Abstract

The European Union's (EU) commitment to achieving carbon neutrality by 2050 necessitates a significant transition in its energy systems. Increasing the penetration of Renewable energy sources (RESs), such as wind and solar, offers an essential pathway for decarbonisation. However, RESs and electricity demand are not evenly distributed geographically across Europe. The challenge lies in harvesting the large-scale RES generation over long distances and delivering them to the demand centre. Hence, this research designed a super hybrid grid infrastructure where the overlapping High-voltage direct current (HVDC)/High-voltage alternating current (HVAC) network coexists. More specifically, the HVDC network is constructed to transfer wind and hydro electricity from north-western Europe and solar electricity from north Africa, while the HVAC network is used to distribute electricity within each country or among adjacent areas. Compared with the pure HVAC grid, the integrated HVAC-HVDC grid can significantly reduce greenhouse gas emissions and pollutants, further reducing the number of deaths from air pollution. In addition, the super hybrid grid can accommodate a higher penetration of RES without causing infeasible power flows. The findings offer a potential solution for designing the future European grid, solving the energy crisis in Europe and strengthening the socio-economic development of North Africa.

However, the proposed physical infrastructure presents economic operational challenges. The increase of RES capacity and the relevant generation profiles create different power flow patterns and change the location of the structural congestions. These problems incur extra re-dispatching costs for the transmission system operators (TSO) and cause social welfare losses. To mitigate these issues TSO faces, modifying the definition of bidding areas, also known as market zone reconfiguration, is often considered a viable solution.

Before implementing reforms, it is crucial to establish a theoretical foundation for assessing the market performance of both current and proposed zone definitions. Therefore, this research aims to develop a comprehensive multi-dimensional evaluation system that considers key factors such as economic, system security, and sustainability.

First, A benchmark-based approach was introduced to evaluate market mechanisms. Performance indicators were designed to compare target market mechanisms against benchmark mechanisms such as pure economic dispatch and network-constrained dispatch with nodal representation. Then, building on the benchmark-based approach, a multi-dimensional evaluation framework was developed to assess market zone configurations. The framework incorporated

dimensions across time scales (short-term and long-term) and influential factors, including Economic (market efficiency, market liquidity, and price volatility); Grid Security (congestion frequency and impact on security); Sustainability (reduction in greenhouse gas (GHG) emissions). By combining these dimensions, a comprehensive set of performance indicators was formulated. As a case study to validate the framework, the Italian bidding zone reconfiguration demonstrated enhanced market efficiency and grid security.

Ultimately, the research aims to develop a novel approach for market zone redefinition that improves the market performance of the proposed hybrid grid, which provides the necessary tools and insights for European market regulators to undertake comprehensive market zone reforms. Building upon proposed assessment indicators, a robust optimisation model was developed to address diverse European Green Deal scenarios. This model identified a target European bidding zone configuration optimised for the RES penetration, market efficiency, and congestion. Key recommendations included dividing Great Britain into Scotland and England-Wales zones and reorganising Norway into six zones.