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Exploring the mean-variance portfolio optimization approach for planning wind repowering actions in Spain

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ABSTRACT

The repowering of already installed wind farms is considered one of the most promising and cost-effective short-term strategies to scale-up wind capacity. In this study, we apply Markowitz's mean-variance (MV) portfolio optimization theory to explore alternative repowering actions in Spain. The efficient portfolios – a direct outcome of the MV optimization – offer optimal repowering alternatives to current wind farm generation mixes. They deliver the highest possible average power output (yield) for a given level of supply risk. Different repowering scenarios are considered in this paper that range from a full restructuring of the existing wind generation mix to restricting by certain amounts the percentage of down-/uprating of each reference region. Results show that, depending on the configuration of the MV portfolio optimization problem, hourly fluctuations in the aggregate power supply can be reduced as much as 12–31%, while retaining the current level of energy productivity. In addition, for the level of energy supply risk experienced with the existing portfolio of Spanish wind farms; we can derive more efficient mixes that boost-up productivity by 16–55%. This work aims at providing valuable insight for energy policy-making in the direction of optimally repowering future renewable generation.

1. Introduction

Among all renewable energy (RE) resources, wind power is probably the most technologically mature and cost-effective. In the coming decades, it is expected that wind energy will take the leading role in the gradual replacement of fossil fuels [1,2]. In fact, wind energy is expected to provide almost 9% of global electricity demand by 2030 and 12% by 2050 [3]. In the case of the Spanish power system, wind energy is considered a key ingredient. Spain was, along with Denmark and Germany, one of the first countries that clearly promoted this technology as an alternative to fossil fuels, and currently has the second largest cumulative installed wind capacity in Europe. In 2015, the installed wind power capacity in the country was 23 GW serving 19% of the total demand for electricity [4]. Moreover, the installed wind capacity is Spain is expected to peak in the future – even reaching 28 GW of onshore capacity in 2020 – according to the most favorable projections [5]. Despite though the initial interest in wind power, investments in this sector have shrunken as a consequence of the recent financial crisis. In fact, a newly published report by the Spanish Wind Energy Association [6] states that only 1,932 MW's have been installed in the last four years, and advises that the only way to achieve the aspired EU targets is to install 6.4 GW of new wind capacity, as declared in the Spanish Government's energy planning for 2020. To achieve this, policymakers are promoting various actions, including the repowering of existing onshore wind farms.

Wind farm repowering is considered in many aspects one of the most promising ways of increasing energy productivity, minimizing, at the same time, the requirements for investment capital [7–11]. In fact, some authors argue that the true wind energy potential of committed sites will never be fully unleashed, unless newer-generation wind turbines gradually displace older ones, which are less efficiently designed both in terms of nominal power

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and hub height [12]. Repowering is, in a sense, imperative for achieving a more efficient exploitation of wind energy. Even in purely economic terms, repowering has been proven more advantageous. A recent study [13] demonstrated that the repowering of an existing wind farm project can be often considered as a more attractive investment alternative to installing new farms. With repowering, we anticipate a reduction in operation and maintenance costs by deploying newer, more reliable, equipment (characterized by a smaller number of moving parts) [14]. Moreover, certain environmental benefits are expected from repowering, especially in the direction of reducing the visual impact ("clutter effect") of wind power projects. This is because with modern technology wind turbines, we can meet the same capacity rating using smaller-size arrays of wind power generation units [10,11,14,15].

For some European countries, such as Denmark [16,17] and Germany [8,18], owning a large number of aging wind farms, repowering is often considered a top-priority action. The same holds for other countries, such as the United States [19] and India [7]. In Spain, there have been several studies evaluating the economic benefits of repowering already-installed wind farms [11,13]. Actual repowering actions are either nonexistent or, at best, at a very early stage. Studies [11,13] showed that there is currently a market for repowering approximately 2.3 GW of installed power in the entire Spanish territory, corresponding to projects of a lifetime more than or equal to 13 years. Moreover, it is expected that this volume will increase in the next few years (at a rate of ~1 GW per year) as wind farms age. Therefore, repowering appears to be a realistic and feasible option for increasing wind energy penetration in the Spanish energy mix.

However, the volatile nature of wind power (as a direct consequence of fluctuating weather patterns) remains one of the main obstacles even to large-scale repowering scenarios. The management and smoothing of these intermittencies substantially increase the cost of wind energy and render this technology less competitive to traditional power systems based on fossil fuels. Wind power forecasting is definitely a way of dealing with the intermittent nature of wind [20–23] also in the context of repowering. Nevertheless, the level of skill in state-of-the-art forecasting systems is still not fully satisfactory making almost imperative the use of spinning reserves to offset forecast errors.

Knowledge of the spatiotemporal variability of the wind resource, and its coupled variability with other renewable resources in a region, has been reported in the scientific literature as a successful way of reducing fluctuations in the delivered output [24–26]. These spatial patterns, which can often be unraveled using simple multivariate statistical techniques (such as principle components analysis), provide a valuable indication to the decision-maker on how to counterbalance below-normal renewable generation events in some areas of the grid with over-production events happen at other sites. However, in order to derive a fully functional repowering plan one has also to specify the *sizing* of the production arrays, i.e., the exact amount of nameplate capacity to be installed at selected locations. This issue can be systematically addressed in a multi-objective optimization framework, such as the mean-variance (MV) portfolio theory of Markowitz [27]. In the context of renewable energy, MV analysis has been already used in the selection of an adequate diversification strategy for renewable technologies [28,29]. MV portfolio selection has also been exploited in terms of determining optimal spatial allocations for renewable energy capacity. In fact [30], analyzed wind power production across European countries, obtaining an optimal European-level (cross-country) portfolio that minimizes the variance of the aggregate energy supply. The authors concluded that an optimal allocation of wind capacity across countries can significantly improve the reliability of wind power supply. So far, few studies have dealt with the use of the portfolio theory for simultaneously deriving the optimal spatial configuration and sizing of renewable power capacity, especially across different technologies. In Ref. [31], the authors proposed a portfolio-based strategy for large-scale exploitation of wind and solar resources in the southern half of the Iberian Peninsula. They applied mean-variance optimization techniques to jointly detect the optimal spatial diversification level as well as the share of each renewable generation technology (concentrating solar power plants and wind farms) in the region mix. In the context of the aforementioned study, optimality was defined based on two performance criteria for the aggregate power supply: maximization of the average delivered output and minimization of variability.

In this study, we apply MV portfolio optimization techniques to explore different wind repowering scenarios in Spain. The aim is to provide energy policy makers with a range of possibilities for optimal redistribution of wind capacity. The resulting energy generation plans achieve a better trade-off between aggregate power productivity and stability than the existing wind generation mix. To demonstrate the maximum potential offered by repowering actions, we considered three MV portfolio optimization settings which differ in terms of the type/tightness of constraints. The first is an *ideal repowering* scenario which allows full decommissioning of an existing wind farm and an unlimited amount of wind capacity to be placed at each location. A second and most realistic alternative is the so-called *full repowering* case, which is based on the assumption that the share of each location can drop to zero as long as the installed capacity at every site stays below an upper bound (further specified in Section 3.2). The final scenario is called *partial repowering*, which is similar to the full repowering case except for the fact that each location participating in the mix maintains its currently installed capacity (so the lower weight bound is active). For both the full and partial repowering cases, we further investigate how the composition of the suggested optimal portfolios changes as a result of tightening the ceiling constraints (upper bounds each site's share).

The data used in all experiments mentioned above consist of hourly *implied* generating capacity factors of the existing wind farms spanning a period of 10 years (2001–2010). These time series are calculated in two stages. First, the Weather Research and Forecasting (WRF) [32] numerical weather prediction model was used to obtain wind speed estimates at 80 m above ground level for each farm location in Spain. These estimates were subsequently used as input to a reference wind farm power curve to obtain a proxy for the generating capacity factor.[1]

The rest of the paper is structured as follows. Section 2 details the methodology and Section 3 presents the results. The main conclusions of this study are summarized in Section 4, which also discusses directions for future research.

2. Data and methods

2.1. Onshore wind capacity in Spain

The geographic allocation of wind capacity in Spain at the beginning of 2015 is presented in Fig. 1. This map was compiled using information provided by the Spanish Ministry of Industry and the Spanish Wind Energy Association.

[1] We use the term "implied" to differentiate this estimate of generating capacity from the actual capacity factor, which is often used in practice and calculated based on historical generation of the power plant.