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Original article

Investigating trade-offs between the operating cost and green house gas emissions from water distribution systems

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ABSTRACT

For electricity grids with an increasing share of intermittent renewables, the power generation mix can have significant daily variations. This leads to time-dependent emission intensities and volatile electricity prices in the day-ahead and spot market tariffs that can be better utilised by energy intensive industries such as water supply utilities. A multi-objective optimisation method for scheduling the operation of pumps is investigated in this paper for the reduction of both electricity costs and greenhouse gas emissions for a benchmark water distribution system. A set of energy supply scenarios has been formulated based on future projections from National Grid plc (UK) in order to investigate the range of cost savings and emission reductions that could be possibly achieved. Pump scheduling options with fixed time-of-use and day ahead market tariffs are analysed in order to compare potential reduction tradeoffs for both electricity costs and greenhouse gas emissions using Pareto optimality. The presented analysis concludes that the explicit inclusion of greenhouse gas emission reductions in optimising the scheduling of pumps operation in water distribution systems could provide considerable benefits; however, more compelling fiscal and regulatory incentives are needed.

1. Introduction

The water industry is a large consumer of energy and an emitter of carbon, much of which is associated with the electricity it uses [1]. Although the UK water industry is expected to substantially contribute towards the emissions reduction targets established under the Climate Change Act (34% by 2020 and 80% by 2050) [2], there are currently no clear targets of what emissions reductions the water industry should be aiming for and within what time-frame. In anticipation of pending regulatory targets and fiscal incentives, and also water resources and assets management challenges associated with climate change, some UK water utilities are working towards carbon neutrality by 2050 [3,4], delivered through a combination of operational efficiency, renewable energy generation and the purchase of low-carbon grid electricity.

The majority of the electrical power utilised by water companies (65–80%) is for operating pump motors in order to deliver potable water from sources to customers [5,6]. Pumps in water distribution systems (WDS) operate with control schedules that satisfy flow and pressure head requirements in order to guarantee a supply of water while minimising the cost of operation. This minimisation is achieved by making use of time periods with a low-price electricity tariff to fill tanks and reservoirs and minimise the operation of pumps during periods of high-price electricity [7].

As intermittent renewables are projected to generate a large share of grid electricity, energy storage technologies and variable pricing models are becoming increasingly important to support the load management and grid stability [8]. As a result, water utilities could pro-actively use pump scheduling to participate in demand side response schemes to reduce both their electricity costs and GHG emissions, and contribute to grid stability [9].

Greenhouse gas emissions of the pump operation can also be minimised by changing the optimisation problem to specifically minimise GHG emissions and make use of the diurnal fluctuations of GHG emissions of the electricity supply [10,11]. To best assess GHG emission reductions and cost minimisation from pump scheduling, the problem is formulated as a multi-objective optimisation problem. To ensure the resulting schedules and operating cost, in terms of financial cost and GHG emissions, can be compared, a mathematical optimisation procedure that can quantify the optimality gap is applied. Different pump operating schedules are compared within a set of electricity supply scenarios for a benchmark water supply network. These scenarios are derived

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from the Future Energy Scenarios provided by National Grid plc (UK) [12] in order to examine plausible changes in the utilisation of intermittent renewables. In addition, various electricity purchasing options for water utilities are considered such as time-of-use (TOU) and day-ahead market (DAM) tariffs. A mathematical multi-objective Pareto optimality method is then applied to determine the optimal electricity costs and GHG emissions for the operation of pumps under future energy supply scenarios and various tariff structures.

2. Methodology and analysis

The reduction in both electricity costs and GHG emissions through optimising the operation of pumps in WDS under different energy supply scenarios has been carried out in two stages.

Firstly, future energy supply scenarios were defined as the *Green* and *No-Progress* scenarios for year 2035 based on analysis by National Grid plc [12]. These scenarios reflect expected changes in power generation technologies and fuel supply in the UK. Details of formulating the future energy supply scenarios are described in Section 2.1. The pump schedules are then optimised to reduce the electricity costs for a WDS operating with either a fixed time-of-use (TOU) tariff with peak pricing as commonly used by UK water utilities or variable electricity tariffs using day-ahead-market (DAM) tariffs. Secondly, optimal pump schedules and their associated electricity costs and GHG emissions were derived and compared using a branch and bound algorithm [13] that also includes the quantification of an optimality gap. The applied multi-objective global optimisation method is explained in Section 2.2.

The operating cost and GHG emissions resulting from the operation optimised for different objectives in different energy scenarios are compared by analysing the operation of the WDS on selected operating days.

2.1. Energy supply scenarios

Future energy supply scenarios vary significantly in their projections for the penetration rate of renewable energy in the UK [12]. An analysis of a wide range of future energy scenarios confirms that high penetration rates of renewables are feasible [14]. To ensure the applicability of our results and conclusions to many scenarios the operation in a broad range of scenarios is considered. Energy scenarios or software packages modelling energy scenarios or energy-water scenarios, that could be used to construct future operating scenarios cannot consider the hourly variance observed in the energy supply [15].

In this analysis, the assumed energy supply scenarios take both mean and extreme values from projections made by National Grid plc (UK) [16]. However, these energy supply scenarios do not consider the hourly variance observed in a diurnal energy supply [15]. Therefore, the energy supply scenarios were modified based on time series describing the electricity generation mix in terms of fuel type and total supplied energy, in order to provide half-hour time estimates. Technology specific Emission Factors (EFs), for each power generation type including the interconnections that supply the UK grid, were taken into account to derive GHG emissions time series with the required temporal resolution. The pricing data, which were used to compute the operating costs of the benchmark WDS, is based upon electricity tariffs used by three UK water utilities and spot market prices for 2014 [17]. The GHG emissions for a benchmark WDS has been investigated under four different grid (fuel mix) scenarios: the 2014 grid and three possible future scenarios which are defined as *No-Progress*, *Green* and *Green** (based upon information presented in [16]).

2.1.1. No-Progress energy supply scenario

This scenario assumes that the UK's renewable energy target of 15% for 2035 [2] is not met. Sustainability and decarbonisation of the energy sector are not policy priorities, which results in more emphasis on Combined Cycle Gas Turbines (CCGTs) over nuclear and renewables [16]. The fuel combination for this scenario in 2035 assumes that the contribution of natural gas increases to 47% while coal is reduced to 1% of the generation output. Renewables moderately change by 2035 with photovoltaics contributing 2%, wind energy increases to 19% and the generation from biomass contributes 5% [16].

2.1.2. Green energy supply scenario

The *Green* scenario assumes that the renewable energy target of 15% for 2035 is met. In addition, new European renewable energy targets are set to stipulate 23% energy supply from renewables by 2030 and 39% by 2050 [16]. It is assumed that the UK government adopts these recommendations and meets the targets for renewable energy production. Decarbonisation efforts are strengthened which lead to significant changes in the electricity supply with a high penetration of renewable energy. The most significant change to the fuel mix of the electrical energy supply would be the reduction of coal from 32% to 6% by 2035, which will be further coupled with carbon capture and storage (CCS) technologies. Consequently, the EF from coal is reduced from 870 to 220 g CO_2-e/kW h. Furthermore, the contribution from wind energy is expected to rise to 40% in 2035. Biomass fuel and other renewables such as photovoltaic generation will increase their contributions to 6% and 4% respectively by 2035 [16].

2.1.3. Green* energy supply scenario

An alternative *Green** energy supply scenario has also been formulated due to technical, institutional and economic uncertainties associated with CCS [18]. In this case, the GHG emissions under the *Green* scenario are recalculated for the same fuel combination; however, the emissions intensity reduction through CCS are deduced.

2.1.4. Formulation of representative operating days

A previous analysis by [10] proposed a future electricity supply by increasing the wind power generation and reducing coal power generation accordingly. In comparison, the energy supply scenarios applied in this analysis were formulated using grid data obtained from the Balancing Mechanism Reporting System [23] and APX Power UK [17]. Based on the proposed modelling method, a future scenario will have different overall energy supply, but weather, price and consumption patterns will preserve the variation and volatility of the energy supply from data for a benchmark year (e.g. 2014). The presented analysis focuses on relative changes between different operating conditions that arise from the short-term fluctuations in the emission intensities and electricity prices. These fluctuations cannot be represented accurately in an aggregated model. The emission intensity (EI) of the energy supply for a given time is given by:

$$EI_{s,t} = \frac{1}{1 - T_{loss}} \frac{\sum_{f=1}^{f=n} E_{f,t} \times EF_f}{\sum_{f=1}^{f=n} E_{f,t}} \tag{1}$$

where $EI_{s,t}$ is the emission intensity (EI) of scenario s at time t. The electricity source EI factors are summarised in Table 1. $E_{f,t}$ is the power generated at time t by fuel type f and EF_f is the emission factor for fuel type $f \in \{1, n\}$. The transmission and distribution losses T_{loss} are assumed constant (7.6%) for all energy supply scenarios [24].