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Benefits and cost implications from integrating small flexible nuclear reactors with off-shore wind farms in a virtual power plant

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ABSTRACT

Nuclear power currently supports the goals of the European Union low-carbon society by being a dependable source of energy, while emitting no CO_2. In the future, more flexible nuclear systems could enable wind to achieve a 50% share of the renewable contribution to the energy mix. Small and medium-sized reactors (SMRs) could provide firming power generation to back-up the supply from renewable resources and follow-load. This study involves the hypothetical combination of an off-shore wind farm and a SMR, operated together as a virtual power plant (VPP). Results using wind data from the North Sea indicate that the combination results in 80% less wind power variation to the grid, effectively creating a virtual baseload power plant. This gain comes at the loss of 30% SMR capacity utilization. The research identified that the reduction of 1000 MW off-shore wind farm variability was best achieved with 700 MW SMRs using 100 MW modules. In demand-following mode the VPP could maneuver output to improve synchronization with demand by 60–70% over a wind-only system. Power variability was indifferent to the SMR module size. The VPP could not reduce 100% of the wind variation, as additional balancing measures (e.g., smart grid, storage, and hybrid-nuclear systems) are still needed.

1. Introduction

In Holland, the windmill provided a critical technology for removal of the waters of the North Sea from the polders to reclaim the land now used in agriculture, dairy, and production of the world famous tulips. Fleets of up to 50 drainage mills were put in service to pump the polder water by stages to river channels. By 1850 there were 9000 windmills in Holland that provided a dependable means for emptying the polders, as ebbs in the wind could be made up by the flows when the wind was blowing. However in the second half of the 19th century windmills began to be replaced with steam engines which could perform the work more quickly and on a larger scale. In the years following World War I the electrification of the rural districts ultimately led to the use of electric pumps. Nowadays, only 1200 windmills survive in the Netherlands, primarily for historical preservation.

Today, wind power is an important component of the renewable energy portfolio that supports the European Commission (EC) roadmap for a competitive low carbon economy in 2050 (EC, 2011a). However, for wind to meet the stringent conditions for reliability and grid safety, it is increasingly becoming dependent on a new smart grid, energy storage, and flexible low-carbon energy sources. This dependency becomes particularly acute when variable renewable energy systems (RES) exceed ~20% of the total power mix. Some researchers suggests that even at levels greater than 10%, a more flexible dispatch of different types of power plants will be needed than what exists today (Greenpeace, 2008).

Electricity power generation forecasts from 2011 to 2050 indicate that production from RES could increase from 15% to

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55% of total EU generation (EC, 2011a). Among the RES technologies, wind power is more than half of this gain with a planned expansion of 378 GW. Electricity generation with high shares of intermittent and decentralized RES will challenge the reliability and operational management of electricity systems. Future energy systems need added flexibility in matching supply and demand and will be integral in providing ancillary services to future markets (Eurelectric, 2009).

This paper addresses the problem of increasing the share of renewables in the energy system. It advances the concept of integrating small and medium-sized reactors (SMRs) with off-shore wind (and potentially other renewable energy sources) in a Virtual Power Plant (VPP). The combined system would promote the use of low-carbon technologies in helping renewable energy achieve high penetration levels within the power mix and it would emit practically zero CO_2. Without new measures as suggested in this paper, the flexibility of the energy system to accommodate variations in supply may be restricted due to limitations in future supplies of dispatchable hydro storage and reduced reliance on natural gas due to concerns of energy security, fuel price volatility, and CO_2 emissions. The implementation of a SuperSmart Grid (SSG) is hoped to absorb much of the RES variability, however the substantial expense and timelines for constructing thousands of kilometers of new inter-regional high-voltage transmission infrastructure, creation of active supply-side management and demand-side measures, and provision of energy storage and back-up measures is yet to be fully quantified according to the European Commission—Joint Research Centre (EC-JRC, 2011). Through the integration of flexible nuclear reactors with renewable sources, the demands for the SSG and other expensive measures may be deferred or ultimately reduced in scope. Only through diversification of energy sources and use of highly integrated systems can we avoid repeating the history of the ill-fated windmill.

In Section 2, a VPP consisting of a large wind farm and an SMR is described along with the potential advantages from coupling the two technologies to stabilize the power output to the grid and demand-follow. Section 3 describes the study methodology including the data sources and computations used to determine the wind farm power output. This section also describes the SMR power characteristics and modeling constraints. Section 4 compares the power variability resulting from several different VPP configurations, utilizing different degrees of flexibility and number of modules, and performance in demand-following. Section 5 describes the economic viability of the VPP approach, Section 6 the future research opportunities, and Section 7 presents the main conclusions from the study.

2. Framework: scenario for SMR integration with large scale wind

Interest in off-shore wind in the EU is growing, with particular interest in the area of the North Sea. The North Sea is estimated to be able to supply 26 GW of electricity by 2020 and 83 GW by 2030 (ENTSO-E, 2011). All the countries bordering the North Sea have plans for tapping into the off-shore wind potential. The largest capacity shares are being carved out by Great Britain, Germany, and the Netherlands. In 2011 off-shore wind farm installed capacity in the EU was 3.8 GW (EWEA, 2012) and the projections are for 40 GW and 150 GW of off-shore capacity by 2020 and 2030, respectively (EWEA, 2011).

The system illustrated in Fig. 1 would operate as a VPP to provide energy management and enable generation monitoring. IDC Energy Insights (Nicholson et al., 2009) defines this capability as a plant with the technical, operational, and economic construct that aggregates the distributed supply and demand resources in a manner that

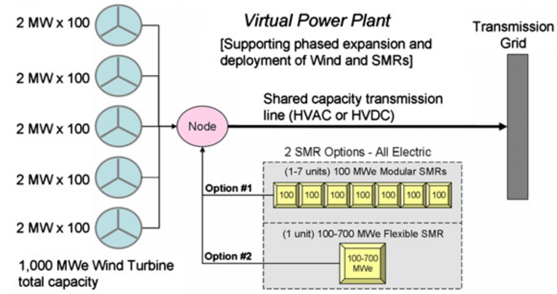

Fig. 1. Illustration of a virtual power plant consisting of wind turbines and a SMR.

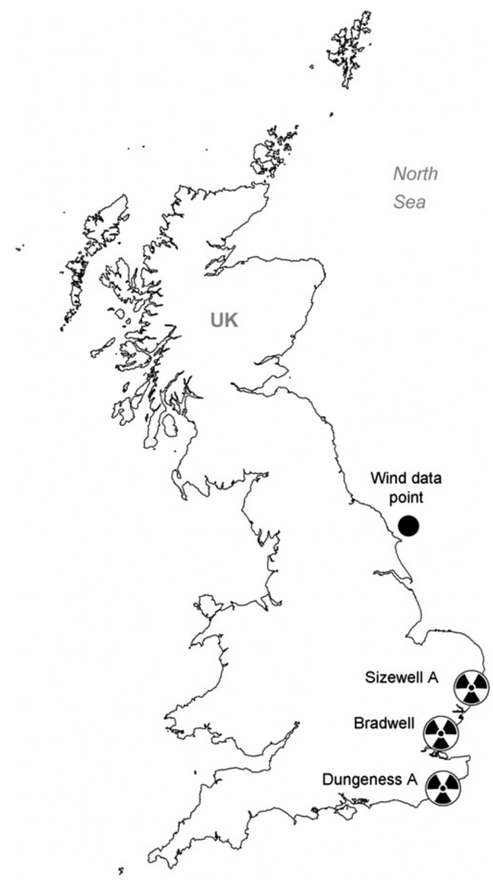

Fig. 2. Location of nuclear power plants and the selected wind data point in the UK.

enables the operator to treat the distributed energy resources as if they were a single power plant. The generation capacity could be sold on the power exchange and the reserve capacity sold through auctions. The VPP could also provide demand-driven production planning, production optimization, monitoring, and control.

The VPP modeling approach was chosen over basic unit commitment modeling or energy system analysis. This VPP approach allows a more in depth understanding of the issues and complexities from integrating very different energy systems. In this study, the implications on a common transmission resource were considered. The authors also wanted to gain insight to the complementarities of plant sizes and operational requirements. The VPP approach provided insights to sharing common transmission resources. The pairing of off-shore wind and nuclear is logical, since thermal power plants (such as nuclear reactors) require cooling resources from large bodies of water (i.e., North Sea). For example, in Fig. 2 there are