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Wind power design in isolated energy systems: Impacts of daily wind patterns

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HIGHLIGHTS

- ▶ We apply a methodology for synthetic wind speed data including daily wind patterns.
- ▶ We study the impact of daily wind patterns on the energy system of two islands.
- ▶ We compare trade-offs between surplus energy and renewables penetration rate.
- ▶ We discover that placement of turbines can be used to minimise surplus energy.

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ABSTRACT

Increasing levels of intermittent renewables, especially wind power, in energy systems require accurate temporal characterisation of the resources' availability at seasonal, daily and hourly scales. This is crucial for isolated energy systems, where increasing wind power penetration is limited due to costly backup power generation requirements. In the case studies presented in this paper, the energy systems of two islands are simulated using a new methodology for synthetic wind speed scenarios including daily wind patterns. A trade-off analysis was conducted in terms of surplus wind power and renewables penetration rate, with the objective of supplying decision support on wind turbine placement. Results show that there may be a significant advantage in locating future wind parks on sites where wind speed patterns better match electricity demand patters, rather than just choosing a site with the highest mean wind speed, but only if the annual mean wind speed is still sufficiently high to make the investment economically feasible.

1. Introduction

The Azores archipelago, an autonomous region of Portugal, has a long history of using renewable energy to satisfy its energy needs. The first source of electricity on the islands was a hydro power station built in 1899 [1]. Also, the first wind park of Portugal, consisting of nine 30 kW turbines, was installed in the Azores in 1988 [2]. In 2010 wind power accounted for 4% of the Azores total electricity demand, whereas with current hydro and geothermal power the share of renewable sources rises to 28% [3]. The goal of the regional government is to increase renewables' penetration in the archipelago to reach 75% of total electricity demand by 2018 [4] and consequently wind power is likely to play an important role also in the future electricity mix of the archipelago.

A key technical challenge in reaching such ambitious renewables penetration targets is the management of surpluses and shortages of intermittent energy resources such as the wind, while securing the quality of supply. For example by combining building and transportation end-uses, a coherent solution for integrating high levels of wind power is possible, even without centralised storage [5]. However, for detailed economic evaluation, it is fundamental to accurately characterise the wind energy resource in terms of wind power availability and the timing and scale of surpluses and shortages before the feasibility of options such as demand response, smart grids and electric vehicles can be evaluated.

Suomalainen et al. [6] studied the impact of daily wind patterns on energy systems with high wind penetration and concluded that daily wind patterns can have a significant impact on the timing of energy surpluses and shortages along the day. In the energy systems analysis presented in this paper, the trade-offs between fuel use and surplus energy resulting from the different wind characteristics of different locations on two islands, are evaluated. A comparison is made with scenarios of various installed capacities of wind power at a coastal and a mid-island location on both

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islands, and a common offshore location. This paper also demonstrates the impact that daily wind speed patterns can have on results from energy systems planning tools and the error resulting from neglecting these patterns in locations where these patterns are frequently present.

The following section gives a background to wind power in isolated energy systems. Section 3 presents the case study and summarises the methodology used for generating synthetic wind speed scenarios with daily patterns. Section 4 presents the results of applying these scenarios to the case studies followed by a discussion and conclusions in Section 5.

2. Wind power in isolated energy systems

In this section a quick glance is given to the existing studies of wind power in isolated energy systems and some of the lessons learned. Also some of the needs in wind power characterisation for isolated systems and the potential benefits of a more detailed assessment of daily variability of the wind resource are identified.

2.1. Wind variability and characteristics in isolated energy systems

Numerous studies and cases of isolated energy systems with wind power have been documented [7,8]. In a wind energy potential assessment study Bekele and Palm [9] identified a diurnal effect of afternoon winds in their wind data from Ethiopia. In terms of wind energy availability this becomes relevant especially in climates where electricity demand peaks in the afternoons, e.g. due to increased air-conditioning.

Wind characteristics in Saudi Arabia were identified for five geographically and climatologically different locations by Al-Abbadi [10]. Daily, monthly and frequency profiles of the wind speed showed that two sites, Dhulum and Arar, have higher wind energy potential than the other sites due to the higher annual mean wind speeds. However, at the coastal sites, although the annual mean wind speed is lower than at Dhulum and Arar, the wind speed increases significantly during afternoon hours. They concluded that grid-connected wind power at these sites provides an advantage in satisfying demand during peak hours.

Bowen et al. [11] studied the performance of an isolated wind-diesel system for one household. They report that while almost a fifth of the wind power had to be dumped to water heating, over one quarter of total electricity supply still came from diesel. The winds generally reached maximum in the mid afternoon showing a strong influence of the coastal sea breeze especially in the summer months. The household electrical load showed regular peaks around lunchtime and early evening, most activity ceased by 22:30 and resumed again in the early morning. They conclude that the fact that the primary energy source, the wind, and the load have similar profiles across a typical day was a very positive feature and an excellent characteristic for a remote wind energy power system. They agreed with Infield and Scotney [12] saying that even a small amount of energy storage can have a significant impact on the system performance. In addition, significant improvements in system efficiency could be achieved if the energy fed into the batteries was minimised by arranging the energy demand timing to fit generation more closely.

In a more detailed study on the effects of temporal wind patterns on the power system Fripp and Wiser [13] concluded that temporal patterns have substantial impact on the capacity factor of wind parks during peak hours. Locations that were best correlated with demand peak periods produced 30–40% more power during the top 10% peak hours than on the annual average. The worst correlated sites produced 30–60% less power than on average. The relationship between wind resource patterns and electricity demand was also studied by Sinden [14]; it was shown that during peak demand periods the capacity factor of wind power in the UK was approximately 30% higher than on average, in this case showing a positive correlation between temporal wind patterns and demand.

For many island energy systems, due to a typically high dependence on imported fuels, increasing the penetration of local renewable energy sources to the energy mix has become an objective and a challenge. Chen et al. [15] looked at several islands with various renewable energy resources, including wind, and concluded that the deployment of renewable energy in islands is a particularly interesting opportunity for testing new technologies, in circumstances where conventional technologies are costly, and new solutions are more efficient.

Also Duíc et al. [16] has conducted a number of case studies on increasing renewables' penetration on islands and concludes that by adding a suitable storage solution it is possible to significantly increase the penetration of local energy resources, and thus increase security of supply and decrease dependence on imported fuels. What remains unanswered is the question of optimising the energy system design for islands with significant wind resources, and this requires including daily wind patterns in the resource characterisation.

It is clear that daily wind patterns are frequently found in both general climatic studies as well as in wind resource characterisation studies for energy systems modelling purposes. However, daily wind patterns are frequently omitted in energy system studies, including studies with high wind penetration levels in relatively small energy systems, such as islands. For example Katsaprakakis et al. [17] conducted a study on a wind powered pumped hydro storage system for an isolated power system, using wind speed measurements for dimensioning and siting the wind park and estimating the annual electricity production. No daily wind patterns or alternative locations were evaluated. In fact, due to the uncertainty of the wind power availability the system was designed to not allow the wind power enter directly into the grid at any time. This is one example of where including daily wind patterns, likely to occur on islands, could give valuable additional information on the availability of wind power during peak demand hours. Thus, a higher amount of the thermal production could possibly be offset directly with wind power and possibly a smaller reservoir could be constructed for the pumped hydro station, if the daily wind patterns could be characterised.

According to Zhou et al. [18], who reviewed the current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems, unavailable meteorological wind speed data is typically obtained by synthetically generating data from monthly average values. This paper provides an example of a methodology to generate such wind speed data but including daily patterns, giving thus a higher level of characterisation of the wind resource.

Khan and Iqbal [19] analysed a small wind-hydrogen stand-alone hybrid energy system noted that site specific resource and load variations, and optimum sizing issues contribute to a challenge in such system development. The presented methodology of the current paper supports the next step of such studies where local specific dynamics between the wind resource variation and power demand must be addressed. Whereas their wind model consisting of the sum of a mean term and a noise term is sufficient for the time-span of their study, a higher level of variations needs to be considered for energy systems modelling purposes, i.e. including hourly, daily, seasonal and annual variations.

Kaldellis et al. [20] developed a stochastic model for estimating the wind energy contribution in remote island electrical networks. They characterise the wind resource by a wind speed probability distribution and conclude that wind energy cannot play a key role in solving the electrification issues in many Greek island regions