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Economic sizing of a hybrid (PV–WT–FC) renewable energy system (HRES) for stand-alone usages by an optimization-simulation model: Case study of Iran

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ABSTRACT

Hybrid renewable energy systems, combining various kinds of technologies, have shown relatively high capabilities to solve reliability problems and have reduced cost challenges. The use of hybrid electricity generation/storage technologies as off-grid stand-alone systems is reasonable to overcome related shortcomings. Solar and wind energy are two rapidly emerging renewable ones that have precedence in comparison to the other kinds. In this regard, the present paper studies four specific locations in Iran, which are candidates for research centers. Based on the solar radiation and average wind speed maps, techno-economically optimized systems are designed by simulating behavior of various combinations of renewable energy systems with different sizing, including wind turbine (WT), photovoltaic (PV), fuel cell (FC), and battery banks. According to the results obtained by a computer program, it is concluded that the hybrid systems including WT and PV with battery backup are less costly compared to the other systems. Moreover, we found that among non-hybrid systems, in most regions of Iran's territory PVs are more economical than WTs. Despite of its advantages, FC has not been applied in the optimal systems due to its high initial cost and its low replacement life.

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1. Introduction

In the recent years, due to the value of non-energy uses of fossil fuel products in industry (e.g. petrochemical industries that produce various valuable products by reforming methane and propane), along with high prices of crude oil and global environmental problems, new energy resources have been extremely emerging all around the world. Fossil energy resources are exhaustible, while the prices are influenced by various political factors, as well as economic conditions. On the other hand, compared to conventional technologies, economy of renewable energy technologies plus reliability issues of the resources are yet obstacles, which slow down fast replacement of clean abundant new energies for their old competitors. However, the use of hybrid renewable energy systems as stand-alone systems for remote areas, like environmental research centers, could be a reasonable approach to overcome the mentioned weaknesses [1]. Hence, using these technologies could turn out to be affordable in remote areas as a stand-alone hybrid system due to the high costs for network extension [2].

In single renewable systems, such as WT and PV, derived energy is unreliable due to instability. The purpose of combining renewable energy technologies is to exploit the strengths of one technology that covers the weaknesses of others so that the reliability of the entire system is increased and economic and environmental aspects are improved [3,4].

One of the major challenges, encountered when using stand-alone RESs, is their need for energy storage systems because of the unpredictable nature of their resources. Energy storage plays an important role in the development and operation of a renewable system in a Stand-alone Power Systems (SPS). Several energy storage techniques, such as batteries, flywheels, and hydrogen production for use in FC are available. In a SPS, the main parameters to optimize the energy storage systems are their capacity, resource availability, and the response time of the storage system. Traditionally, batteries are used for energy storage; despite maturity of their technology and market, costs and disposal (or salvage) after their lifetime are batteries limitations. In addition, batteries need maintenance; their performance depends on the working temperature that should be controlled during the operation time. What is more, batteries' self-discharging is a bottleneck, especially in cold regions. However, normal batteries offer good modularity, fast-time response, and good energy-mass ratio storage.

In comparison to the batteries, FCs also present good modularity and the possibility of partial working, as well as good energy storage capability, that can be simply attained by correct sizing of a hydrogen tank (HT). The main weakness of FCs is its slow dynamics [3]; they have high time constants, which mean much time they need to start the production process. Furthermore, the maintenance of FCs is still a problem because of catalyst replacement issues. Alternatively, a battery bank becomes a good choice for short-term energy storage owing to its high charging–discharging efficiency along with its capability to counteract and take care of the equipment in face of the effects of instantaneous demands and wind energy's fluctuation. On the other hand, because of their low energy density and self-discharging, batteries are not appropriate for long-term storage. Conversely, H_2 as the fuel of FCs is well suited for storage applications in longer periods for its high energy density. Therefore, a combination of battery banks with long-term energy storage in the form of H_2 can significantly improve the performance of stand-alone RE systems, where the electrolyzer (EL) generates H_2 while excess solar and wind energy is available as well. When solar and wind energy is not sufficient, the FC employs this H_2 to produce electricity. Table 1 summarizes the main cons and pros for these systems individually which can be compensated with the other in a hybrid system.

Table 1
Cons and pros of battery and FC.

	Energy density	Dynamics	Cost
Batteries	Low	Fast	Medium
FCs	High	Slow	High

There are many issues to be studied in case of hybrid systems. Shakya et al. [5] in 2005 studied the combination of modified diesel engine with hydrogen fuel, WT, and PV to supply the demand of an educational and interpretive center in Australia. In 2009 Saheb et al. [6] published a paper in which they had described the techno-economic aspect of the combination of WT and PV with diesel backup systems, simulating its behavior for residential demand in remote areas. Furthermore Dursun [7] in 2012 studied techno-economic aspect of PV and FC for a campus in Turkey. In 2012 Genc et al. [8] carried out a study on Hybrid systems in Turkey. In this study the energy demand of a chicken farm in Pinarbasi was supplied by using a WT-FC-EL energy system. Also Abedi et al. [9] in 2011 researched on the techno-economic aspects of a hybrid system that contains WT, PV, and FC for a region in the North West of Iran. Moreover, in their 2012 study, Abdolrahimi et al. [38] simulated and compared two hybrid systems in Iran, the former containing WT and PV and the latter containing WT and PV with diesel backup system. In 2012 and 2013 Asrari and Ghasemi [11,12] studied the different combination of WT, PV, battery, and diesel generator for a remote village in Iran, and Fallahi et al. [13] optimized a hybrid PV/wind/tidal system for a port in south of Iran. Also, Ren et al. [14] have evaluated hybrid energy storage technologies for a solar–wind generation system.

Among the conducted studies, various tools and methods are used to achieve the goals. For instance, Amutha et al. [15], Velo [16] and [17–19] have used HOMER, whereas [5,20] have employed TRNSYS. THERMIE [21] and WindHyGen [22,23] are also other software used by others. Moreover, authors [24–26] have made a use of Simulink, while LABVIEW has been used to model a hybrid energy system by Eroglua [27]. A review of software tools for hybrid energy systems has been presented in [28]. From another point of view, researchers have taken a variety of approaches to search for the best solutions. This variety shapes a spectrum of methods from simple to difficult. As an example, Genc [8] has adopted mathematical programming, while a simple economic analysis is applied by Malik [29]. On the other side, artificial intelligence has been used by researchers such as HongXing [30]. A review of different approaches for optimum design of hybrid renewable energy systems has been presented in [31].

In addition to classification by tools, some researchers have classified the literature by other aspects. For instance, Bajpai [3] has divided sizing methods into two groups, based on the availability of weather-related factors such as irradiance, clearness index, and wind speed. As a second example, Luna-Rubio [32] has focused on complexity level of sizing methods, reaching to four groups: probabilistic, analytical, iterative, and hybrid. The summary of other works in the literatures are presented in Table 2 in order to facilitate comparison to the present study.

Another issue is dispatch strategy of hybrid energy systems. There are different strategies to backup systems control. In a hybrid system consisting of battery without any backup system, the dispatch strategy is simple: when there is excessive power from the base system, the battery is recharged and when there is a lack of power, it is supplied by the battery. Conversely, if a hybrid system consists of a backup system, the dispatch strategy can be complicated, wherein the procedure of supplying loads with less

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