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Power-to-gas plants and gas turbines for improved wind energy dispatchability: Energy and economic assessment

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HIGHLIGHTS

- The issue of uncertainty in production programs of wind parks is addresses.
- A statistical approach to production forecasting error is applied.
- Management principles of a power-to-gas and gas turbines balancing system.
- Optimization of the size of the devices based on economic parameters.
- Comparison of several future economic and policy scenarios.

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ABSTRACT

Limited dispatchability of wind parks and unexpected grid power injections create unbalances between the generated electric power and the actual required power that has to be reduced for proper operation of the electrical grid. The increasing amount of renewable energy sources stresses this problem in several countries, where the responses in terms of reinforcement of transmission lines and ancillary services are not sufficiently fast or effective. In this study, we analyze the potential of a grid balancing system based on different combinations of traditional gas turbine based power plants with innovative 'power-to-gas' plants. Power-to-gas is a promising solution to balance the electric grid, based on water electrolysis, which can effectively contribute to reducing the uncertainty of dispatch plans. According to this system, the excess power produced by renewables is converted into hydrogen, which can be then injected into the natural gas grid. Different economic scenarios are assessed in this work, leading to a set of optimal sizes of the proposed system, using a statistical approach in order to estimate wind farm productivity and forecasting errors, as well as each component load conditions. Economic parameters, equivalent operating hours, CO_2 emissions and lost wind energy are the main performances indexes considered in this work to compare gas turbine and electrolysis balancing systems. From an economic point of view, hybrid systems including both balancing technologies generally lead to the best performances. The scenario which leads to the highest power-to-gas capacity (with installed electrolysis power of about 6% of wind park nominal power) is determined coupling a mid-term perspective of reduction in investment costs with favorable energy market conditions or with incentives ("green-gas" or carbon taxes). In such conditions, an equivalence between the two technologies in terms of optimum installed power can be reached at an electricity-to-natural gas cost ratio between 1.8 and 2. In most interesting scenarios, the P2G system brings about a lower total wind electricity injected in the grid, due to wind-to-gas energy conversion, while it allows reducing energy losses due to grid congestion and curtailment of the wind park; however, the additional CO_2 emissions due to gas turbines operation and due to the reduced electricity production tend to offset or to limit the positive effect of the carbon-free gas production.

1. Introduction

Renewable energy share is continuously increasing in most of the industrialized countries, allowing environmentally friendly power production but entailing growing issues in power grids management [1,2]. Power generation by fossil fuel power stations,

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Nomenclature

AD	aero-derivative gas turbine
CAES	compressed air energy storage
CSP	concentration solar plant
EL	electrolysis-based balancing system
GT	gas turbine-based balancing system
HD	heavy duty gas turbine
NG	natural gas
PEM	polymeric electrolyte fuel cell
PHS	pumped-hydro storage
P2G	power-to-gas
PV	photo-voltaic
TSO	transmission system operator
Subscripts	
el	electric
disp	dispatched
min	minimum
max	maximum

traditionally used for balancing purpose together with pumped-hydro plants, can hardly compensate power output fluctuations of increasing number of power plants based on non-predictable energy sources, especially wind and PV technologies. The resulting increasingly fluctuating operations required to traditional plants and their lower efficiency at partial load, reduce the availability of balancing reserve and add pressure on shrinking power plant operational margins [1]. In IEA Energy Technology Perspectives for the 2050 [3], the share of renewables is forecasted at 57–71% of the global electricity production if international community will pursue a strong CO_2 emissions reduction policy (*"2DS"* and *"2DS-HiRen"* scenarios). Otherwise, a reference scenario (*"4DS"*) limits the expected contribution of renewables to 36%. In this work, we are interested in the increasing share of wind and solar power which are nowadays covering the majority of power in new renewables installations. Their production is well-known as non-dispatchable with the current technology (except for CSP solar plants with thermal storage, which are however currently marginal with respect to wind and PV). A large effort has been devoted in the last years in finding solutions capable of mitigating the effects of the oscillation of non-dispatchable generated power on the quality and reliability of the electricity service [1,4,5].

A first option is the adoption of a more flexible generation system involving traditional technologies with improved start-up and load following capabilities. According to this viewpoint, flexible combined cycle power plants layouts are being developed [6,7] and a higher number of simple GT cycles might be introduced in the generation park [8].

Additionally, in order to face the challenges of larger presence of unpredictable renewables, energy storage systems (ES) are currently developed and many solutions are already available [9–14]. Among them, pumped-hydro storage (PHS) plants are well known to provide fast power balancing. However, the possibility to install large hydro plants is limited by the availability of attractive sites depending on the geographical location, as well as by environmental impact and social acceptance issues, so that in most countries it is not considered feasible to deploy very large new hydro plant installations in the mid-term future [15]. Anyway, in the next future (2050 horizon), PHS installed capacity in EU countries could reach up to 91–188 GW, depending on the scenario, due to new plants installation or repowering of the existing fleet (current European installed PHS capacity is about 40 GW) [16,17]. Compressed air energy storage plants (CAES) are also considered as an alternative option [3,12], although similar issues of site availability exist, and the technology has been demonstrated in a few cases (i.e. Huntorf, Germany, 1978, 290 MW/870 MW h [18]; Mcintosh, USA, 1991, 110 MW/2.8 GW h [19]).

Within ES technologies, another possibility is the development of electrical energy storage technologies (EES), including batteries, supercapacitors and flywheels which are particularly suitable for frequency and voltage control on fast time scales. Nevertheless, only a limited number of EES (e.g. some kind of electrochemical batteries or flow batteries) can contribute in reducing massive transmission curtailment, providing load following and time shifting capabilities that can require long term storage (minutes to days).

An alternative research field involves hydrogen-based energy storage systems (HES), adopting electrolysis devices, which are nowadays considered a promising solution to support PHS and CAES [9,20,21].

In addition to the possibility of storing hydrogen for subsequent electricity production or other uses, e.g. feeding refueling stations for hydrogen vehicles, HES systems can be developed with the scope of injecting hydrogen (at limited percentages) in the existing natural gas infrastructure, according to an approach which has been recently receiving attention [21,22]. The aim of such system is to handle large electrical power fluctuations by providing negative balancing power and exploiting the excess energy otherwise curtailed, avoiding issues and costs due to a local hydrogen storage and reconversion. This solution is usually known as "power-to-gas" (P2G). Various layouts can be adopted, according to the electrolysis technology (alkaline or PEM) and to the additional possible introduction of a methanation process to convert hydrogen into synthetic methane before pipeline injection.

The aim of this paper is to evaluate the potential of power-to-gas technology as energy balancing system on an economic, energy and environmental basis, in order to estimate its effectiveness in balancing the power produced by a large group of wind farms, interconnected to the national grid of a European country [23,24]. In a previous work [25] the authors have assessed the potential of P2G compared to a traditional balancing system based on gas turbines, considering the two systems separately. In this paper, we explore how the power-to-gas concept can be effectively coupled and integrated with a balancing system exploiting a fleet of gas turbine plants: the two systems are working on opposite operating principles, so that a positive synergy can be expected. The comparison is made considering different sizes of the two balancing systems, optimized for various economic scenarios on the basis of a common statistical approach for the expected errors in wind forecast.

2. Power-to-gas concept

As anticipated, Power-to-gas technologies consist in producing pure hydrogen by water electrolysis and injecting it into the natural gas infrastructure, directly or after upgrading to synthetic methane. The approach considered in this work is the first, which does not require integration with a CO_2 source required for the methanation process. In principle, this kind of plant is based on well-known technologies as alkaline water electrolyzers gas transport infrastructure components. Nevertheless, in order to follow the fluctuations of non-dispatchable renewable sources,