[23]. Razmi, A.R., et al., *Green hydrogen*, in *Future Grid-Scale Energy Storage Solutions*. 2023, Elsevier. p. 573-619.

[24]. Alirahmi, S.M., A.R. Razmi, and A. Arabkoohsar, *Comprehensive assessment and multi-objective optimization of a green concept based on a combination of hydrogen and*

compressed air energy storage (CAES) systems. Renewable and Sustainable Energy Reviews, 2021. **142**: p. 110850.

[25]. Razmi, A.R., et al., *A green hydrogen energy storage concept based on parabolic trough collector and proton exchange membrane electrolyzer/fuel cell: thermodynamic and exergoeconomic analyses with multi-objective optimization.* International Journal of Hydrogen Energy, 2022. **47**(62): p. 26468-26489.

[26]. Razmi, A.R., A.R. Hanifi, and M. Shahbakhti, *Design, thermodynamic, and economic analyses of a green hydrogen storage concept based on solid oxide electrolyzer/fuel cells and heliostat solar field.* Renewable Energy, 2023. **215**: p. 118996.

[27]. Nabat, M.H., et al., *Investigation of a green energy storage system based on liquid air energy storage (LAES) and high-temperature concentrated solar power (CSP): Energy, exergy, economic, and environmental (4E) assessments, along with a case study for San Diego, US.* Sustainable Cities and Society, 2021. **75**: p. 103305.

[28]. Alirahmi, S.M., et al., *A comprehensive techno-economic analysis and multi-criteria optimization of a compressed air energy storage (CAES) hybridized with solar and desalination units.* Energy Conversion and Management, 2021. **236**: p. 114053.

[29]. Mousavi, S.B., et al., *A comprehensive study and multi-criteria optimization of a novel sub-critical liquid air energy storage (SC-LAES).* Energy Conversion and Management, 2022. **258**: p. 115549.

[30]. Sharafi, M. and T.Y. ELMekkawy, *Multi-objective optimal design of hybrid renewable energy systems using PSO-simulation based approach.* Renewable energy, 2014. **68**: p. 67-79.

[31]. Bansal, A.K., R. Gupta, and R. Kumar. *Optimization of hybrid PV/wind energy system using Meta Particle Swarm Optimization (MPSO)*. in *India International Conference on Power Electronics 2010 (IICPE2010)*. 2011. IEEE.

[32]. Katsigiannis, Y.A., P.S. Georgilakis, and E.S. Karapidakis, *Hybrid simulated annealing–tabu search method for optimal sizing of autonomous power systems with renewables.* IEEE Transactions on Sustainable Energy, 2012. **3**(3): p. 330-338.

[33]. Dincer, I. and M.A. Rosen, *Exergy: energy, environment and sustainable development*. 2012: Newnes.

[34]. Afgan, N.H., et al., *Energy system assessment with sustainability indicators.* Sustainable Assessment Method for Energy Systems: Indicators, Criteria and Decision Making Procedure, 2000: p. 83-125.

[35]. Afgan, N.H. and M.G. Carvalho, *Multi-criteria assessment of new and renewable energy power plants.* Energy, 2002. **27**(8): p. 739-755.

[36]. Afgan, N.H. and M.G. Carvalho, *Sustainability assessment of a hybrid energy system.* Energy Policy, 2008. **36**(8): p. 2903-2910.

[37]. Chatzimouratidis, A.I. and P.A. Pilavachi, *Technological, economic and sustainability evaluation of power plants using the Analytic Hierarchy Process.* Energy policy, 2009. **37**(3): p. 778-787.

[38]. Evans, A., V. Strezov, and T.J. Evans, *Assessment of sustainability indicators for renewable energy technologies.* Renewable and sustainable energy reviews, 2009. **13**(5): p. 1082-1088.

[39]. Brent, A.C. and D.E. Rogers, *Renewable rural electrification: Sustainability assessment of mini-hybrid off-grid technological systems in the African context.* Renewable Energy, 2010. **35**(1): p. 257-265.

[40]. Stein, E.W., *A comprehensive multi-criteria model to rank electric energy production technologies.* Renewable and Sustainable Energy Reviews, 2013. **22**: p. 640-654.

[41]. Caliskan, H., I. Dincer, and A. Hepbasli, *Energy, exergy and sustainability analyses of hybrid renewable energy based hydrogen and electricity production and storage systems: modeling and case study.* Applied thermal engineering, 2013. **61**(2): p. 784-798.

[42]. Frangopoulos, C., *STATIC AND DYNAMIC POLLUTION AND RESOURCE RELATED INDICES.* Exergy, Energy System Analysis and Optimization-Volume III: Artificial Intelligence and Expert Systems in Energy Systems Analysis Sustainability Considerations in the Modeling of Energy Systems, 2009. **3**: p. 231.

[43]. Davidsson, S., *Life Cycle Exergy Analysis of Wind Energy Systems: Assessing and improving life cycle analysis methodology*. 2011.

[44]. Ayres, R.U., L.W. Ayres, and K. Martinas, *Eco-thermodynamics: exergy and life cycle analysis.* 1996.

[45]. Wall, G., *Life cycle exergy analysis of renewable energy systems.* The Open Renewable Energy Journal, 2011. **4**(1).

[46]. Joshi, A.S. and A. Tiwari, *Energy and exergy efficiencies of a hybrid photovoltaic–thermal (PV/T) air collector.* Renewable Energy, 2007. **32**(13): p. 2223-2241.

[47]. Fakehi, A.H., S. Ahmadi, and M.R. Mirghaed, *Optimization of operating parameters in a hybrid wind–hydrogen system using energy and exergy analysis: Modeling and case study*. Energy Conversion and Management, 2015. **106**: p. 1318-1326.

[48]. Iqbal, M., *Simulation of a small wind fuel cell hybrid energy system.* Renewable energy, 2003. **28**(4): p. 511-522.

[49]. Lund, H. and E. Münster, *Modelling of energy systems with a high percentage of CHP and wind power*. Renewable Energy, 2003. **28**(14): p. 2179-2193.

[50]. Zhou, W., H. Yang, and Z. Fang, *A novel model for photovoltaic array performance prediction.* Applied energy, 2007. **84**(12): p. 1187-1198.

[51]. Bostan, I., et al., *Resilient energy systems: renewables: wind, solar, hydro*. Vol. 19. 2012: Springer Science & Business Media.

[52]. Lagunas, J., et al. *Model design of wind/PV/fossil-fuel hybrid systems*. in *Siguiendo el camino de las estrellas: libro de actas del VII Congreso Ibero Americano de Energa Solar*. 2004. Asociacin Espaola de Energa Solar.

[53]. Ngan, M.S. and C.W. Tan, *Assessment of economic viability for PV/wind/diesel hybrid energy system in southern Peninsular Malaysia.* Renewable and Sustainable energy reviews, 2012. **16**(1): p. 634-647.

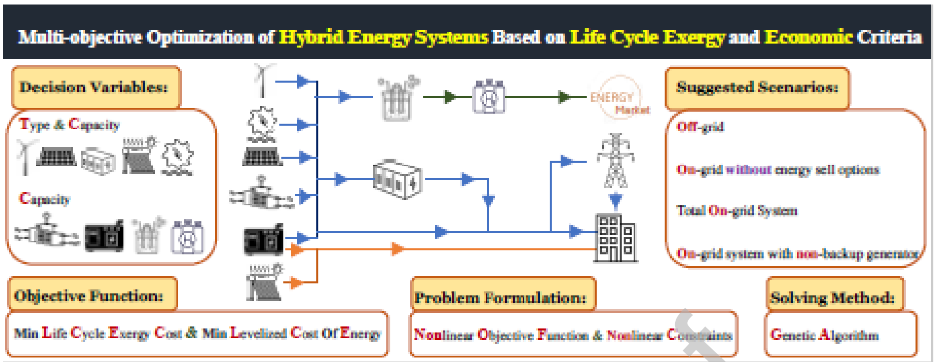
[54]. Panapakidis, I.P., D.N. Sarafianos, and M.C. Alexiadis, *Comparative analysis of different grid-independent hybrid power generation systems for a residential load.* Renewable and Sustainable Energy Reviews, 2012. **16**(1): p. 551-563.

[55]. Kanase-Patil, A., R. Saini, and M. Sharma, *Integrated renewable energy systems for off grid rural electrification of remote area.* Renewable Energy, 2010. **35**(6): p. 1342-1349.

[56]. Bhat, V.I. and R. Prakash, *Life cycle analysis of run-of river small hydro power plants in India.* The Open Renewable Energy Journal, 2008. **1**(1).

[57]. García-Triviño, P., et al., *Optimized operation combining costs, efficiency and lifetime of a hybrid renewable energy system with energy storage by battery and hydrogen in grid-connected applications.* International Journal of Hydrogen Energy, 2016. **41**(48): p. 23132-23144.

Graphical Abstract



Credit author statement

Mohammad Rezaei: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Visualization, Investigation, Validation.

Yadollah Saboohi: Conceptualization, Supervision.

Gary Wang: Supervision.

Amirhossein Fathi: Reviewing and Editing,

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: