Abstract

Decarbonization targets are pushing energy systems toward large-scale adoption of variable renewable energy sources (vRES), raising new challenges in system stability and planning. This dissertation develops a unified optimization framework that integrates energy system planning and operational modeling into a single environment, explicitly addressing the evolving needs of high-vRES systems. The framework includes: (1) a water–energy nexus model treating desalination as a flexible load, (2) unit commitment constraints for dispatchable generators and desalinators, and (3) a reserve management structure based on a novel stochastic estimation method. The latter, inspired by the ENTSO-E guidelines but extended to cover high-vRES scenarios and generalized to be applicable to different power system configurations, is first validated on the South African power system before being applied to the small and non-interconnected isle of Pantelleria. Indeed, small non-interconnected islands are adopted as testbeds due to their high vRES potential, limited grid flexibility, and lack of standardized reserve management practices. These characteristics make them ideal case studies for exploring future energy system needs under tight technical and environmental constraints. At the same time, they offer a controlled setting to develop and validate methodological advances in energy planning, laying the groundwork for future scaling to larger and more complex systems. The results show that operational constraints significantly shape both investment decisions and dispatch strategies. In the case of Pantelleria, omitting the operational features of fuel-fired generators (FFGs) led to an underestimation of the optimal photovoltaic and Battery Energy Storage System (BESS) capacities by 30% and 40%, respectively. On the power reserve management side, when only FFGs were allowed to provide reserves, neglecting downward reserve requirements resulted in a BESS over-sizing of over 100% and a threefold increase in fuel consumption. Moreover, excluding both upward and downward reserve requirements caused a 50% underestimation of system operating costs and led to distortions in the optimal energy mix of up to

150%. Conversely, allowing BESS to contribute to reserve provision stabilized the system at negligible additional cost, confirming its role as a key enabling technology for flexibility. A separate point of analysis concerns the comparison between deterministic and stochastic reserve estimation approaches. They yielded comparable investment results under high BESS penetration; yet, the stochastic method better reflects the actual dispatch strategies observed, *i.e.* in systems where reserve provision is predominantly ensured by FFGs. Furthermore, the stochastic reserve estimation methodology's ability to capture uncertainty without relying on rigid assumptions enhances the generalizability and robustness of energy planning across different system configurations. The code implementing this methodology has been made openly available to support reproducibility and further development. Lastly, beyond its application to energy planning, the optimization framework is also employed as a system-aware evaluation tool to support the development of early-stage renewable technologies, with a particular focus on offshore applications. A methodology is introduced to assess Wave Energy Converter configurations not only in terms of energy yield, but also based on their systemic impacts, such as BESS requirements and curtailment levels. This approach enables a comparative ranking of design options according to how well they integrate within future high-vRES systems. Rather than optimizing for device-level performance, it supports the selection of devices that contribute more effectively to overall system efficiency and flexibility. As such, it offers valuable guidance to developers and investors, aligning early-stage technology development with long-term power system needs and policy goals. Altogether, this work lays the foundation for next-generation energy planning models that are both operationally grounded and capable of informing technology innovation to support the transition toward resilient and decarbonized energy systems.