

Effective utilization of excess energy in standalone hybrid renewable energy systems for improving comfort ability and reducing cost of energy: A review and analysis



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ABSTRACT

One of the features that characterize renewable energy sources is their variability and intermittency. Intermittency covers both the predictable and unpredictable variations of their power outputs and uncertainty in the power availability. To overcome the drawback of intermittency, special design considerations should be taken into account. These additional design considerations increase the overall cost of the renewable energy systems. Adding storage system and/or backup source to the renewable sources is one of the measures used to guarantee the continuity of power supply to the loads, and therefore improve the reliability of the renewable energy systems. The operation of renewable energy systems results in the creation of surplus energy, which is the energy generated by renewable energy systems, but is not consumed by the loads in standalone power systems. Effective utilization of this excess energy has the potential to decrease the cost of energy (COE) production by these hybrid renewable energy systems. In this paper, a review of the literature will be carried out in order to provide further insight into the approaches suggested in the literature on how to deal with the utilization of excess energy. Furthermore, various possible configurations of hybrid systems will be analyzed in detail for the effective utilization of the excess energy produced by hybrid systems. This is done in order to evaluate the effectiveness of utilization of excess energy by various means, especially for improving the living space comfort ability and decreasing the COE. Case studies will be carried out to demonstrate the proposed configurations for the effective utilization of the excess energy, and the results will be presented.

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1. Introduction

Great efforts are made to develop new and renewable energy technologies along with energy storage systems and encourage their entry to the market of electric industry. These technologies can be operated as standalone sources, as part of hybrid systems, or as distributed generation connected to a microgrid or a distribution grid. These sources include photovoltaic systems, wind energy systems, diesel engines, fuel cells, microturbines, and different other renewable sources and storage systems.

These efforts are seeing a marked increase recently due to the fact that different types of fossil fuel that conventional sources of energy depend on are going to be depleted. When this is taken into consideration, along with the fact that high levels of global warming gases are emitted as a result of combustion of these fossil fuels, this encourages different institutions and authorities worldwide to invest in local generation from renewable energy sources [1–3]. This involves finding substitutes, or at least reducing the dependency on fossil fuels. Furthermore, an overview of the literature on rural electrification proves shows that renewable energy sources are one of the most effective solutions to provide power to rural areas that are located far from the electrical power grid. Delivering high quality and reliable electricity for different applications in these remote areas were also proven to be feasible [4–6].

Renewable energy sources are non-depleted, non-polluting, and location dependent. Recently, utilization of renewable sources has become more attractive, cost effective, and significant. However, because renewable sources are variable and intermittent, a need for a storage system and/or backup source arises to ensure continuity in supplying the load [7–9].

Hybrid energy systems are systems that combine two or more energy conversion sources (electricity/heat generation and/or storage devices), and when combined, will overcome any inherent limitations [10–14]. If one of these energy sources is renewable, this hybrid system can be treated as a hybrid renewable energy system.

When hybrid systems operated effectively, they increase the overall efficiency of the system and become a more reliable energy supply. Moreover, hybrid renewable energy systems can significantly reduce the cost of generation and the environmental impacts. Utilization of hybrid systems that combines renewable sources with backup sources and energy storage reduces the limitations of renewable sources, and open up markets for investment that might not otherwise exist. Hybrid systems take the best features of differing, but complementary resources in its construction [15,16].

For systems with more than one energy sources used to supply a load, a criterion to manage the power flow between these sources should be specified. This management strategy should define the priorities to dispatch the energy between the different sources. For the system considered in this study, the priority is to maximize the utilization of energy generated by the renewable sources (e.g. PV panels) and the energy stored in the battery bank. In case of inability of these sources to cover the load demand, one or more non-renewable (e.g. microturbine or diesel generator) or renewable but schedulable (biomass) standby resources can be used to counteract demand-generation mismatch in these standalone hybrid systems. For the case where the generated energy exceeds the load requirement and the battery, if available in the hybrid system, is not able to store anymore as it is full, an excess

energy that should either be dumped or utilized for ancillary service (or other purpose) to maintain a power balance in the system. Fig. 1 shows the flowchart guiding the management strategy to achieve energy balancing for this situation.

Different configurations can be followed in designing standalone hybrid systems to effectively utilize the available renewable energy sources and to serve the customer loads. Any combination of renewable sources is possible, but it may require an optional backup source and/or storage system. To select the most appropriate configuration for a specific site, a feasibility study considering the meteorological data of this site and based on life cycle cost analysis should be done.

One of the drawbacks of the renewable energy systems is their high capital cost compared to conventional ones. Using hybrid systems that combine more than one energy source and the size optimization of each of the components constructing these systems are some of the measures that can be taken to reduce their capital costs. Effective utilization of any excess energy that hasn't been consumed by the load or used to charge the battery in standalone hybrid systems can be considered as one of the approaches used to decrease the cost of energy (COE) production for these hybrid systems.

Actually, this excess energy, if not dumped, may damage the battery due to the fact that it might result in an overcharge. It may also cause over voltages in the standalone hybrid systems that, in turn, may adversely affect the equipment connected to the system. The traditional way to overcome this excess energy is through using dump loads to consume it. Resistors are usually used for this purpose, and a controller usually diverts the extra power away from the battery banks and directs it into the designated (dedicated) dump load when the desired voltage of the battery bank is reached. Values of these resistors should be selected in order to allow enough current to pass through. The diversion control circuit may be included in the charger regulator circuit, in the inverter circuit, or in the rectifier circuit, as most of the manufacturers of these power electronic interfaced renewable energy systems usually include these diversion control circuits within their products [17].

Instead of dumping the excess power through a dump load, other alternatives to deal with this excess power have been suggested by many researchers, and can be found in the literature. To the best of the authors' knowledge, a detailed analysis to evaluate the effectiveness of utilization of the excess energy has not been previously carried out. In this paper, a review of the literature will be carried out in order to assess approaches being suggested to deal with the excess energy produced but not used either to supply the load or charge the batteries. Furthermore, hybrid system configurations will be analyzed in detail in order to evaluate the effectiveness of utilization of excess energy by various means, especially for improving the living space comfort ability without any additional cost.

2. Quantification of excess energy in hybrid renewable energy systems—A review

In this section, a review of various studies carried out in different locations around the world will be presented. The purpose of this review is to indicate the percentage of the excess

Nomenclature

COE	cost of energy
C_{pw}	water specific heat ($C_{pw}=4.18 \text{ kJ/kg/}^{\circ}\text{C}$)
E_h	heat energy (kW h)

m_w	water mass (kg)
P_{Load}	load power (kW)
P_{RE-out}	output power from renewable sources (kW)
T_{fin}	final temperature ($^{\circ}\text{C}$)
T_{ini}	initial temperature ($^{\circ}\text{C}$)

energy generated but not used by different configurations of hybrid systems analyzed in these reviewed studies.

For a study conducted by Demiroren and Yilmaz [18] to supply the electrical requirement of the Island Gokceada, Turkey, it was found that the optimal scenario is the one constructed from wind turbines. For this optimized scenario, it was found that the excess energy constructs about 64.2% of the total electrical production.

For another study carried out for the case of remote location in India, Sen and Bhattacharyya [19] found that 25% of the total energy is generated by a hybrid system, which is constructed using a PV system, wind turbines, a hydropower system, and bio-diesel generators, goes to dump loads.

For a study directed to Waterloo in Ontario, Hafez and Bhattacharya [20] analyzed four different cases to supply a certain load.

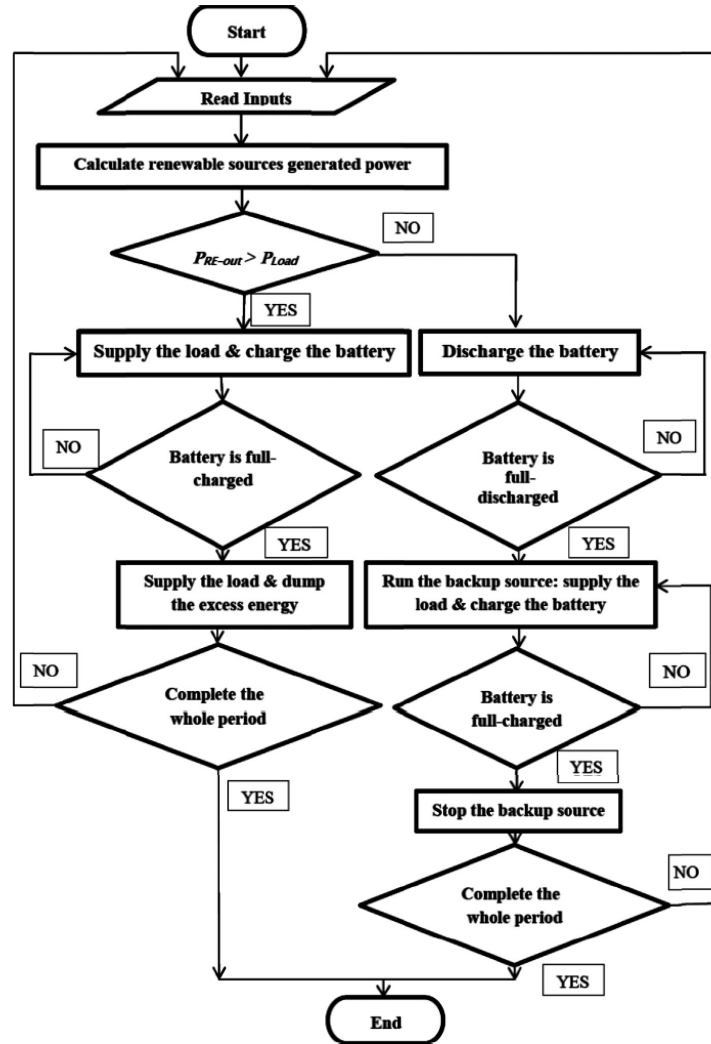


Fig. 1. Flowchart for the energy management strategy.

They found that 70% of the total energy production goes to dump loads for a fully renewable scenario where the sources are wind turbine, solar panels, and a small-scale hydro station. For the diesel only case, this percentage is 51.1%, whereas, it is 16.9% for the mixed case. For a standalone system constructed from PV panels and wind turbines without any storage system, Ipsakis et al. [21] found that it was 56.4% of the total time, and excess energy is available. This evaluation was conducted through simulated experiments for the region of Xanthi, Greece. For another study directed for a remote location in Palestine, Daud and Ismail [22] found that 33% of the total generated energy has not been used. The hybrid system analyzed in this study was constructed from PV panels, wind turbine, battery system, and diesel generator.

For a separate study conducted at Qurayat (Northern Province of the Saudi Arabia), Shaahid et al. [23] concluded that the percentage of the excess energy increases as the PV penetration in a PV/battery/diesel generator hybrid system increases. For a 65% PV penetration, the excess energy is 35%, whereas it is about 47% for a 69% PV penetration. In a separate study that was also conducted for Saudi Arabia, Rehman and Al-Hadhrani [24] found that the excess energy from a PV/battery/diesel generator hybrid system was 0.67% of the total generated energy, where the PV penetration was 21%. They stated that this percentage would increase to 9.94% if the PV penetration would increase to 42%. An analysis of a case study for a rural remote area in India illustrated that the amount of excess energy was 0.48%, and this occurred for a 20% PV penetration in a PV/diesel generator/battery system [25]. In a study conducted to optimize and design a hybrid system constructed from PV panels, battery bank, and diesel generator in order to supply a remote house in Langkawi Island-Malaysia, Ismail et al. [26] found that the excess energy that couldn't be used by the system amounts to 14% of the total generated energy. Moghavvemi et al. [27] found that the excess energy that was generated but not used was about 16.3% of the total generated energy. The system supplied power to a remote controlled commercial large scale FM transmitter using a PV/battery/diesel generator hybrid system. In a separate study conducted for Malaysia, Khatib et al. [28] found that about 2.3% of the total generated energy was excess energy. In their analysis of the hybrid system that was constructed from PV panels, diesel generator and battery, they allowed a certain value for the loss of load probability (LLP) rather than zero.

In their study, Ismail et al. [29] found that 8% of the total generated energy went to dump loads. This study involved supplying power to a remote small community in Palestine using a PV/battery hybrid system, with a microturbine as a backup source.

Razak et al. [30] evaluated the effect of the load profile and the amount of the load energy on the amount of the excess energy. They have concluded that the load profile shape has an obvious effect of the amount of the excess energy.

Table 1 summarizes the percentage of the excess energy for various hybrid system configurations analyzed in various studies conducted previously.

According to the previously reviewed studies in this section, it can be concluded that the amount of excess energy generated by any hybrid renewable energy system depends on the types of the energy sources used in the hybrid system, the sizes of these components, the availability and the profiles of the meteorological quantities, and the load profile variations with respect to variations in meteorological quantities.

3. Frameworks and suggestions to utilize excess energy—A review

In this section, a review of many studies carried out in various locations around the world will be presented. Part of these studies

Table 1

Percentage of excess energy for various hybrid system configurations analyzed in various studies carried out previously.

Reference	Type of hybrid system	Percentage of excess energy
[18]	PV/wind/battery	64.2
[19]	PV/wind/hydropower/bio-diesel generators	25
[20]	PV/wind/hydropower	70
[20]	Diesel generator	51.1
[20]	PV/wind/hydropower/diesel generator	16.9
[21]	PV/wind	56.4*
[22]	PV/wind/battery/diesel generator	33
[23]	PV/battery/diesel generator	35**
[24]	PV/battery/diesel generator	9.49***
[25]	PV/battery/diesel generator	0.48****
[26]	PV/battery/diesel generator	14
[27]	PV/battery/diesel generator	16.3
[28]	PV/battery/diesel generator	2.3
[29]	PV/battery/microturbine	8

* Percentage of the total time at which an excess energy is available.

** At the case where the PV penetration equals to 65%.

*** At the case where the PV penetration equals to 42%.

**** At the case where the PV penetration equals to 20%.

suggests dumping this excess energy by using dump loads, whereas the rest suggest utilizing this excess energy by various means.

Mousavi [31] suggested that the dump load be used to consume the excess energy generated by the wind/tidal/microturbine/battery hybrid system. In their study, the dump load used consists of three phase resistors. Demiroren and Yilmaz [18] suggested allowing the excess energy to be exported to the grid. In a study conducted on the performance analysis of hybrid renewable energy systems, Jebaselvi and Paramasivam [32] suggested using dump loads in order to get rid of the excess generated energy. Ziogou et al. [33] suggested utilizing the excess energy to produce hydrogen through a proton membrane electrolyzer. They also recommended storing this hydrogen in pressurized cylinders to be used in a proton exchange membrane fuel cell for the case of power shortage. In a study directed to design and analyze a hybrid energy system with wind and solar power, Kabalci [34] suggested dump loads to be used to consume excess power. In another study conducted to design isolated hybrid renewable systems, Sreeraj et al. [35] suggested dumping the excess energy generated by their proposed system in dump loads. Ranjeva and Kulkarni [36] proposed selling excess energy generated by the hybrid systems back to the grid. Sebastian and Quesada [37] recommended using dump load to consume any excess energy generated by their analyzed hybrid systems dominated by wind turbine as a renewable source. The dump load used in [37] consists of eight three-phase resistors connected in series, and gate turn-off thyristor switches are used to connect and disconnect these resistances. In the energy management strategy stated in the study conducted to analyze the economic and the environmental aspects of standalone energy systems, Fux et al. [38] recommended diverting any excess energy to a dump load. In a study conducted to analyze the feed-in-tariffs and their effect on promotion of storage systems, Krajacic et al. [39] suggested delivering any excess energy to the grid, or use it to pump water uphill or dump it. In a study conducted to model, simulate, and control flat PV solar collectors with the ability to store thermal energy for heating and cooling purposes, Mosallat et al. [40] proposed storing any electrical or thermal excess energy to be used for cooling or to be used during the cool season if a long-term storage has been applied. Actually, this is also important to prevent damage to the solar collectors. A thermal storage tank with a built in heat exchanger is proposed for this purpose. The heat extracted from the flat collectors via

Glycol flowing through pipes installed in the collectors is transferred via the heat exchanger to the water in the tank. Sen and Bhattacharyya [19] suggested feeding any excess energy generated by their analyzed off-grid renewable systems to dump loads. Inversion et al. [41] and Agbossou et al. [42] suggested using hydrogen storage technology in order to utilize the excess energy produced during the surplus periods. This excess energy was used to power an electrolyzer to produce and store hydrogen. This stored hydrogen was used as a fuel for a fuel cell to supply loads in deficient periods. In two additional studies, Vosen and Keller [43] and Bernal-Aguistin, and Dufo-López [44] suggested using, in addition to the battery bank as a storage system, a hydrogen storage system in case of excess energy. In a study to design of hybrid renewable energy systems, Hafez and Bhattacharya [20] proposed supplying the excess energy to the dump load. They used HOMER to perform the optimization, and they suggested using a heat load as a dump load, and supplying it using the excess energy. A comparison between the case where the excess energy was just fed to a dump load and the case where the excess energy was fed to the heat load was not included in this study. In a study conducted to optimize a renewable standalone system to supply power to Dongfushan Island-China, Zhao et al. [45] suggested including a seawater desalination system to work as a controllable load. As they stated, this would relieve water supply challenges in the island and serve as a balance for any excess energy generated by the renewable energy sources. Kaldellis and Zafirakis [46] suggested rejecting any excess energy generated by their proposed PV/wind turbine hybrid system to water heating as a dump load. As an alternative, they suggested using this excess energy to supply heat pumps for heating and cooling purposes. The power management strategy developed by Ipsakis et al. [21] stated that any excess energy generated by a standalone renewable energy system should be used to generate hydrogen via water electrolysis to be used in a polymer electrolyte membrane fuel cell to generate electricity during power shortage. If the hydrogen tank is filled, a battery bank shall be charged using the surplus in generated energy. A dump load should be used to prevent overcharging of the battery when its state of charge reaches 100%. Li et al. [47] described in their study a virtual power station that suggested aggregating small-scale PV systems to be presented to the wider electrical system as a lumped point. For managing the intermittency of the photovoltaic system, dumping of excess energy into dump loads (resistor banks or heaters) or using battery banks for excess energy storage has been suggested. Two scenarios were studied to deal with the system dumping; in the first one, it was suggested that the excess energy for each individual source be dumped, and then aggregate the rest, while in the second scenario; however, in the second study, it was suggested that the individual energies be aggregated, and the excess energy dumped. It was found that using the second scenario resulted in more energy aggregation and more earning in the income. In the study presented in [23], the authors suggested supplying the excess energy to dump loads. In a review study regarding the grid-tie generation systems without storage systems, Yanine and Sauma [48] have stated that the overall efficiency of the grid connected system is better than the standalone system efficiency, as the grid behaves as unlimited storage system, and due to this, it is not required that it dumps excess energy to dump excess energy. They have recommended not dumping excess energy, especially for remote locations, where the need for energy is vital. So, they suggest utilizing the excess energy by different means: space heating or cooling, water heating, water pumping, water desalination, and others. Gupta et al. [25], in their study, suggested diverting any excess energy to a dump load, which was assumed to be electric water heaters. In their study to analyze the technical and the economic aspects of integrating renewable sources with

energy storage systems, Connolly et al. [49] suggested using the excess energy to replace the thermal production. Malla and Bhende [50] analyzed the factors that affect the voltage of PV/wind standalone systems. They suggested feeding the excess energy of the proposed hybrid system to the aqua electrolyzer. Since electrolyzers are still expensive, and in order to specify their sizes, the authors recommended considering only 60% of the maximum available excess energy. Khan and Iqbal [51] suggested using the excess energy in space heating or water pumping. This increased the overall efficiency of their analyzed standalone hybrid energy systems. In a study conducted to model and simulate hybrid renewable energy systems, Tsao et al. [52] suggested supplying the excess energy to electrolyze water in order to produce hydrogen for use as fuel to the fuel cell as part of their hybrid system. Patsios et al. [53] suggested using electrolyzer to dump excess energy. Additionally, they suggested using dump resistive loads to dump any excess energy not being used by the electrolyzer. In [28], it was suggested that any excess energy that may exist after charging the battery be injected to the main grid.

According to the types of components constructing the hybrid system, the excess energy may be electrical, or it might be in other forms. Some of the means proposed utilizing the excess energy directly when it is available; space heating or cooling are example of these means. The others utilize the excess energy when it is available to be stored in one of various storage means. Storing this excess energy in storage batteries allow it to be used later to supply electrical loads, obtaining hot water, and storing it in storage tanks to be use later for various domestic applications, obtaining hydrogen, and storing it to be used later in fuel cells to generate electricity, and pumping water to an elevated storage tank to be used later to run a hydro generator to generate electricity are some of the examples of storage means.

The hybrid renewable energy system may include one or more of these means. This depends on the type of the components of the hybrid systems and the amount of the excess energy. In the case of more than one means of utilizing excess energy, a controller that receives its control signals from the various components should be included to manage the excess energy flow within the hybrid system.

A block diagram of a hybrid system that includes various means to utilize the excess energy is shown in Fig. 2. This block diagram also includes various types of energy sources, number of storage technologies, and various types of loads.

4. Analysis for effective utilization of excess energy and reduction of cost of energy (COE)

The purpose of this study is to analyze the effect of utilizing excess energy on the COE. For this purpose, the authors used the earlier studies for both the Palestinian case [22], and the Malaysian case [26]. Each of these two studies analyzes hybrid renewable energy systems in detail to supply domestic loads. In each of these two studies, it was recommended that the excess energy generated through the operation of these analyzed hybrid systems be dumped.

The COE production is the cost of generating one unit of energy (kW h). To calculate its value, all types of costs have been taken into account. The initial costs of various components constructing the hybrid system, the installation costs, the maintenance costs, the operating costs, and the replacement costs have been considered in the analysis. The value of money, the economic figures (the inflation rate and the interest rate) and salvage value for components to be replaced have been also taken into account in this analysis. More details regarding this can be found in both [22] and [26].

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