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Sizing of off-grid renewable energy systems for drip irrigation in Mediterranean crops

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ABSTRACT

In the Mediterranean region, there are many drip irrigation systems with pumps that are powered by diesel generator sets (gensets). Although they could be powered by renewable energy produced on-site, technical and economic factors make that difficult. Moreover, the seasonal nature of demand requires an oversizing of energy generation and/or storage, increasing system costs. In this paper, we sought renewable energy systems that were economically optimal. We focused on six farming facility case studies to find the optimal energy generation solution using a simulation and optimization tool based on genetic algorithms. Photovoltaic-diesel hybrids and diesel systems were found to be optimal, with energy costs from 0.13 to 1.08 €/kWh and from 0.32 to 0.52 €/kWh, respectively. The strong effect of demand management was an interesting finding, as it may indicate significant system size and cost reductions. In addition, the optimum photovoltaic fixed tilt angles depended not only on the seasonal profile of the demand, but also on the pumping schedule. Although the difference between market interest rates and the rise of fuel prices strongly influences the advantage of incorporating, or not, renewable generation, this study supports that hybrid photovoltaic-diesel systems can make profitable use of renewable energy in drip irrigation.

1. Introduction

The use of renewable resources to replace fossil fuels brings sustainability, independence, and cleanliness. These advantages are especially remarkable in rural and agricultural areas [1,2]. Additionally, it is not always profitable or convenient to build electrical grid extensions. In fact, diesel gensets are widely used in rural areas because of their simplicity and low purchase price [3]. Drip irrigation, in which water is pumped to reach the proper pressure, is a typical installation that frequently uses gensets, as the electric grid is not often available. In many cases, water is also extracted from underground by pumping, with or without a storage pond.

Vines and olive trees are typical Mediterranean crops that have similar watering needs and for which drip irrigation is usually used [4]. Moreover, these plants' annual watering needs are concentrated in a few months. This very seasonal demand behaviour is an obstacle to the incorporation of renewable generation [5,6]. Power supply continuity and stability are therefore needed, in contrast to the variability of solar and wind resources. These challenges have pushed us to study the economic feasibility of renewable energy integration by searching for systems specially adjusted to this kind of application [7].

A recent work that reviewed the numerous studies in the literature [8] about pumping systems powered by renewable energy also identified their limitations. Among the future research lines suggested, further development of hybrid systems, more advances in the study of technical and economic feasibility, and better knowledge of the influence of photovoltaic tilt angle stand out.

Our main hypothesis was that renewable energy systems may become market-competitive against grid extension or diesel gensets in the agriculture field [9,10]. In this sense, some studies have shown the competitiveness of photovoltaic versus diesel generation in irrigation when agricultural cultivation is shared with household electricity supplies [11]. In fact, many easy and simple options can be applied without electricity storage, such as direct pumping, using wind turbines, photovoltaic panels, or both [12]. Nevertheless, power delivery is not constant in these methods and, particularly for wind energy, can be zero for several consecutive days. This variability is inherently incompatible with drip irrigation.

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Therefore, the need for stable energy sources could mean renewable generation might not be technically and economically feasible [13]. A proposed solution is to achieve the required constant pressure by water accumulation in an elevated tank [14]. This requires a large storage tank to equalize the strong fluctuations in renewable resources. However, because of the large volume of water required, it is hardly feasible and extremely expensive except on very small farms. Under these conditions, it is necessary to consider electric storage to ensure a continuous and stable power supply. Thus, hybrid wind-photovoltaic systems with energy storage [15,16] and renewable-diesel hybridization [17] may be considered potential solutions to the stated problem. Regarding photovoltaic systems, the optimal tilt angle depends on geographic latitude, but it also can be affected by the relationship between solar radiation and energy demand in the period under consideration [18–21]. Indeed, the seasonality of the energy demand for irrigation pumping warrants further research.

To our knowledge, no study has been conducted to ascertain how the characteristics of drip irrigation facilities determine the optimum design and sizing of hybrid renewable energy systems. In our study, we looked for the viability and optimal size of renewable energy systems to power drip irrigation facilities in comparison with existing diesel generation. Moreover, we expanded the search to diesel hybrid systems, taking into account the full range of solutions, from 100% renewable to 100% diesel and various combinations thereof. In addition, we also addressed a highly seasonal demand, this being one of the keys in our research. Our first objective was to demonstrate the technical and economic feasibility of the renewable energy systems for powering drip irrigation facilities that are common in the Mediterranean area. In the same vein, we wanted to determine the characteristics that were economically optimal for that use.

2. Methodology

2.1. Hybrid power system

Fig. 1 shows the actual and usual drip irrigation system with pumps that are powered by diesel generators and the proposed hybrid power system [22] for the study cases analyzed in this paper. In the hybrid power systems, all possible components have been represented, but in several cases only some of them will be part of the system. For example, in a location where the wind is not sufficiently high, the wind turbine should not be present.

The diesel generator is a source of electrical energy that is independent of meteorology. If renewable generation and storage are not considered, the gensets are a widespread solution for isolated pumping systems. However, they may also be useful as a backup source in hybrid systems. Simulations in this study considered all those possibilities. Also, considering the life cycle's equivalent CO_2 emissions (the emissions in the manufacturing, transporting, and decommissioning of the PV panels, batteries, and other components), they are high enough in many cases to make the diesel generator a good option to be added in the hybrid system; i.e. hybrid systems with diesel generators in many cases release less life cycle emissions than systems that do not include diesel. Systems without diesel generators must be over-dimensioned (large PV generators, large battery banks, etc.) to supply the whole load during periods of low renewable sources. This implies that their life cycle emissions can be higher than if the system includes a diesel generator (where the PV generator, battery bank, etc. can be much smaller) [23].

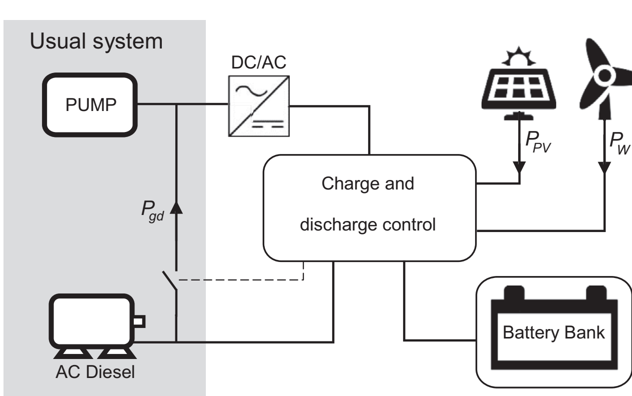

Fig. 1. Proposed hybrid power system.

The diesel generator can be controlled using the “cycle charging” or “load following” strategy [24]. Using the cycle charging strategy, when the battery state of charge (SOC) is below a given threshold and the renewable sources cannot provide sufficient power to recharge it, the diesel genset is called upon to deliver its maximum power (to supply the net load and charge the batteries until a specific SOC is reached, usually 90 or 95%). With this strategy the diesel genset is operated at close to its optimal load factor, improving the fuel efficiency of the generator and reducing maintenance costs. Using the “load following” strategy, the diesel genset starts in order to generate the power demanded by the pump, but the battery bank is not charged. The diesel genset is used to charge the battery bank only if the user connects the charger manually. With this strategy, if the irradiation is very low for a period of time, then it is habitual for the user to charge the battery bank using the genset.

2.2. Case studies and demand data

To base our study on actual power needs for irrigation pumping, we selected six existing drip irrigation facilities of different sizes and locations. All of them are situated in main viticultural zones of the Aragon region in the Ebro basin, located in the northeast of Spain. This relatively small Spanish region can be considered significant in cultivation of the vine, both for itself and for its proximity to some of the largest vineyard regions in Spain (Castilla La Mancha, La Rioja, Navarra, Ribera del Duero, Catalonia, etc.). They all add up 771,374 ha of crops, a large portion of the total 954,020 ha of vines in Spain. The six pumping systems are powered by diesel fuel and have been operating for several years. In two cases (Pueyez and Tallaqueso), water comes from surface ponds that are filled by gravity. In these, a single surface pump is required to push the water through a pressurized irrigation system. In two cases (Merla and Bancales), a submersible pump extracts water from a well to the surface pond and a surface pump drives it from the pond to the irrigation system. Because of water accumulation in the pond, the management of the submersible pump can be somewhat independent of the management of the irrigation pump. In the other two cases (Masatrigos I and Masatrigos II), a single submersible pump draws water from the well while at the same time activating the irrigation system. In these latter cases, no pond is required. A compendium of characteristics of the irrigation facilities is shown in Table 1. For each case study, six datasets were obtained: solar resource, wind resource, water demand, system size, system management criteria, and power consumption.

The typical year demand was obtained through interviews and questionnaires with agronomists and technicians in charge of the crops. When possible, the data were compared with existing historical records of watering and were found to be consistent. Irrigation decisions were known to be made at specific intervals,