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A two-level decision making approach for optimal integrated urban water and energy management

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ABSTRACT

A spatial-temporal model is proposed for optimal integrated water and energy resource management in urban areas, considering daily surplus output from residential grid-connected rooftop photovoltaics as an energy source for sustainable supply. The model addresses optimal investment and operational decisions of a desalination-based water supply system driven by surplus photovoltaic output and grid electricity. The two-level mixed integer linear programming model considers demands, systems configuration, resources capacity and electricity tariffs and gives the solution such that the highest compatibility with available renewable energy is achieved. The model is then applied to Perth, Australia and solved for three operational scenarios. The results show, for a given year, hourly (flexible) basis scenario leads to \$9 521 425 and \$18 673 545 economic benefits over seasonal (semi-flexible) and yearly (fixed) basis scenarios, respectively. They also indicate 19.9% better economic performance in terms of annualised unit cost of water production over existing Southern seawater desalination plant in Perth. Additionally, it is shown that the seasonal change on the optimal solutions mainly corresponds to the share of each energy resource to meet water-related energy demand. Finally, the results indicate higher sensitivity to the variation of the photovoltaic installation density compared to financial rate.

1. Integrated urban water and energy management

Diminishing natural water resources, increasing population growth and rapid urbanisation more than ever highlight the necessity of deploying drought-proof technologies such as desalination for secure drinking water supply in urban areas. In fact, in some arid and semi-arid regions such as Middle East and Australia, these technologies contribute significantly to urban water supply. However, the energy intensity of these technologies is one of the main obstacles to turn them into the first priority among existing water supply options.

Constant advance in desalination technologies has made it possible to address the issue by considering renewable energies for water-related energy demand. However, to deal with the intermittency of renewable energies and consider such water supply systems as a sustainable solution, the optimal integrated water and energy management is essential. In this context, optimisation is a strong tool that can be applied to find investment options and operational scheduling to provide the most system compatibility and consequently resulting in the least total cost.

There are numerous optimisation studies on integration of desalination plants with renewable energy sources at the point of production. These studies have addressed the optimal investment or operational decisions of the system at the scales of a unit or a multi-utility plant. At a unit scale, Shalaby [1] have reviewed the studies on reverse osmosis (RO) desalination powered by photovoltaic (PV) and solar Rankine cycle power systems including optimisation models. Similarly, Ref. [2] has presented a review on optimisation studies using renewable energies to power membrane-based desalination process. The studies on different desalination process driven by various renewable energy sources (solar, geothermal, wind and ocean energy) have been reviewed in Ref. [3]. At the scale of a multi-utility plant, Perković et al. [4] have addressed the optimal energy flows in a hybrid energy system coupled with desalinated water production and storage using linear programming (LP). Bourouni et al. [5] and Ben M'Barek et al. [6] have proposed a model based on the genetic algorithms to address the optimal configuration of the integrated RO desalination process with diverse combinations of energy units (i.e. PV panels, type and number of batteries). Clarke et al. [7], have addressed the

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optimal sizing and techno-economic assessment of a stand-alone renewable energy sources integrated with desalination unit under static and dynamically changed water demand and compared the optimal solutions derived from intelligent techniques (particle swarm optimisation) with HOMER software. Rubio-Maya et al. [8] proposed a mixed integer non-linear programming (MINLP) model for the optimal selection of the system configuration and sizing of the integrated system among different possible candidates. Also, in Ref. [9], authors compared the economics of different size and configuration of small-scale RO system with hybrid energy sources (solar/wind/diesel) using simulation model coupled with optimisation methods (Nelder-Mead simplex as well as genetic algorithms for different problem formulations). In addition, there are several studies that have addressed simultaneously optimal investment and operational decisions of the integrated system. For instance, at unit scale Antipova et al. [10], have applied multi-objective MINLP model for the optimal design of a RO plant integrated with solar Rankine cycles and thermal energy storage as well as scheduling of the energy flows in the thermal energy storage. At the scale of multi-utility plant, Segurado et al. [11] have applied a derivative free multi-objective optimisation method (Direct MultiSearch) to optimise the size and operational strategy of a wind powered desalination plant and a pumped hydro storage system to address both water and energy supply. The mentioned studies provide a valuable insight into the optimal design and operational scheduling of the integrated water supply units with renewable energy sources. However, they generally miss the broader perspective of water supply system, from the production point to the end use, which is needed in practice, for holistic optimisation of the system and therefore sustainable supply.

There are a few studies considering all main components of the desalination-based water supply system in a holistic way. These models have been mainly developed at national and regional scales. For instance, in Refs. [12,13], authors have developed a LP model for the optimal scheduling of the main components of a desalination-based water supply system fuelled by hybrid energy sources including water production, storage and transfer at a national scale. In Ref. [14], the optimal economic dispatch of water and energy networks including water and power plants, co-generation plant and hybrid energy sources has been addressed using a mixed-integer quadratic constrained program. In another study, Saif and Almansoori [15] have applied a mixed integer linear programming (MILP) model for the optimal capacity expansion of the integrated water and power supply chain taking into account renewable power plants at a regional scale. These studies have addressed either the operational decisions of the supply system or investment decisions taking into account yearly operational details. However, in order to move towards an affordable and sustainable supply system and to ensure the validity and robustness of the decisions, it is necessary to specify the optimal investment decisions together with their short-term operational considerations.

To the best of our knowledge, there is no optimisation study at a city scale addressing simultaneously investment and short-term operational decisions of the desalination-based water supply system fuelled by hybrid energy sources (fossil fuels and renewable energies) in a holistic way while capturing both spatial and temporal aspects of the problem. The following section explains the problem, which this study addresses in order to fill the mentioned knowledge gap in the existing optimisation models in the context of the integrated water and energy management.

2. Surplus residential grid-connected photovoltaics output, as an energy source for urban water supply system

Installation of grid-connected PVs on residential rooftops can have a significant share in the urban energy mix. In land-restricted urban areas, small-scale rooftop PVs have the privilege of being space-saving compared to centralised solar farms and can perform efficiently due to being close to the point of load [16]. However, the extent of their installation is generally limited to the hosting capacity of the existing electrical grid to deal with the intermittency of surplus PV output fed to it. This surplus PV output is the result of the mismatch between supply and demand, which usually occurs during a day in urban residential areas.

In this regards, electricity storage technologies such as batteries on the demand side have been widely proposed in the literature to combat this issue. These studies include both techno-economic analysis and optimisation of the PV-battery system. Mulder et al. [17] have provided a complete investment analysis to achieve the optimal PV-battery system considering the subsidy systems and electricity price. Hoppmann et al. [18] have reviewed the studies addressing the economics of batteries integrated with small-scale PV systems and investigated the profitably of the integrated PV-battery systems with diverse capacities under different electricity price scenarios. Recently, Linssen et al. [19] have applied a battery-PV-simulation (BaPSi) Model for techno-economic analysis and cost-effective configuration of the integrated system considering different consumer load profiles and electricity tariffs. In Ref. [20], authors have reviewed the developed optimisation models for design of the PV-battery systems and presented a multi-period MILP model for optimal configuration and size of such system incorporating the operational decisions. In another study, Ranaweera and Midtgård [21] have addressed the energy management system of an integrated PV - battery system and applied dynamic programming to solve the associated non-linear constrained optimisation problem. Sani Hassan et al. [22] have optimised the power flows among different components of grid-connected PV –battery system using MILP model integrated with distributed energy resources customer adoption model (DER-CAM) software tool. Pena-Bello et al. [23] have applied a genetic algorithm for optimal scheduling of battery storage integrated with grid-connected residential PVs for two applications of PV self-consumption and demand-load shifting under different electricity tariff structures. In a recent study, Wang et al. [24] have solved a discrete LP problem for energy management of a shared battery storage between customers and local distribution network operators under variable electricity tariffs.

These studies emphasise on the benefits of electricity storage systems in terms of protecting the electrical grid from the intermittent electricity penetration and saving the surplus PV output for later use. However, the application of small-scale batteries at household level is still subjective and depends highly on government support through decreasing costs of these systems and implementing feed-in tariffs (FiT) as well as increasing retail electricity prices [25].

An alternative to electricity storage technologies is to create compatibility between load and supplied electricity at the time of electricity generation. In the context of integrated urban water and energy management, this can be achieved by considering the components of a desalination-based water supply system as deferrable loads to the electrical grid [12,26]. In other words, operational scheduling of different components of water supply system, including desalinated water production, storage and transfer, can be adjusted such that it can use the most out of available surplus PV output. This approach, therefore not only benefits the energy sector but also contributes to sustainable delivery of water.

In our previous study [26] a LP optimisation model was presented for operation of a desalination-based water supply system driven by daily surplus PV output and existing grid electricity