Hydrogen-based energy storage systems for off-grid locations

Summary

Renewable energy sources (RESs) are key elements to promote the energy transition towards a decarbonized society. Their installed capacity is expected to increase considerably over the next few years to address the problems of fossil fuels depletion and mitigation of greenhouse gas emissions. However, the fluctuating behaviour of variable RESs (such as solar and wind) complicates their integration in electricity systems. Thus, electrical energy storage (EES) becomes crucial to address the RES-related issues and favor their widespread diffusion both in grid-connected and off-grid applications.

Focusing on off-grid areas, local RESs represent a promising way to decrease the use of diesel generators and avoid the need for unreliable and invasive connections to the grid. EES solutions should be integrated in stand-alone energy systems to improve the exploitation of local renewables and achieve higher RES penetration levels. At present, batteries are the most used EES option due to their high performance, flexibility, and increasingly lower costs. However, when the energy storage is required for longer periods, batteries alone become too expensive and their hybridization with other typologies of storage can result in a cost-effective solution.

The optimal design of off-grid hybrid renewable energy systems (HRESs) is a challenging task that often involves multiple and conflicting goals: cost of energy, reliability of the power supply service and environmental issues should be jointly addressed at the design stage of the HRES. Variability in RES production and load requires that the various components continuously adapt their operating point to reliably cover the load demand and store the surplus renewable energy. Thus, performance curves and modulation ranges should be implemented in the optimal design problem to simulate the part-load behavior of the HRES devices. The seasonal fluctuation of the RES supply and demand profiles also requires considering a year-long time horizon to adequately size the long-term storage, thus leading to a greater computational complexity of the sizing problem. Moreover, cost-effective system configurations usually involve the hybridization of power generators and storage systems, which increases the number of devices that have to be sized and operated.

The main objective of the present work is to address these challenges and better investigate the potential benefits arising from the inclusion of hydrogen-

based storage solutions. Different methods to deal with the optimal sizing of stand-alone HRESs were defined. The design optimization framework was then applied to different case studies and system configurations. However, this thesis seeks to provide a general modelling approach that can be applied to the design of any hybrid renewable energy system, going beyond the analysis of specific case studies. The work also takes advantage of valuable data and experience from the REMOTE project[1], whose aim is to develop and test hydrogen-battery storage systems to support communities characterized by unreliable, or even missing, connection to the grid.

Metaheuristic and mixed integer linear programming (MILP) methodologies were formulated to optimally size stand-alone HRESs based on batteries and/or hydrogen as storage medium. Both methods were found to be effective in modelling the longer-term storage capability of the hydrogen system. The MILP approach requires a higher computational time for the problem resolution because of the greater complexity and the much larger number of decision variables. However, the inclusion of representative days in the MILP problem allows the CPU time to be reduced significantly.

Hybrid renewable energy systems in different kinds of remote locations (from alpine to insular), with different typologies of local RESs (solar, wind, biomass and hydro) and user loads (residential and small industrial) were investigated. Techno-economic evaluations showed that the need for fossil fuels can be drastically reduced thanks to the exploitation of RESs integrated with a battery-hydrogen storage system. Moreover, the renewable solution was proved to be cheaper than the alternative options (diesel or grid-connection) either in the short term or longer term for all the sites. This is because of the high operating costs due to the diesel fuel consumption and of the capital-intensive initial cost to provide a connection to the main grid.

Results from the sizing simulations revealed that the hydrogen storage is crucial in off-grid areas to improve the independence from fossil fuels without causing a sharp increase in the cost of energy. In fact, because of its cost-effective long-term capability, hydrogen avoids the need for batteries with too large capacity and allows the local RESs to be better exploited.

[1] REMOTE project official website. 2018. https://www.remote-euproject.eu/