Multi-objective optimal control of integrated water-energy systems in small off-grid islands

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Abstract: Small Mediterranean islands constitute a paradigmatic example of closed, off-grid systems, where water supply and electricity generation are intrinsically coupled and interdependent. A carbon intensive energy system based on diesel generation coupled to high energy consuming desalination technologies to produce potable water make these systems strongly inefficient and unsustainable. To improve their sustainability, a viable and promising solution is to introduce renewable energy sources coupled to power storage technologies in order to produce clean energy at lower costs. However, although several studies focus on identifying the best hybrid energy system design, only few works optimize the system operations in order to fully exploit the benefits that renewable energy sources introduction might bring to both water and energy systems. In this work, we propose a multi-objective optimization approach to identify optimal control policies of the integrated water-energy system of small off-grid islands, focusing on a fixed hybrid energy system design, which includes diesel generation, renewable energy sources and batteries. Results show the effectiveness of the approach in identifying optimal control policies, which allow to explore potential trade-offs between sustainability and reliability objectives.

Keywords: water-energy nexus, hybrid systems control, multi-objective optimal control, off-grid islands

1. INTRODUCTION

Small Mediterranean islands constitute a paradigmatic example of closed, off-grid systems, where water supply and electricity generation are intrinsically coupled and interdependent (Singal et al., 2007). The lack of safe and accessible water sources, the distance from the mainland and the high seasonal variability of both water and electricity demand strongly and critically influence the operations of both water and energy systems.

On one hand, energy security is based on stand-alone carbon intensive diesel generators, which are usually oversized to meet peaking summer electricity demand driven by high touristic fluxes (Duić and Da Graça Carvalho, 2004). Diesel generation is a mature and reliable power technology, but also one of the major sources of air pollution and greenhouse gas emissions on the earth. In addition, price volatility and high dependence upon imported fuel strongly increase the cost for electricity generation.

On the other hand, potable water, typically transported from the mainland by boat, is nowadays produced by energy consuming desalination technologies, which usually ensure the entire water demand to be covered but put additional pressure on the unsustainable and inefficient electricity system (Voivontas et al., 2003).

To improve the overall sustainability of small islands, a viable and promising solution is represented by the introduction of renewable energy sources (RES) coupled to power storage technologies in order to produce clean energy at lower costs by exploiting the high solar and wind potential of the islands. The identification of the optimal hybrid system design in off-grid settings is a widely explored problem in the literature (Clarke et al., 2015). Many studies evaluate different type and sizing of power and storage technologies in order to identify the system configuration that minimizes the total net present cost over a medium/long project horizon (Ibrahim et al., 2010). However, these works usually simulate the system operations using fixed electrical loads and pre-defined, non-dynamic control strategies, which define priority rules for power allocation (Kaldellis et al., 2012). When introducing conventional (e.g., batteries) or non-conventional (e.g., desalination plant) storage technologies, these non-dynamic control rules could prevent from exploiting the storage flexibility, limiting the capacity of fully exploring the benefits that RES introduction might bring to both electricity and water systems. For example, the desalination plant and the connected water storage can be dynamically controlled by optimally modulating the water production and, consequently, the associated electrical load in order to both exploit the RES power and satisfy the water demand. On the energy side, the optimal control of battery storage allows to dynamically identify the optimal power generation mix, balancing between the reliability of the system and its sustainability.

In this study, we propose a multi-objective optimization

approach to identify optimal control policies of the integrated water-energy system of small off-grid islands, focusing on a fixed hybrid energy system design, which includes diesel generation, RES and batteries. We thus solve an optimal control problem considering, as control variables, the water produced by the desalination plant, the batteries electricity output and the number of diesel generators to be switched on. As for the optimization objectives, we consider the total net present costs J^C (to be minimized), the CO_2 emissions J^E (to be minimized) and the system reliability J^R (to be maximized), defined as the capacity of the system to instantaneously respond to a sudden increase in the electrical load or a sudden decrease in the RES power output through programmable power sources (e.g., diesel) or storage technologies (e.g., batteries). We also constraint the system to always cover the electrical load and to always satisfy a given water demand.
We solve the optimal control problem for the real case study of the Italian Ustica island in the Mediterranean Sea, using an Evolutionary Multi-Objective Direct Policy Search (EMODPS) approach.

2. CASE STUDY

Ustica is a small Italian island with an area of 8 km^2 and is located about 50 km north of Sicily in the Mediterranean Sea (Figure 1a). It has a resident population of 1,559 inhabitants, which nearly doubles during the summer touristic months.
Electricity is entirely produced by 5 diesel generators with a total installed capacity of 4.6 MW. Household consumption accounts for nearly 70% of the annual electricity demand, with the remaining 30% covered by the desalination plant, built in 2016 to satisfy the entire water demand. The plant is composed of two modules of 35 m^3/h each and is able to produce about 1,600 m^3/d of potable water, which is stored in 5 reservoirs with a total capacity of 11,000 m^3, and released through the water distribution network (Figure 1b). Due to the high touristic fluxes, both electricity and water demand have a high seasonal variability.
In order to improve the sustainability of this costly and inefficient system, the introduction of RES and batteries is planned as a solution to produce clean energy at lower costs. In this study, we focus on a fixed hybrid energy system composed of the 5 existing diesel generators, 2000 kW of photovoltaic (PV), 10 wind turbines of 60 kW each and a battery storage capacity of 2000 kW.

3. RESULTS

Figure 2 shows the optimal control solutions in the space of the objectives. The x-axis represents the objective J^E, the y-axis shows the objective J^R, and the color illustrates the objective J^C. The arrows identify the direction of preference of each objective. The ideal solution would be a yellow point in the upper left corner of the figure. We can notice a clear conflict between system reliability J^R and CO_2 emissions J^E. To maximize the reliability, the number of diesel generators to be switched on has to necessarily increase in order to guarantee the capacity of responding to sudden changes in the electrical load or in the RES power. However, when a diesel generator is switched on,

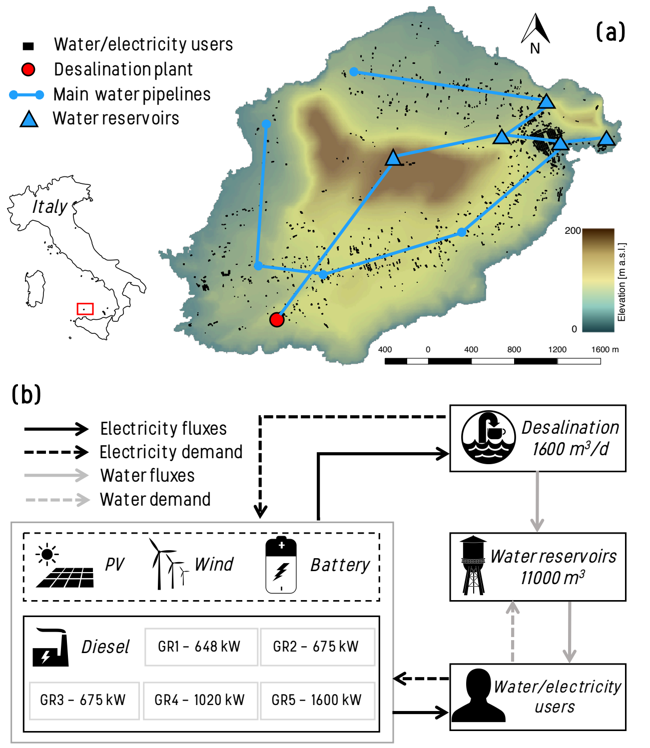

Fig. 1. (a) Location and map of Ustica island with the desalination plant, the water reservoirs and the water pipelines highlighted. (b) Schematization of the existing and planned water-energy system of Ustica.

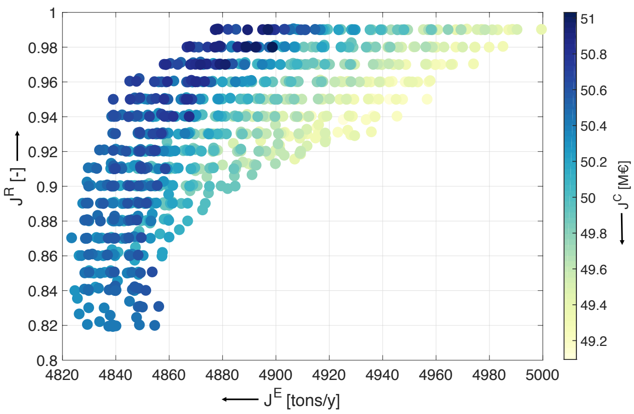

Fig. 2. Visualization in the space of the optimization objectives of the optimal control solutions.

its electricity output is set to a percentage of its capacity. This brings the diesel generator to produce electricity also when the RES power would be able to cover the entire load, leading to higher CO_2 emissions, higher costs and lower RES penetration.
It is also worth noting that for a fixed system reliability, the CO_2 emissions increase with a decrease in the operating costs, which depend on both the amount of fuel used for diesel generation and the number of charge-discharge cycles of the batteries. In the optimal control solution that minimizes the costs, the batteries are always kept full and their operating costs are thus almost equal to zero (i.e., charge-discharge cycles are null). In this case, the batteries provide their maximum contribution to the system

reliability, as the stored electricity can be discharged at any time to cover sudden increase in the electrical load or decrease in the RES power. The entire electrical load is covered by a RES-diesel generation mix, whose operating costs only depend on the fuel consumed. This also brings to the highest CO_2 emissions. The same level of reliability can be also optimally obtained using a completely different control policy: in the optimal solution with the highest costs, part of the load is covered discharging the electricity stored in the batteries. The higher number of charge-discharge cycles increases the operating costs of the batteries. This also brings to a reduction of their contribution to the system reliability, which is now assured increasing the number of diesel generators to be switched on. The same electrical load is, in this case, covered by a RES-diesel-batteries mix that is characterized by lower CO_2 emissions, yet by higher costs.

The results show the effectiveness of the optimization approach in identifying efficient control policies with respect to different sustainability and reliability objectives. On one hand, the control of the desalination plant allows to dynamically modulate the electrical load in order to fully exploit the RES power by ensuring the water demand to be covered. On the other hand, the control of the electricity system (i.e., batteries storage, number of diesel generators to be switched on) allows to identify optimal power management policies, exploring the potential trade-offs between sustainability and reliability objectives.

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