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Sensitivity of optimal tradeoffs between cost and greenhouse gas emissions for water distribution systems to electricity tariff and generation

Wenyan Wu

PhD Candidate, School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, 5005, Australia

wwu@civeng.adelaide.edu.au

Angus R. Simpson

Professor, M.ASCE, School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, 5005, Australia

asimpson@civeng.adelaide.edu.au

Holger R. Maier

Professor, School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, 5005, Australia

hmaier@civeng.adelaide.edu.au

Abstract

Increased awareness of climate change has shifted the focus of water distribution system (WDS) optimization research from cost minimization only to the incorporation of energy or associated greenhouse gas (GHG) minimization. In this study, a sensitivity analysis is conducted to investigate the impact of electricity tariff and generation (emission factors) on the results of multiobjective WDS optimization accounting for both total economic cost (both capital and operating costs) and GHGs. A multiobjective genetic algorithm based optimization approach is used to conduct the analysis. The results show that electricity tariff has a significant impact on the total economic cost of WDSs and the selection of optimal solutions. In contrast, the changes of emission factor into the future have a significant impact on the total GHGs from WDSs. However, it does not alter the final solutions on the Pareto-optimal front.

Key words

Water distribution systems; Multiobjective optimization; Greenhouse gas emissions; Climate change; Sensitivity analysis; Genetic algorithms.

Introduction

Increased awareness of climate change has shifted the focus of water distribution system (WDS) optimization research from cost minimization only to the incorporation of energy minimization or associated greenhouse gas (GHG) minimization. The first study considering the direct impacts of WDSs on global warming was conducted by Dandy et al. (2006), in which a single-objective approach was used to minimize the material usage and associated GHG emissions from WDSs. Subsequent studies investigated the optimal tradeoffs between GHG emissions and life cycle economic costs of WDSs (Wu et al., 2008) and the impact of discount rate on these tradeoffs by using a multiobjective optimization approach (Wu et al., 2010b). In the same year, Wu et al. (2010a) explored the impact of carbon pricing on the single- and multi-objective optimization of WDSs accounting for GHG emissions. In related work, Herstein et al. (2009) included an environmental index as one of the objectives of a multiobjective WDS optimization problem, which is a single parameter consisting of measures of resource consumption, environmental discharges (including GHG emissions) and environmental impacts. In another study, Ghimire and Barkdoll (2010) found that reduction in water demand, main pump horsepower, and booster horsepower can lead to significant energy savings from operations of WDSs.

While previous optimization studies have identified that there are significant tradeoffs between total costs and GHG emissions, they have not explored the sensitivity of these tradeoffs to such issues as electricity tariff and emissions associated with electricity generation. This is mainly because currently most water utilities and energy producers operate independently and water utilities have little control over electricity tariff and generation. However, the water and energy industries are closely related: a large amount of water is needed for energy production and a large amount of energy is needed for treatment, transmission and distribution of water. This paper explores the water - energy nexus and its impact on the tradeoffs between cost and GHG emissions from WDSs. As part of the sensitivity analyses conducted in this paper, realistic ranges of the above two factors are considered based on data from Australia. In total, two different scenarios including five different combinations of the two factors are considered.

Problem formulation

Case Study Description

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A water transmission network (Figure 1) is used as the example network for this study. A similar network configuration has been investigated in previous studies that have considered optimal tradeoffs between cost and GHG emissions (Wu et al., 2010a). The required flows to the three storage reservoirs are assumed to be the same (i.e. one third of the total water demand). The water levels in the storage reservoirs are assumed fixed and under the control of local water utilities. It is also assumed that the storage reservoirs are appropriately sized to meet different loading cases, such as fire flow and emergencies. Pipe sizes are considered as decision variables and ductile iron cement mortar lined (DICL) pipes are used. Detailed information of the pipes and network can be found in Wu et al. (2010a).

Objective function evaluation

The problem considered in this paper is formulated as a multiobjective WDS design optimization problem, in which two objectives are used: the minimization of the total economic cost of the system and the minimization of the total GHGs emitted from the system. The formulation used in this study is similar to the one presented in Wu et al. (2010b). The difference is that instead of using real fixed-speed pumps as decision variables in the optimization process, as has been done in previous studies (Wu et al., 2010a; Wu et al., 2010b), the pump power estimation method developed in Wu et al. (2011) is used to estimate the maximum pump capacity and the annual energy consumption (AEC) in kWh for calculation of operating costs and emissions. For further details regarding the objective function evaluation process, refer to Wu et al. (2010b) and Wu et al. (2011).

Factors considered in sensitivity analysis

In this study, three options for each of the two factors are considered based on uncertainties or possible government strategies into the future. The assumptions for the two factors are based on Australia, and presented in the following two subsections and are for illustration purposes only. However, the methodology presented here is generally applicable to other locations by using local conditions. At the end of this section, the two optimization scenarios considered in the sensitivity analysis are summarized.

Electricity tariffs

The average electricity tariffs (prices) in the retail market in Australia are determined by both wholesale prices and contract market prices (Electricity Industry Supply Planning Council, 2005). The average electricity wholesale prices have been relatively constant since the introduction of the National Electricity Market in 1998, but have increased significantly after 2007 due to high demand and tight supply (Australian Bureau of Agricultural and Resource Economics, 2008). In contrast, the electricity prices in the contract market are difficult to predict. Saddler et al. (2004) suggested that in 30 years time, brown and black coal will still be the main sources of electricity in Australia and that the prices of electricity generated by all fossil fuels will be significantly higher. Therefore, three future electricity tariff options are assumed in this study, as shown in Figure 2. For these options, electricity tariffs are assumed to average $0.14 per kWh at year one, which is estimated by averaging on-peak and off-peak values, and to increase at e=+1.5% per annum (pa) (option 1), e=+3% pa (option 2) and e=+4% pa (option 3), respectively.

Electricity generation

In this paper, the impact of electricity generation on GHG emissions is considered via the use of emission factors, which are the kilograms of CO_2-e (carbon dioxide equivalent) emitted per kWh electricity purchased by end electricity users (The Department of Climate Change, 2008). The value of emission factors depends on the mix of the sources of electricity, such as combustion of fossil fuel, nuclear energy, solar energy or hydroelectric energy, and may change over time and across regions. In this paper an annual average value is used for the sensitivity analysis. This average value is considered to change over time resulting from changes in the mix of energy sources due to a government's response to global warming, for example. The UN Intergovernmental Panel on Climate Change (IPCC) advises developed countries to cut their carbon emissions by 25–40% of 1990 levels by 2020 to avoid catastrophic impacts due to climate change. The Federal Government of Australia has committed to carbon reduction by reducing carbon emissions by at least 5% of 2000 levels by 2020 (The Department of Climate Change, 2010). A linear interpolation of this target will result in over 25% reduction of carbon emissions of 2007 levels in 100 years. However, it is difficult to project long term emission factor values. Consequently, three hypothetical options are used in this study based on previous full fuel cycle emission factor values for South Australia (The Department of Climate Change, 2008) and assumptions made in relation to Government policies.

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According to The Department of Climate Change (2008), the emission factor of electricity in South Australia has been decreasing since 2000. However, according to the Australian Bureau of Agricultural and Resource Economics (2008), the generation of electricity in Australia will not be able to transfer into renewable sources quickly within the next 30 years. Consequently, coal, gas and oil are likely to remain the major sources of electricity in Australia. Therefore, the first option is assumed to be a constant emission factor equal to the 2007 value, which is 0.98 kg CO_2-e per kWh (The Department of Climate Change, 2008). This option is mainly used as a baseline option for comparison purposes. The second option is based on the assumption that the Australian Government is able to reduce GHG emissions by at least 5% below 2000 levels by 2020 (The Department of Climate Change, 2010); as a result, the emission factor will reduce by em=-30% (to 70% of 2007 levels) by the year 2106 (100 years from 2007). The third option is based on the assumption that the Australian Government is committed to reinforcing tough GHG reduction policies and therefore, the emissions from electricity production will be reduced by em=-60% (to 40% of 2007 levels) in a 100 year period. For both options 2 and 3, a linear reduction is assumed, as shown in Figure 3.

Optimization scenarios and combinations of factors considered

In order to test the sensitivity of the optimization results to the two factors described above, two optimization scenarios, each dedicated to one of the factors, are considered. In each of the two optimization scenarios, one factor is varied and the remaining factor is set at the moderate value of the three options considered (e.g. option 2 for electricity tariff (e=+3% pa) and emission factor (em=-30% by year 100)). This leads to a total of five combinations of the two factors, which are shown in Table 1.

Multiobjective genetic algorithm optimization

In this study, a multiobjective genetic algorithm called WSMGA (Water System Multiobjective Genetic Algorithm) (Wu et al., 2010b) is used to solve the multiobjective WDS optimization problem. In WSMGA, an integer coding scheme is used to account for the discrete decision variables (pipe sizes), the EPANET2 hydraulic solver is used to simulate network behavior, and a pump power estimation method developed by Wu et al. (2011) is used to estimate the maximum pump capacity and energy consumption for each solution network. For details of the solution evaluation process incorporating the pump power estimation method, refer to Wu et al. (2011). Details of the GA parameters settings are given in Wu et al. (2010a, b).

Sensitivity analysis results

The results from the multiobjective GA runs for each of the combination of factors investigated (see Table 1) are plotted in Figure 4. Each plot in Figure 4 shows the optimization results from one optimization scenario (each including three factor combinations) (see Table 1). The network configurations of four typical optimal designs from the Pareto-optimal fronts presented in Figure 4 are summarized in Table 2. The selected designs are sorted according to total pipeline cost, which is a function of the sizes of the pipes selected: the higher the design number, the more expensive the pipeline. The numbers next to the solution points in Figure 4 correspond to the design numbers in

Table 2. In addition, the breakdown of the total cost and emissions of these solutions is summarized in Table 3. Detailed results from the sensitivity analysis are presented in the following two subsections.

Impact of electricity tariff

The electricity tariff used has an impact on the total cost of the network. Table 3 shows that a more rapidly increasing electricity tariff (e.g. e = +4.0%) into the future will increase operating costs considerably, which in turn increases total costs as shown in Figure 4(a). In addition, electricity tariff may also alter the solutions on the optimal front. Figure 4(a) shows that a higher electricity cost into the future removes some networks with higher GHG emissions from the optimal front. Design 1 is one such example. However, the three different electricity tariff options considered lead to networks with similar configurations and GHG emissions within a similar range (105 to 120 kilotonnes). In addition, for the same network configuration, the electricity tariff option selected has no impact on the total GHG emissions of the network, as shown in Table 3.

Impact of electricity generation

The emission factor appears to have little impact on the configuration of the selected optimal networks, as similar solutions within the same cost range are obtained using the different emission factor options (Figure 4(b)). In addition, the emission factor used has no impact on total network cost. Table 3 shows that the same pipe configuration has the same pipe cost, pump station cost and operating cost, irrespective of which emission factor option is used.

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In contrast, the emission factor has a significant impact on the total GHG emissions from the system over the design period. It can be seen from Figure 4(b) and Table 3 that a gradual reduction in the emission factor to 40% of the year zero level in year 100 (em = -60%) could reduce the total GHG emissions from WDSs by more than 23%. This is because the gradual 60% decrease in emission factor in 100 years reduces the operating emissions by around 30%, as shown in Table 3. The 30% gradual reduction in emission factors (em = -30%) over 100 years can reduce the total GHG emissions of the system by 14% and reduce the operating emissions of the system by almost 18%.

Discussion

The results obtained indicate that changes in electricity tariffs into the future can change the composition of the total cost significantly, which also alters the tradeoffs between the two objectives and results in different final optimal solutions. In contrast, as the reduction in emission factors into the future occurs more gently, the primary impact is to scale down the total emissions of the optimal solutions. In addition, the selection of the design life may also have an impact on the optimization results. A shorter design horizon, such as 50 years or shorter, will reduce future impact of WDSs (represented by operating costs and emissions). This may reduce the tradeoffs between the two objectives, which will favor networks with smaller capital costs but higher GHG emissions. However, a long design horizon, such as 100 years, makes accurate projection of electricity tariffs and emission factors into the future difficult due to high levels of uncertainties.

It should be noted that the case study considered is a water transmission network, which are relatively simple compared with water distribution networks, which often have hundreds of pipes. However, it is likely that the impact of electricity tariffs and emission factors on the objective function evaluation process and final optimization results obtained for the case study considered in this paper can be generalized to WDS. In addition, the approach presented in this study is general and can be applied to both water transmission networks and water distribution networks with varying complexity.

Summary and conclusions

In this paper, the sensitivity of the optimal tradeoffs between cost and GHG emissions to electricity tariff and generation are assessed for a case study water transmission network. As part of the sensitivity analysis, two optimization scenarios, including five combinations of the two factors investigated, were considered.

The optimization results show that electricity tariffs have a significant impact on the total cost of WDSs, but little impact on the total GHG emissions from a particular network. However, higher electricity tariffs into the future can remove networks with higher emissions from the Pareto-optimal front, which potentially leads to a final WDS with lower GHG emissions. This indicates that GHG emissions from WDSs can be further reduced by managing the water and energy industries jointly. In contrast, emission factors have no direct impact on the total cost of WDSs. However, emission factors into the future have a significant impact on the total GHG emissions that will be generated by the system. A 60% gradual reduction of emission factor during a 100 year period can reduce the operating GHG emissions of the system by 30% and the total emissions by over 23%.

Acknowledgements

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Figure 1 Case study network configuration (adapted from Wu et al. (2010a))

Figure 2 Three electricity tariff options considered over 100 years (e = electricity tariff change per annum)

Figure 3 Three emission factor options considered over 100 years (em = total emissions reduction over 100 years)

Figure 4 Optimization results from the two scenarios (all optimal designs with same numbers in both plots have exactly the same pipe configurations)

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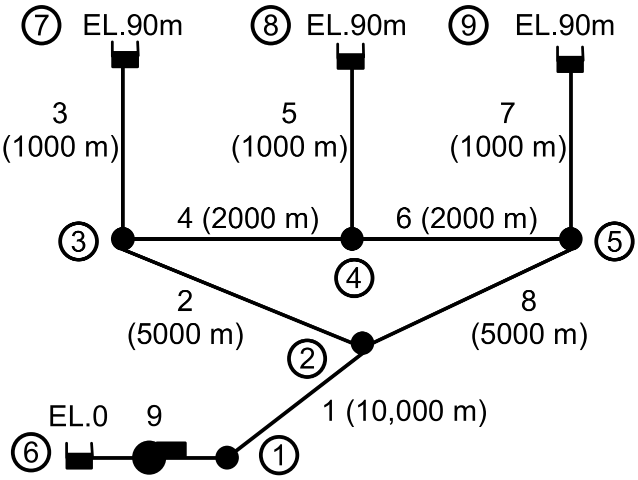

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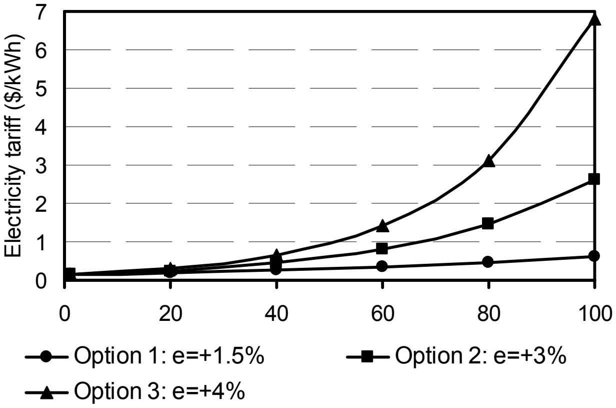

Figure 2 Three electricity tariff options considered over 100 years (e = electricity tariff change per annum)

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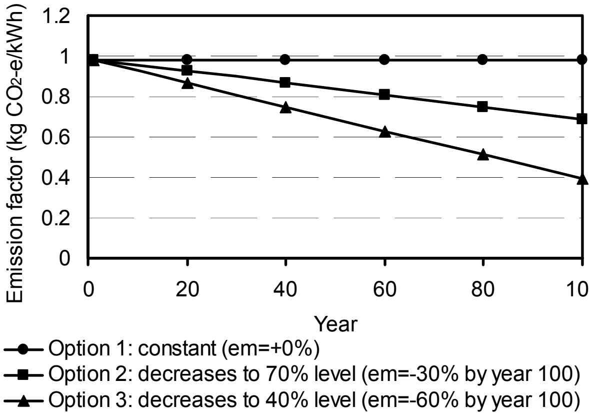

Figure 3 Three emission factor options considered over 100 years (em = total emissions reduction over 100 years)

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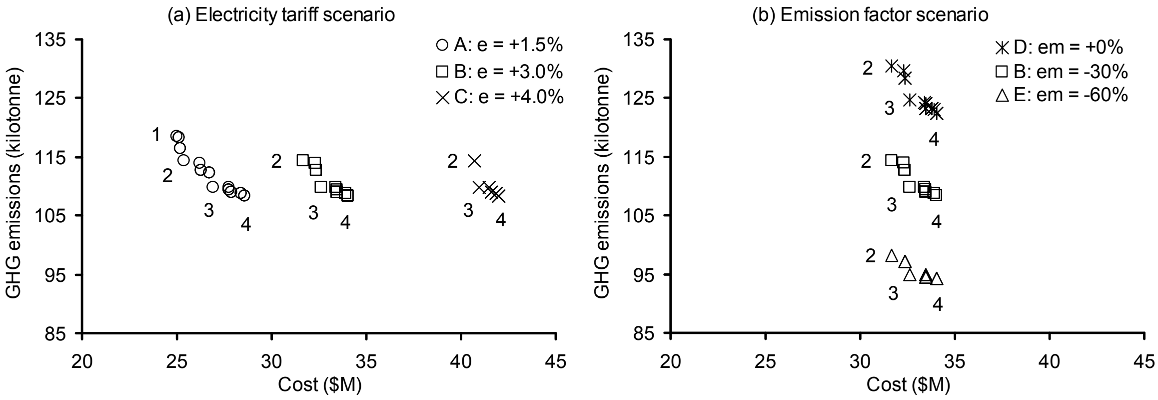

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Table 1 Optimization scenarios and combinations of factors investigated as part of the sensitivity analysis

Optimization scenario	Factor combination	Electricity tariff option (e value)	Emission factor option (em value)
Electricity tariff (e)	A	**1 (+1.5%)**	2 (-30%)
	B	**2 (+3.0%)**	2 (-30%)
	C	**3 (+4.0%)**	2 (-30%)
Emission factor (em)	D	2 (+3.0%)	**1 (+0%)**
	B	2 (+3.0%)	**2 (-30%)**
	E	2 (+3.0%)	**3 (-60%)**

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Table 2 Pipe information of the six typical Pareto-optimal designs

Design number	Pipe diameters (m)								Pipe cost ($M)
	Pipe 1	Pipe 2	Pipe 3	Pipe 4	Pipe 5	Pipe 6	Pipe 7	Pipe 8	
1	375	225	225	100[a]	225	300	225	300	16.0
2	375	300	225	225	300	225	225	300	17.0
3	450	300	225	225	300	225	225	300	19.2
4	450	300	300	100[a]	375	375	300	375	21.3

[a] The designs with the 100 mm pipe are not necessarily suitable solutions when considering network reliability.

Table 3 Breakdown of total cost and GHG emissions of the selected solutions obtained from the two optimization scenarios (e = electricity tariff increase per annum and em = emission factor change over 100 years)

Optimization scenario	Factor combination	Design number	Pip cost ($M)	Pump station cost ($M)	Operating cost ($M)	Total cost ($M)	Pipe GHG (kt)	Operating GHG (kt)	Total GHG (kt)
Electricity tariff scenario (em=-30%)	A (e=+1.5%)	1	16.0	1.4	7.6	25.0	21	97	118
		2	17.0	1.3	7.1	25.4	23	91	114
		3	19.2	1.2	6.5	26.9	26	84	110
		4	21.3	1.1	6.2	28.6	28	80	108
	B (e=+3.0%)	2	17.0	1.3	13.4	31.6	23	91	114
		3	19.2	1.2	12.3	32.6	26	84	110
		4	21.3	1.1	11.7	34.1	28	80	108
	C (e=+4.0%)	2	17.0	1.3	22.4	40.7	23	91	114
		3	19.2	1.2	20.6	40.9	26	84	110
		4	21.3	1.1	19.6	42.0	28	80	108
Emission factor scenario (e=+3.0%)	D (em=+0%)	2	17.0	1.3	13.4	31.6	23	107	130
		3	19.2	1.2	12.3	32.6	26	99	125
		4	21.3	1.1	11.7	34.1	28	94	122
	B (em=-30%)	2	17.0	1.3	13.4	31.6	23	91	114
		3	19.2	1.2	12.3	32.6	26	84	110
		4	21.3	1.1	11.7	34.1	28	80	108
	E (em=-60%)	2	17.0	1.3	13.4	31.6	23	75	98
		3	19.2	1.2	12.3	32.6	26	69	95
		4	21.3	1.1	11.7	34.1	28	66	94