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WATER DISTRIBUTION SYSTEM DESIGN WITH BEHIND-THE-METER SOLAR ENERGY UNDER VARIOUS DISCOUNT RATES

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Abstract

Water distribution systems (WDSs) are essential parts of urban and rural infrastructure systems. The energy consumption including associated costs and GHG emissions for distributing water has increased in recent years. As a result, behind-the-meter (BTM) energy systems such as solar panels and energy storage facilities have been installed by water utilities to reduce energy consumption from the centralised energy grid. There has been a lot of research on the optimisation of the design of WDSs, however, many of these works have not considered BTM energy options or have incorporated BTM energy options in an ad-hoc fashion. Therefore, this study is proposed to optimise the design of WDSs considering BTM solar energy sources. A pressurised irrigation supply system in Victoria, Australia has been used as the case study system. In this paper, the design of a real-world WDS has been formulated as a multi-objective optimisation problem to investigate the trade-offs between the total life cycle cost and total life cycle greenhouse gas (GHG) emissions under various discount rates scenarios used to estimate the operational cost and emissions throughout the service life of the system. It has been found that both the total life cycle cost and GHG emissions have been reduced significantly when BTM solar energy is incorporated. In addition, with the same solar photovoltaic (PV) size, the optimal pipe diameters, as well as the objective function values are sensitive to the discount rate values that have been used.

Keywords
Water distribution systems (WDSs), design, optimisation, pipe sizing, behind-the-meter energy, solar PV.

1 INTRODUCTION

Water distribution systems (WDSs) are essential parts of urban and agricultural infrastructure systems. The energy consumption including associated costs and GHG emissions for distributing water has increased worldwide in recent years due to the rise in water demand resulting from population growth. Therefore, it has been considered by water utilities to optimise the system and find alternative energy solutions, in order to achieve economic and environmental benefits, and promote sustainable development at the same time. In addition, technological development has also contributed to the increased consideration of renewable energy applications, such as on-site renewable energy generation and storage (i.e. "behind-the-meter" (BTM) energy systems). As a result, energy consumption from the centralised energy supply grid and associated GHG emissions can be further reduced.

WDSs are topologically and dimensionally complicated systems, which consist of a range of interconnected components [1]. The optimal design of WDSs commonly involves choosing the best combination of system components (e.g. pipes, pumps and storages) and their sizes and locations to achieve a minimum total life cycle cost [2]. Some other studies have also minimised the GHG emissions simultaneously with multi-objective optimisation approaches [3, 4].

Renewable energy sources in developing BTM energy solutions have been widely considered to either supplement or replace the traditional energy supply [5] in recent years. Among the existing renewable energy sources, solar energy is commonly considered in WDSs [6, 7]. The use of photovoltaic (PV) conversion of solar energy to supply energy to WDSs can significantly reduce the consumption from the electricity grid, and the associated GHG emissions [8], particularly for pumping. Also, in comparison with other forms of renewable energy sources, solar energy supply is more likely to be "behind-the-meter" considering the size and flexibility of the system. Nevertheless, many of the existing studies looking for optimal design and operation solutions for WDSs have not included BTM energy options in the optimisation process.

Considering the complexity, as well as the large costs associated with the life cycle of WDSs, optimisation tools are often used to assist the design of these systems [9, 10]. Deterministic (or classic) and metaheuristic algorithms are two common categories of optimisation techniques used for WDS design optimisation. In comparison with deterministic optimisation methods, metaheuristic algorithms such as Evolutionary Algorithms (EAs), have been found to perform better in solving more complex problems with more decision variables and constraints [11]. Even though they are often associated with a larger computational cost, they have a higher probability of finding optimal or near-optimal solutions due to the exploratory nature of metaheuristics [12].

In this paper, a multi-objective optimisation problem has been formulated to investigate the impact of BTM solar energy on the design of WDSs, considering various discount rates. A fully pipelined irrigation supply system in Victoria, Australia has been chosen as the case study system. Both economic and environmental objectives have been optimised over the system design life.

2 CASE STUDY SYSTEM

The case study system is a pressurised irrigation system located in the Robinvale irrigation district in north-western Victoria, Australia, as shown in Figure 1. A high-pressure pump station on the south bank of the Murray River pumps water from the river throughout the pipeline system to customers for irrigation and domestic water use. Table grapes are mainly planted in this area [13] and they need a large amount of water for irrigation. There are 433 pipes and 244 irrigation outlets in the network. The minimum pressure head required at users' outlets is 35 m. The layout of the network is shown in Figure 2. Pipes diameters considering BTM solar energy are optimised in this study, assuming the locations of pipes are the same as the existing system. Relevant data has been provided by the local water authority Lower Murray Water (LMW). An EPANET model is used as the simulation model for the system [14].

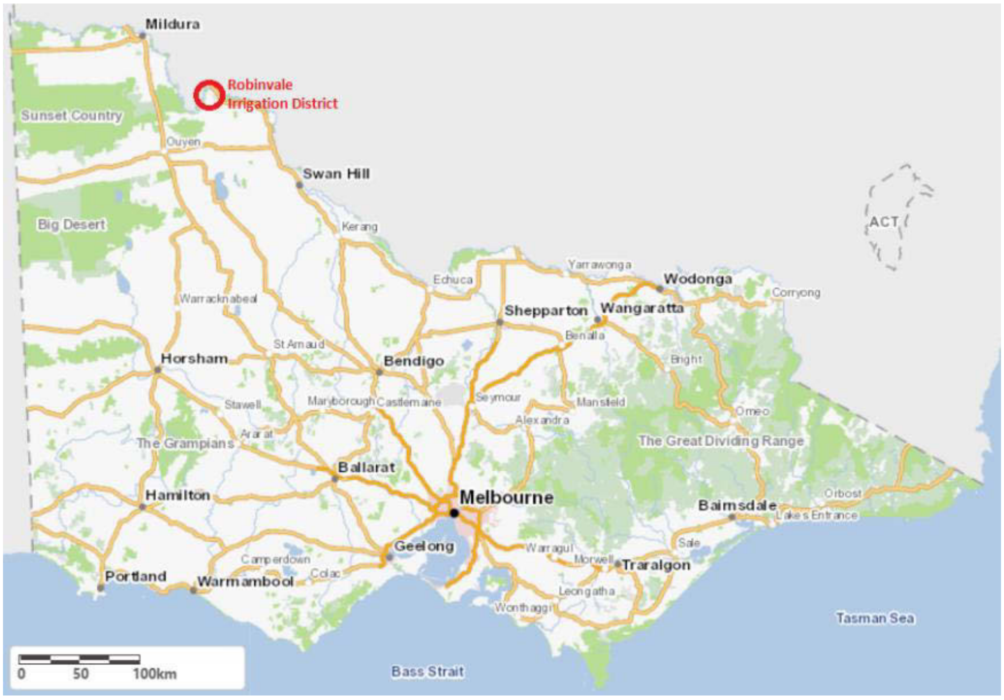

Figure 1. Location of the study area (in red) within the state of Victoria, Australia

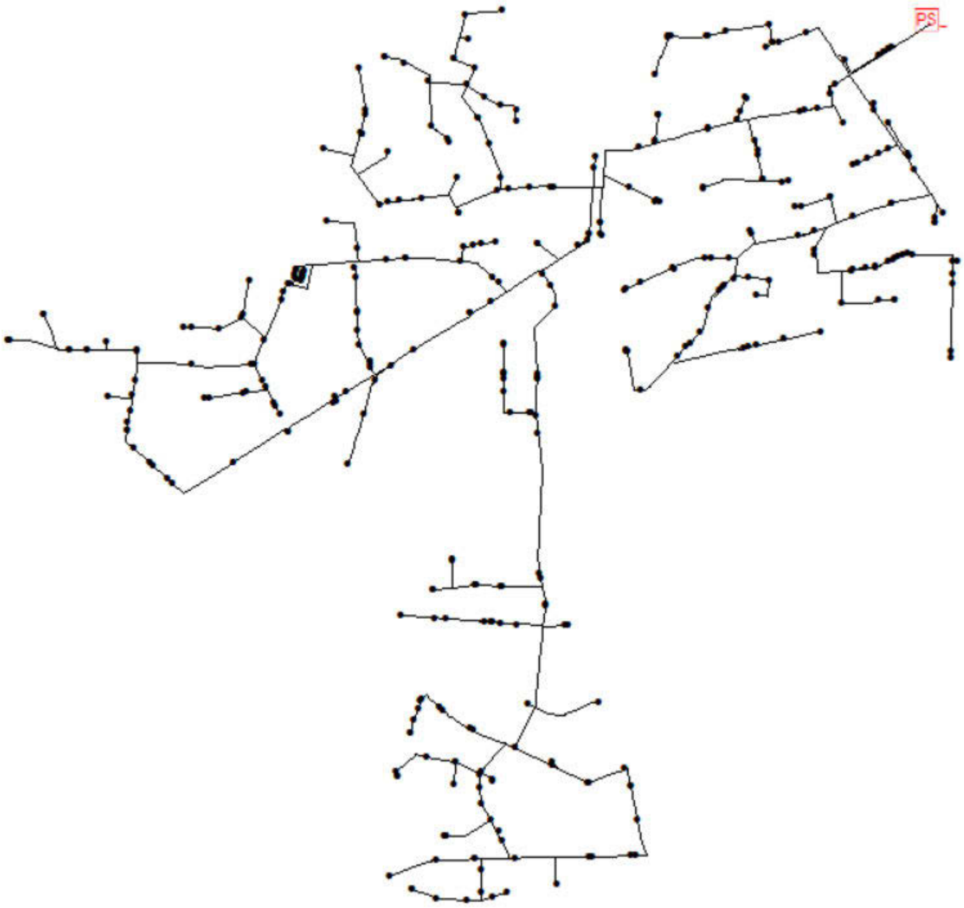

Figure 2. Case study system – a pressurised irrigation system in Robinvale, Victoria, Australia

3 METHODS

3.1 Problem formulation

In this study, a multi-objective optimisation problem has been formulated to minimise total life cycle cost and total life cycle GHG emissions from the case study system. Decision variables are pipe diameters. To improve optimisation efficiency, the 433 pipes in the network have been grouped into 10 decision variables based on energy requirements computed within the network. A minimum pressure head of 50 m (35 m minimum service pressure + head loss of 15 m caused by control valves before the outlet) is used at each node in the EPANET model as the inequality constraint. The algorithm NSGA-II [15] is used in a Python-based optimisation package 'pymoo' [16], with a Python wrapper [17] installed to call functions in EPANET Programmer's Toolkit [18].

Different scenarios have been considered to investigate the impact of solar PV sizes on the optimal design of WDSs. The minimisation of the two objective functions with the incorporation of 0 MW (no solar), 1 MW, 2 MW, 3 MW, 4 MW and 5 MW solar PV has been investigated. A social discount rate of 1.4% [19] is considered initially. The analysis includes the comparison of different Pareto fronts between the six cases of solar PV sizes, trade-off analysis under a specific case (e.g. 5 MW), as well as the comparison of costs and GHG emissions under the 0 MW (no solar) and 5 MW solar case. In addition, other two discount rates (0% and 6%) have been considered to investigate their impact on the optimisation results. The population size and the number of generations for the multi-objective genetic algorithm optimisation runs are both 100 for all optimisation runs.

3.2 Objective Function 1 - Costs

The first objective function (OF1) is to minimise the total life cycle cost, which is given by

$$min\, OF1:\ LCC = CC + OC + PRC + SRC \tag{1}$$

where LCC, CC, OC, PRC and SRC = the total life cycle cost, capital costs, operating costs, pump and solar panel replacement costs respectively. The system is assumed to have the same design life as pipes of 100 years [20]. The capital costs mainly involve purchasing and constructing pipes, pumps and solar panels. The operating costs mainly include spending on electricity purchased from the grid when the energy required is greater than the solar energy production. Pumps and solar panels need to be replaced regularly within 100 years to maintain their performance. Present value analysis (PVA) has been conducted for operating costs, as well as pump and solar PV replacement costs.

Capital cost

The capital cost is given by

$$CC = PiC + PSC + SPC \tag{2}$$

where PiC, PSC and SPC = the capital cost for pipes, the pump station and solar panels. Unit costs of pipes and pumps were sourced from the Department of Primary Industries [21]. A total of 4 different materials and 31 pipe diameters commercially available with corresponding unit costs have been included in the choice table. Pipe lengths were assumed to be the same as the existing system. The capital cost of the pump station has been estimated according to the total power of pumps needed. Average commercial solar panel prices in Victoria as well as solar panel sizes have been taken into account to calculate the solar system capital cost.

Operating cost

The present value (PV) of ongoing electricity operating cost is given below

$$PV(OC) = OC_a\,[\frac{(1+i)^k - 1}{i(1+i)^k}] \tag{3}$$

where i = selected discount rate, OC_a = the annual operating cost (assumed to be unchanged over the design life k = 100 years) which is given as

$$OC_a = \sum_{i=1}^{365} \left(\sum_{t=1}^{T} c_t \times IE_t\right)_i \tag{4}$$

where c_t = electricity tariff at time t, IE_t = the energy imported from the electrical grid at time t, which is given as

$$IE_t = (PowerP_t - PowerS_t) \times \Delta t \tag{5}$$

where $PowerP_t$ is the power required for pumping at time t, considering the required flow, pumping head as well as an assumed motor efficiency of pumps; $PowerS_t$ is the power of solar generation at time t. Excess energy will be fed back to the grid when the solar system generates more energy than that needed for pumping. Pump motor efficiency is assumed to be 95%. The solar system is assumed to be able to generate 3.6 kWh of electricity when 1 kW of a solar panel is installed [22].

Pump & solar panel replacement cost

It has been assumed that pump sets and solar panels have a service life of 20 [20] and 25 years [23], respectively. The present value (PV) of pump and solar panel replacement cost is given by

$$PV(PRC) = PuC\,[\frac{1-(1+i)^{(s-k)}}{(1+i)^s - 1}] \tag{6}$$

$$PV(SRC) = SPC\,[\frac{1-(1+i)^{(t-k)}}{(1+i)^t - 1}] \tag{7}$$

where PuC, SPC = capital costs of pumps and solar panels, respectively; k, s and t = 100, 20 and 25 years, namely the service life of the whole system, pumps and solar panels, respectively.

3.3 Objective Function 2 - GHGs

The second objective function (OF2) is to minimise the total life cycle GHG emissions, which is given as

$$min\,OF2\colon\ LCGHG = CGHG + OGHG \tag{8}$$

where $LCGHG$, $CGHG$ and $OGHG$ = the total life cycle, capital and the operating GHG emissions, respectively. Capital GHG emissions are mainly from the process of manufacturing pipes and solar panels. Operating GHG emissions are mainly from consuming electricity imported from the grid (assumed to be drawn from a certain proportion of fossil fuel sources) when solar production is insufficient. The present value analysis is also required to deal with the operating GHG emissions during the entire 100-year life of the system.

Capital GHG emissions

The capital GHG emissions are given as

$$CGHG = (PiEE + SPEE) \times EF \tag{9}$$

where $PiEE$ and $SPEE$ = the embodied energy for manufacturing pipes and solar panels, respectively; EF = the emission factor. Embodied energy coefficients based on pipe materials and the pipe masses based on pipe lengths and unit weights are used to calculate the embodied energy of pipes. Solar panels are assumed to need the embodied energy of approximately 3700 kWh for producing 1 kW capacity of energy generation [24]. An emission factor of 1.09 kg CO_2-e/kWh has been used, as suggested by the Department of Industry Science Energy and Resources [25].

Operating GHG emissions

The present value (PV) of ongoing operating GHG emissions is given by

$$PV(OGHG) = OGHG_a\left[\frac{(1+i)^k - 1}{i(1+i)^k}\right] \quad (10)$$

where $OGHG_a$ = the annual operating GHG emissions, which are given as

$$OGHG_a = \sum_{i=1}^{365} \left(\sum_{t=1}^{T} IE_t\right)_i \times EF \quad (11)$$

where IE_t = the electricity energy purchased from the grid at time t; EF = the emission factor as above.

4 RESULTS AND DISCUSSION

4.1 Impact of solar panel sizes on optimisation results

As shown in Figure 3, for all six sizes of solar PV considered, trade-offs between the two objective functions have been observed when a 1.4% social discount is used. With an increase of solar PV sizes from top right to bottom left in Figure 3, both objectives have significantly decreased. As indicated in Table 1, the minimum total life cycle cost has decreased by approximately 20% from \$208M to \$167M, with the increase of solar PV size from 0 to 5 MW. Similarly, the minimum total life cycle GHG emissions have been reduced by about 59% from the 0 to 5 MW solar option. Therefore, the consideration of BTM solar PV can bring long-term benefits to the system economically and environmentally.

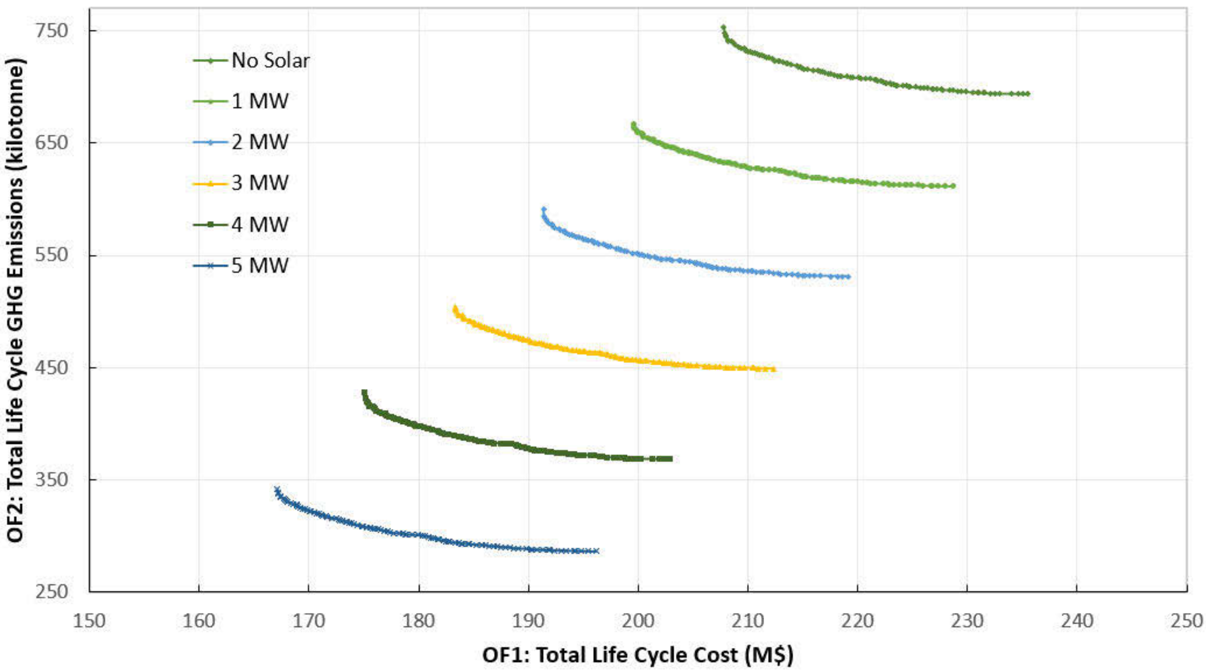

Figure 3. Pareto fronts with 0 MW (no solar), 1 MW, 2 MW, 3 MW, 4 MW and 5 MW solar PV installed (1.4% discount rate)

Table 1. Comparison of minimum objective function values with different sizes of solar PV incorporated (1.4% discount rate)

Solar PV size	0 MW	1 MW	2 MW	3 MW	4 MW	5 MW
Min. LCC (M$)	208	200	191	183	175	167
Min. LCGHG (kt)	694	612	531	449	368	286

A breakdown of costs and GHG emissions for both the least-cost and the least-GHG solutions under the 3 MW solar option as an example is demonstrated in Table 2 and Table 3. In total life cycle costs, the capital cost especially for purchasing and installing pipes represents more than half of the total amount. The operating costs over the 100 years take the second largest percentage. In total life cycle GHG emissions, the operating GHG emissions are much higher than the capital GHG emissions.

Table 2. Breakdown of total life cycle cost for the 3 MW solar option (1.4% discount rate)

<table>
<tr><th colspan="4">Breakdown of LCC (M$)</th><th>Total (M$)</th><th>% of LCC</th></tr>
<tr><td rowspan="6">Total life cycle cost: 183</td><td rowspan="3">Total capital cost</td><td>Pipe cost</td><td>75</td><td rowspan="3">93</td><td rowspan="3">51%</td></tr>
<tr><td>Solar PV cost</td><td>3</td></tr>
<tr><td>Pump station cost</td><td>14</td></tr>
<tr><td colspan="3">Total pump replacement cost over 100 years</td><td>24</td><td>13%</td></tr>
<tr><td colspan="3">Total solar replacement cost over 100 years</td><td>5</td><td>3%</td></tr>
<tr><td colspan="3">Total operating cost over 100 years</td><td>62</td><td>34%</td></tr>
</table>

Table 3. Breakdown of total life cycle GHG emissions for the 3 MW solar option (1.4% discount rate)

Breakdown of LCGHG		Total (kt)	% of LCGHG
Total life cycle GHG emissions (kt): 449	Total capital GHG emissions	91	20%
	Total operating GHG emissions over 100 years	358	80%

Details of the Pareto front obtained from the 0 MW (no solar) option are demonstrated in Figure 4. Clear trade-offs between two objective function values can be observed. An increase in the total cost can reduce GHG emissions and vice versa. A total of 100 optimal solutions have been found along the Pareto front. The least-emission solution has the smallest GHG emissions of 694 kt but the largest cost of $236M. The least-cost solution has the smallest cost of $208M but the largest emissions of 754 kt. As shown in Figure 4, five sample solutions A to E have been chosen for further analysis, including the two points at two ends of the Pareto front. Also, the cost needed to achieve one tonne of GHG reduction between sample points has been calculated. With the decrease of GHG emissions along the Pareto front from top left to bottom right, the cost to reduce 1 tonne of GHG emission increases from $105/tonne to $2,081/tonne of carbon dioxide equivalent (CO_2-e). Further, the detailed Pareto front obtained from the 5 MW solar option is shown in Figure 5. The same calculation steps as above have been applied to this option. It has been observed that the 5 MW solar option needs a slightly higher cost for GHG reduction between every two sample solutions from A through to E, in comparison with the no solar option in Figure 4.

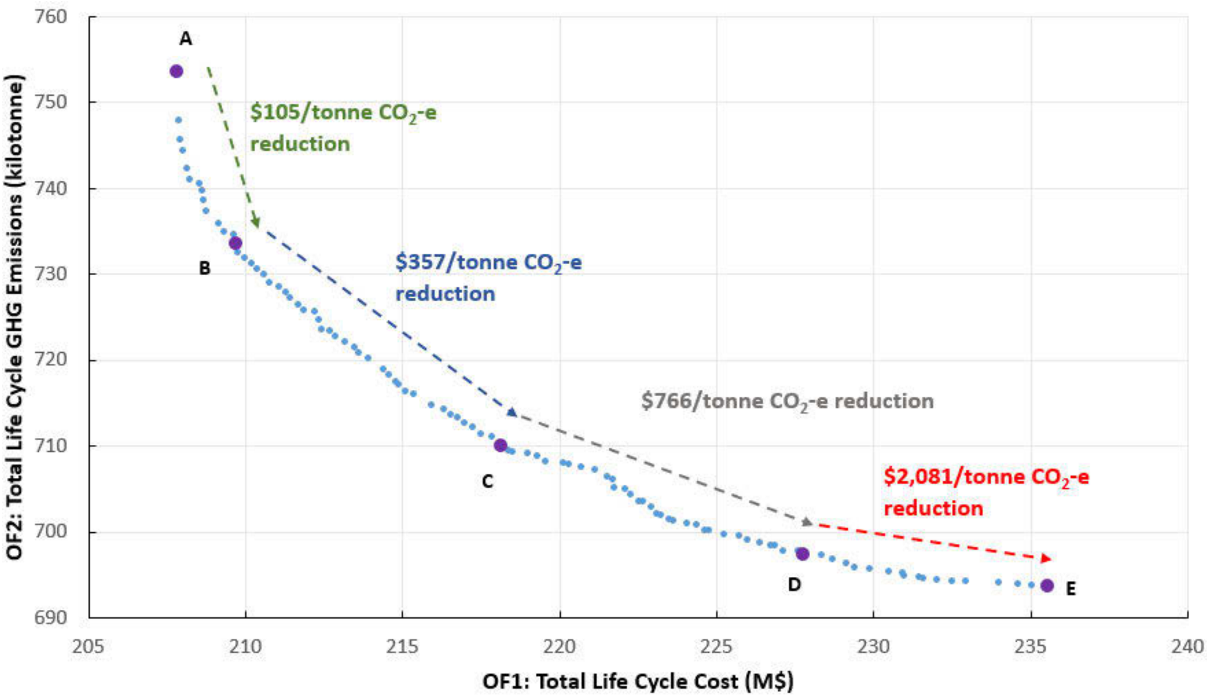

Figure 4. Details of Pareto front under 0 MW (no solar) option (1.4% discount rate)

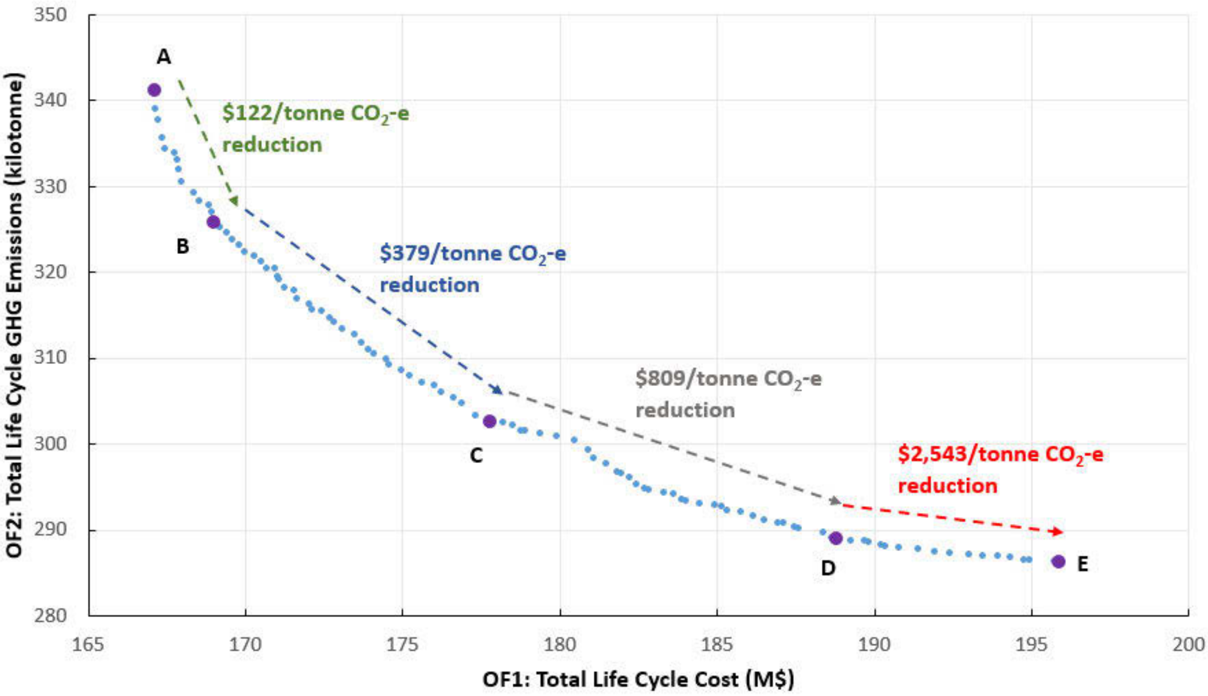

Figure 5. Details of Pareto front under 5 MW solar option (1.4% discount rate)

Further comparison between the 0 MW (no solar) and 5 MW solar options is shown in Table 4. The total life cycle cost has decreased by more than 15% for all five sample solutions after installing 5 MW solar. Also, the total life cycle GHG emissions under the 5 MW solar option have been reduced to less than half of the 0 MW (no solar) option.

Table 4. Comparison of objective function values of the five typical solutions for the 0 MW and 5 MW solar options (1.4% discount rate)

Sample solution	**Total Life Cycle Cost (M$)**			**Total Life Cycle GHG Emissions (kilotonne)**		
	0 MW solar	**5 MW solar**	Change in %	**0 MW solar**	**5 MW solar**	Change in %
A	208	167	20%	754	341	55%
B	210	169	19%	734	326	56%
C	218	178	19%	710	303	57%
D	228	189	17%	697	289	59%
E	236	196	17%	694	286	59%

4.2 Impact of discount rate on optimisation results

Other discount rates have also been considered to investigate the impact of varying the discount rate on the two objective function values. The optimisation process for each scenario has been repeated considering the other two different discount rates: 0% and 6%. The comparison of Pareto fronts among various discount rates of 0%, 1.4% and 6% under the same size of solar PV is shown in Figure 6, Figure 7 and Figure 8. It can be observed from the trend that with the increase of discount rates from 0% to 6%, both objective function values have decreased for all sizes of solar PV incorporated.

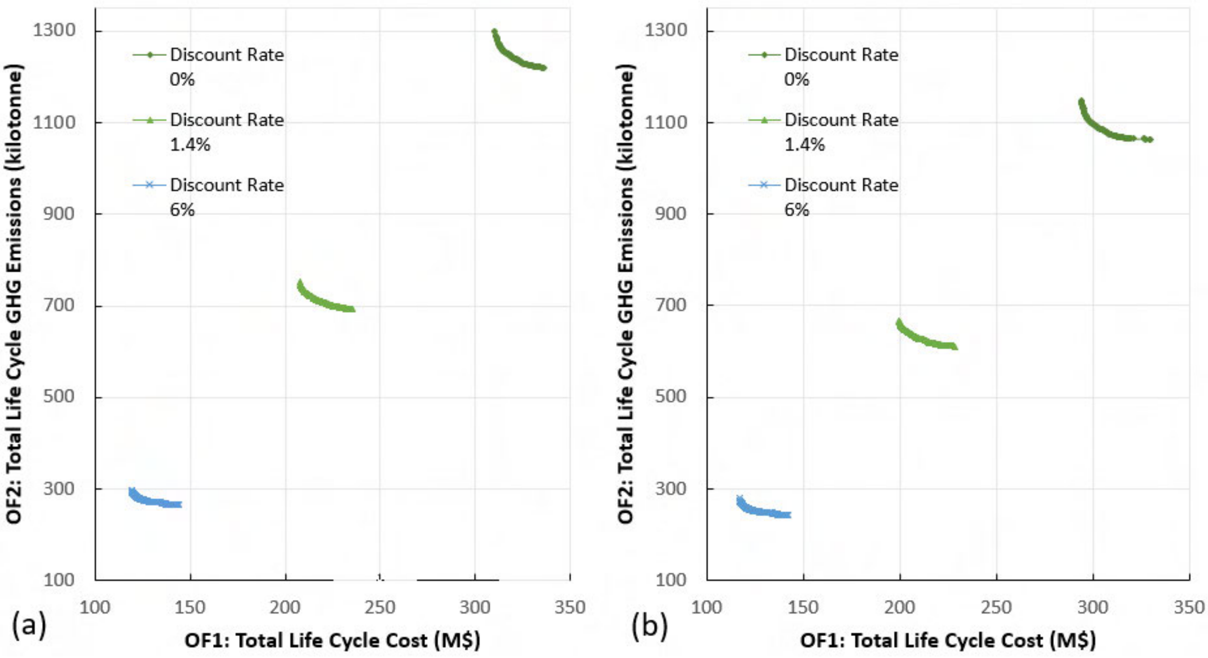

Figure 6. Pareto fronts with variation of discount rates (0%, 1.4% and 6%): (a) no solar; (b) 1 MW solar

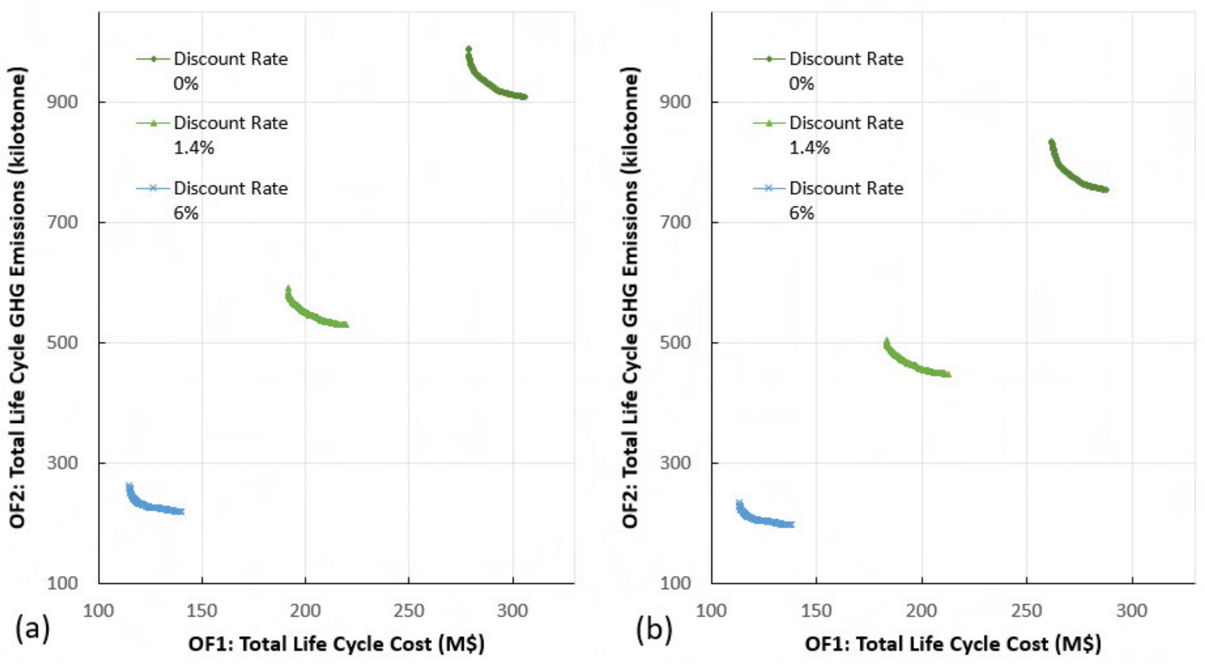

Figure 7. Pareto fronts with variation of discount rates (0%, 1.4% and 6%): (a) 2 MW solar; (b) 3 MW solar

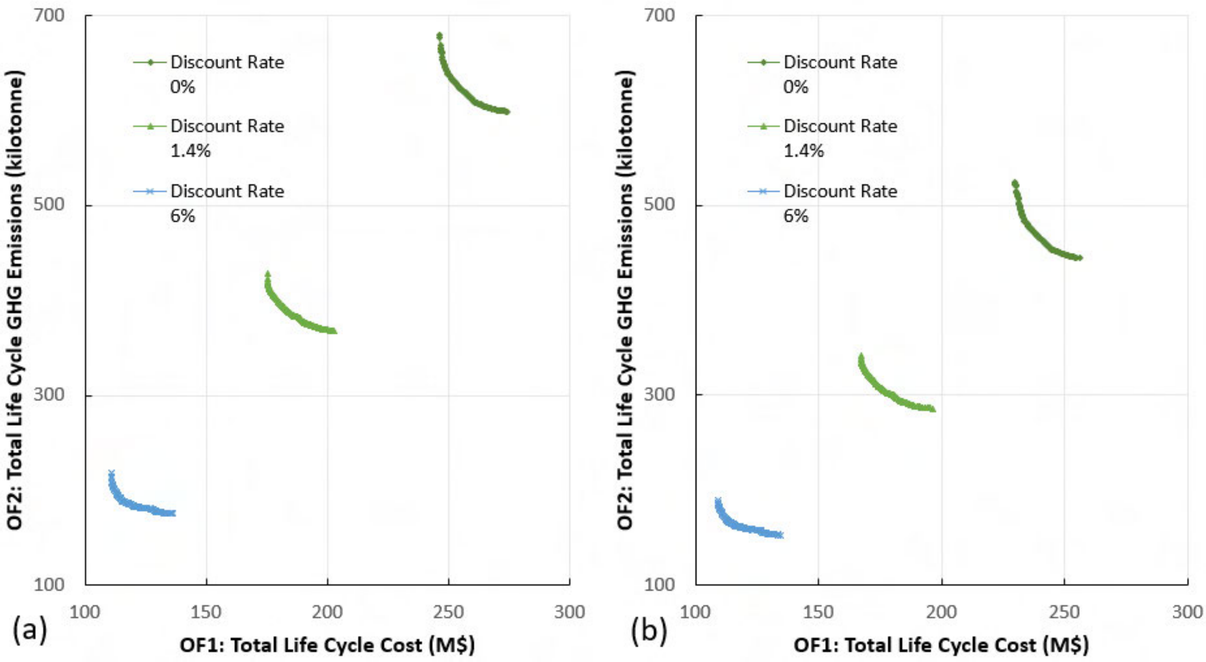

Figure 8. Pareto fronts with variation of discount rates (0%, 1.4% and 6%): (a) 4 MW solar; (b) 5 MW solar

In Table 3 below, d1 to d10 are the optimal pipe diameters obtained for the three discount rates. The total life cycle costs and GHG emissions under different discount rates are shown in Table 4. It can be observed from the results that the optimal pipe diameters (and pipe costs), total life cycle costs and GHG emissions are sensitive to the variation of the discount rate, under the same solar PV size. The increase in the discount rate can lead to smaller pipe diameters (and pipe costs) and less total life cycle costs and GHG emissions, as shown in Table 3 and Table 4.

Table 3. Comparison of optimal pipe diameters and total pipe costs of the least-cost solution for three different discount rates (5 MW solar)

Discount Rate	**d1 (mm)**	**d2 (mm)**	**d3 (mm)**	**d4 (mm)**	**d5 (mm)**	**d6 (mm)**	**d7 (mm)**	**d8 (mm)**	**d9 (mm)**	**d10 (mm)**	**Total Pipe Cost (M$)**
0%	226	412	464	464	520	615	894	1,089	1,388	1,587	**81**
1.4%	226	384	412	412	520	615	894	1,089	1,289	1,488	**75**
6%	202	305	384	412	520	520	778	994	1,089	1,289	**63**

Table 4. Comparison of minimum objective function values for three different discount rates (5 MW solar)

Solar PV size	Min. LCC (M$)			Min. LCGHG (kilotonne)		
	0%	1.4%	6%	0%	1.4%	6%
0 MW	310	208	119	1,220	694	265
1 MW	294	200	117	1,064	612	243
2 MW	278	191	115	909	531	220
3 MW	262	183	113	755	449	198
4 MW	246	175	111	599	368	175
5 MW	230	167	109	445	286	153

5 CONCLUSIONS

In this study, the optimal design of WDSs incorporating behind-the-meter (BTM) solar energy sources has been investigated via a real-world pressurised irrigation system. Both the total life cycle economic cost and total life cycle environmental GHGs throughout the design life of the system have been optimised in the design process. The impact of various discount rates on the optimisation results has also been investigated. Results show that both the total life cycle cost and GHG emissions have been significantly reduced when the BTM solar energy is incorporated. In addition, the optimal pipe diameters, total life cycle costs and GHG emissions are sensitive to the discount rate used while the solar PV size remains the same. The increase in the discount rate can lead to smaller pipe diameters and less total life cycle costs and GHG emissions.

6 ACKNOWLEDGEMENT

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