Open Access

Journal of Energy and Power Technology

LIDSEN Publishing Inc.

Research Article

Saving is Losing: Pumping Cost vs. GHG Emissions in Water Distribution Systems

Brian D. Barkdoll *

Michigan Technological University, Houghton, MI, USA; E-Mail: barkdoll@mtu.edu

* **Correspondence:** Brian D. Barkdoll; E-Mail: barkdoll@mtu.edu

Academic Editor: Abdelazim M Negm

Special Issue: Water-Energy Resources Nexus and Their Sustainable Management

Journal of Energy and Power Technology
2023, volume 5, issue 4
doi:10.21926/jept.2304037

Received: May 26, 2023
Accepted: November 16, 2023
Published: November 21, 2023

Abstract

Global climate change has necessitated the reduction of GHG emissions. Water distribution system (WDS) pumping adds to these emissions and, therefore, should be reduced. Under electricity hourly cost tariffs, utilities are incentivized to pump during the nighttime hours. This can have a deleterious effect, however, on GHG emissions. To quantify this effect, a modeling study of twelve real WDSs was performed with an electricity tariff. The systems all had the typical tank-level-based pump controls but also time-based controls. Results show there can be a tradeoff between pumping cost and GHG emissions, depending on the pump schedule. If the pumps are forced to supply demand in a shorter time to take advantage of the lower cost during off-peak hours, then the flowrate must be higher with a concomitant increase in velocity and headloss, thereby adding to the GHG emissions. This effect was not found for all systems, however. Pumping over all the low-cost hours resulted in the pseudo-optimal solution of lowest combination of cost and GHG emissions for many systems. It might be worth it, however, to incur higher costs and reduce GHG emissions, given the severity of climate change occurring around the world.

Keywords

Climate change; public health; sustainable infrastructure; utility operations; water economics

1. Introduction

Climate change has become more serious in recent times with increased drought, flooding, and dangerous heat domes causing increasing property damage and human death [1]. It is therefore increasingly important to reduce greenhouse gas (GHG) emissions [2]. To support these efforts, the United Nations has created a goal of net-zero emissions [3].

Water distribution systems (WDSs) comprise a set of reservoir(s), pump(s), pipes, and storage tank(s) to supply users that reside at various elevations throughout the service area and use varying demands of water throughout the day and night [4]. The pump(s) use electricity to pump water uphill to the users and store water in the tanks until high demand times occur, during which the tanks are emptied. Water and wastewater systems use about 2% of the total US energy use, and 30-40% of the total municipal government energy consumed, thereby emitting 45 million tons of GHGs yearly [5]. The pumps use electricity that may have varying prices from the electric utility throughout the day and night. This is done to even out the electricity demand on the power grid. This electricity tariff may alter the pumping schedule the WDS managers use to save money. A typical electricity tariff may charge a small cost per kilowatt-hour (kWH) during the night, a high cost during the daytime, and a moderate cost during the evening. This is also how users tend to use water as well, thereby making it difficult to decide a good pumping schedule that minimizes both cost and GHG emissions.

There are many issues with tariffs in WDSs. For example:

- use of a system dynamics approach to study water management and user habits under tariffs [6];
- optimization of pump scheduling for operating costs [7];
- optimization of variable-speed pump scheduling for minimizing both cost and leakage [8];
- the optimization of energy efficiency in WDS operations [9];
- the minimization of pumping energy cost in WDS operations [10];
- pumping costs under tariffs [11];
- pumping under high-cost times related to leakage [12];
- tank size effects on cost and GHG emissions and a possible tradeoff between a larger tank size reducing GHG emissions and higher costs [13];
- software for minimizing cost and GHG emissions using a set of pump schedules [14];
- use of probabilistic assessment of impact of flexible loads under network tariffs in low-voltage distribution networks [15];
- trade-offs between the operating cost and GHG emissions from water distribution systems using varying energy mix [16];
- demand response through pump scheduling for a variety of energy mixes [17].
- pipe enhancement and reduce energy and GHG emissions [18] as well as several other factors [19].
- reservoir level altered by climate change effects on energy consumption [20].
- tanks siting effect on energy use [21].

Two studies are of particular interest, namely [22] and [23], in which multi-objective optimization of WDSs considering cost, reliability, and GHG emissions but with a yearly varying electricity tariff and not an hourly varying one, as in this study. Both studies, however, only use one or three simplified WDSs for study, in contrast to this study that uses twelve WDSs of a wide variety.

Besides cost and GHG emissions, other issues are of interest such as energy and water quality [24-26]; cost minimization only [27]; pump scheduling using a linear programming-based branch and bound technique [28]; energy cost and water quality [29]; pressure, leakage, and electricity usage [30]. Biofuel can be used in small WDSs [31].

No studies, however, studied the tradeoffs of cost and GHG emission for such a wide variety of systems and possible pumping schedules as this study that uses network modelling to analyze this multi-objective (minimize both cost and GHG emissions) optimization approach through enumeration of twelve possible pumping schedules for twelve different real WDSs.

2. Materials and Methods

Twelve real WDSs were studied, which varied in size and configuration (Table 1 and Figures A1 through A12 in the appendix). These systems were chosen because they represent all the system types, and the data were available. The number of junctions ranged from 6 to 12,525. The number of pipes ranged from 8 to 14,824. The number of pumps ranged from 1 to 11, reservoirs from 1 to 2, tanks from 1 to 7, and valves from 0 to 5. There were both looped and branched systems as well as systems that the tank connects directly to a tank or into the system. In some systems the tank was near the source and far away in others. All information regarding the twelve systems was obtained from personal communication from various sources. The names of the municipalities were removed for security purposes. All the systems were real. The price of electricity was not altered from the original value provided for that geographic region. Results are normalized by base-case values, however, and therefore the original electricity price does not change the results.

Table 1 Summary of characteristics for all the real WDSs studied.

System	Junctions (#)	Pipes (#)	Pumps (#)	Reservoirs (#)	Tanks (#)	Valves (#)	Type
S1	6	8	1	1	1	0	Loop
S2	41	41	1	1	1	0	Branch
S3	126	168	2	1	2	8	Loop
S4	118	135	3	1	1	4	Loop
S5	348	395	8	1	2	1	Loop
S6	874	958	3	1	1	6	Loop
S7	12,525	14,824	6	2	4	5	Loop
S8	25	25	1	1	1	0	Branch
S9	44	62	1	1	1	0	Loop
S10	115	115	1	1	1	0	Branch
S11	15	15	1	1	1	0	Branch
S12	388	429	11	1	7	4	Loop

The modeling procedure used the network solver EPANET 2.2 [32]. EPANET uses information about the reservoir(s), pump(s), pipes, nodes, and tank(s) as inputs to solve the mass and energy balances to give outputs of flowrates and pressures throughout the system for each time step over a simulation timeframe. In addition, the energy used, and costs are output.

The modeling procedure consisted of running extended-period simulations in which the demand varies throughout the day and night in one-hour time steps. Simulations were first performed with the original tank-level-based pump controls to represent the base case with no changes in pump scheduling. Tank-level controls turn the pump(s) on when the tank level reaches a lower tank level set point and turns the pump(s) off when the water level reaches an upper tank level set point. The kWh/volume and cost/day values were recorded from EPANET output. The twelve pump scheduling scenarios were individually modelled for each of the twelve systems. The scheduling scenarios consisted of activating the pump during ever-increasing time durations throughout the low-cost nighttime hours and then during the medium-cost evening hours (Table 2). The energy tariff pattern used consisted of factors for each time step that were multiplied by the average electricity cost/kWh (Figure 1). Operation and maintenance costs are not affected by the pump schedule and, therefore, were not included here. The smallest pump possible was used for each scheduling scenario and at the highest efficiency (84%) to avoid any comparability issues regarding the operating point being at or below optimal efficiency. This allowed a fair comparison between systems and scheduling scenarios. GHG emissions were calculated using the value of 0.996 lb CO_2/kWh [32]. A flowchart of the procedure is given in Figure 2.

Table 2 Pumps schedules tested.

original tank-level-based controls
0:00 to 2:00
0:00 to 3:00
0:00 to 4:00
0:00 to 5:00
0:00 to 6:00
0:00 to 7:00
0:00 to 7:00 and 23:00 to 24:00
0:00 to 7:00 and 22:00 to 24:00
0:00 to 7:00 and 21:00 to 24:00
0:00 to 7:00 and 20:00 to 24:00
0:00 to 7:00 and 19:00 to 24:00

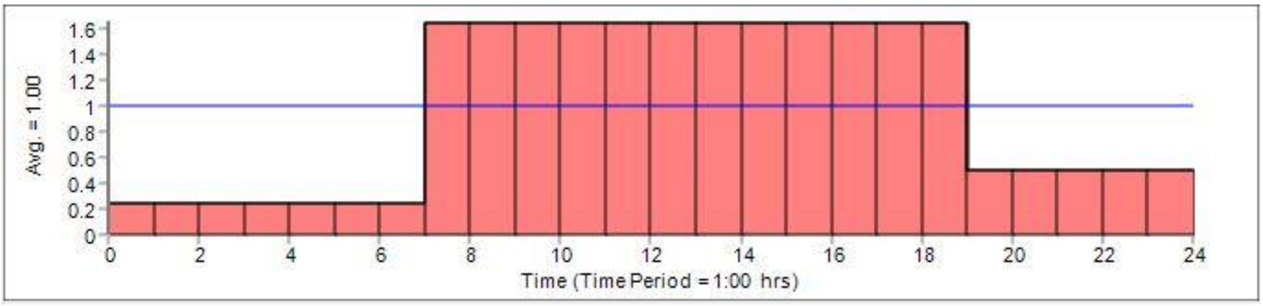

Figure 1 Typical electricity cost tariff employed (factor times the average energy cost for each hourly time step).

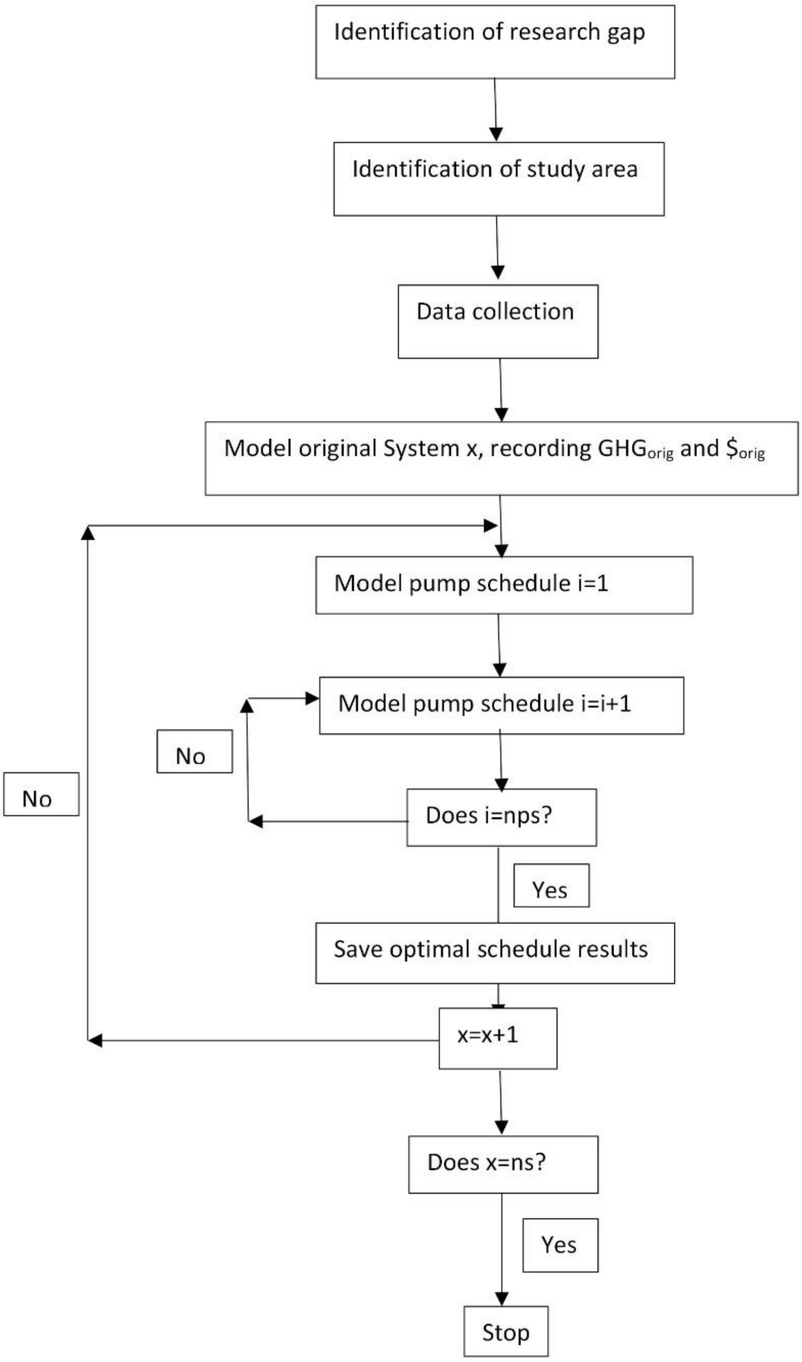

Figure 2 Method flowchart.

From 0:00 to 7:00 were low-cost hours. From 19:00 to 24:00 were medium-cost hours (Figure 1).

The study was performed as a multi-criteria optimization problem to:

Minimize GHG and cost subject to all pressure values above an acceptable minimum value for all nodes for all times.

The network analysis was performed by EPANET, as mentioned before. In addition, the Pareto front tradeoff curve was plotted, consisting of all values of GHG emissions and cost to show the tradeoffs and pseudo-optimal values for pumping schedule options. The pseudo-optimal solution (POS) was the point closest to the origin of zero normalized GHG emissions, GHG/GHG_{orig}, and zero normalized cost, $\$/\$_{orig}$ as denoted by Eq. (1):

$$POS = \sqrt{\left(\frac{GHG}{GHG_{orig}}\right)^2 + \left(\frac{\$}{\$_{orig}}\right)^2} \tag{1}$$

3. Results

The results of the simulations show some common trends between the system tradeoff plots and some differences (Figures 3 through 14), with some tradeoff curves having an inversely proportional shape (Systems S1, S3, S7, S8, S9, and S10), while other systems (Systems S4, S5, S11 and S12) had a proportional or C-shaped curve (Systems S2 and S6). For the inversely proportional relationships, saving cost results in higher emissions and climate change, while spending more money on electricity can reduce emissions. For proportional relationships, lower costs also result in lower emissions. For the C-shaped relationships, it varies depending on what portion of the curve is being analyzed. Table 3 shows a summary of the relationships for all the twelve studied systems. As mentioned before in Table 1, in some systems the tank was located far from the source and in other systems the tank was close to the source. Some systems had the source water being pumped into the system while others had it going directly to the tank. Some systems were branched, and some were looped. The optimal pumping schedule, along with the number of systems with that pump schedule and the number of hours pumped are listed as well and shows a wide variety of optimal pumping schedules and time durations (4 to 11 hours). No clear pattern exists that shows the optimal pump schedule or shape of tradeoff curve for any particular type of system (branched or looped, near or far, direct or system). Figure 15 shows the tradeoff curve for all twelve systems combined, showing a general inversely proportional relationship along with the best-fit equation (Eq. 2). The 2 outlier points come from S12 which had many more pumps than the other systems and, therefore, magnified the effects of GHG emissions. There is a complicated relationship in all the systems between the pump curve, demand pattern, efficiency curve, and tariff hourly timing that may account for the variability seen in these results. For example, pumping over a shorter time duration may cause the pump to pump at a different head value on the pump characteristic curve, which may in turn cause the pump to operate at a different efficiency, thereby affecting the GHG emissions. Also, the initial system size of pipes, pumps, and tanks can affect the results. For example, if all the pipes are over-designed (larger than needed), then the frictional headloss is less and the change in GHG emissions may be less. If the original pump is larger than needed, then changing the pumping scheduling may not affect the GHG emission as much.

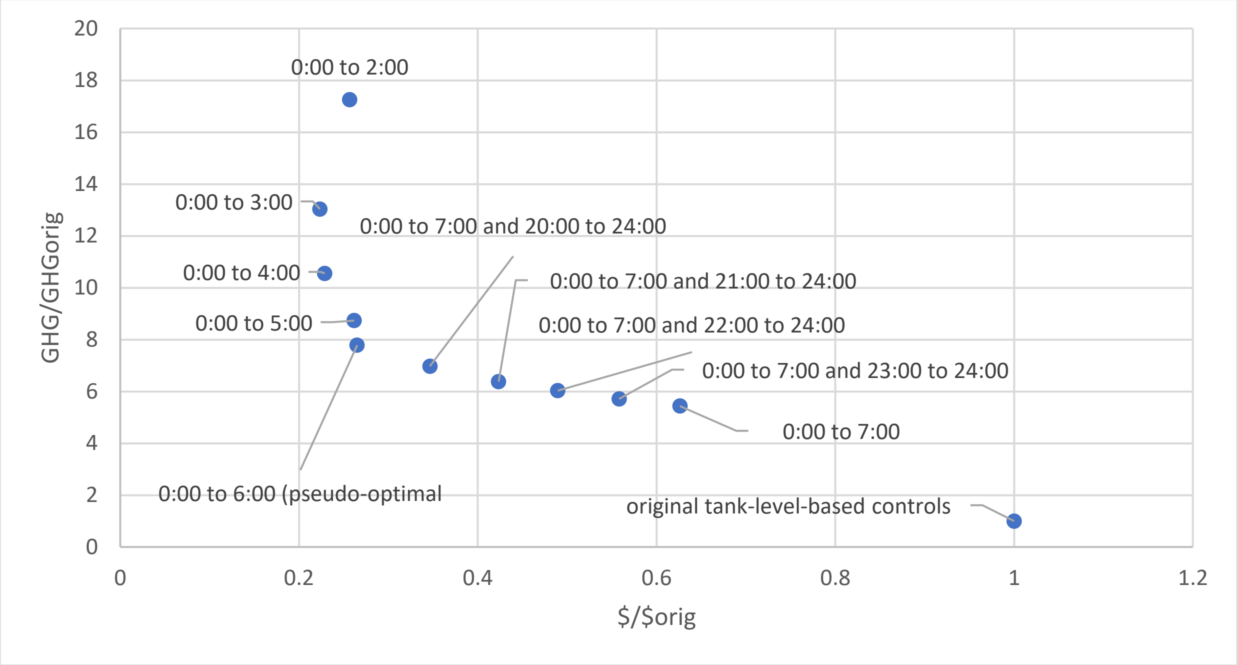

Figure 3 Tradeoff curve for System 1 (S1).

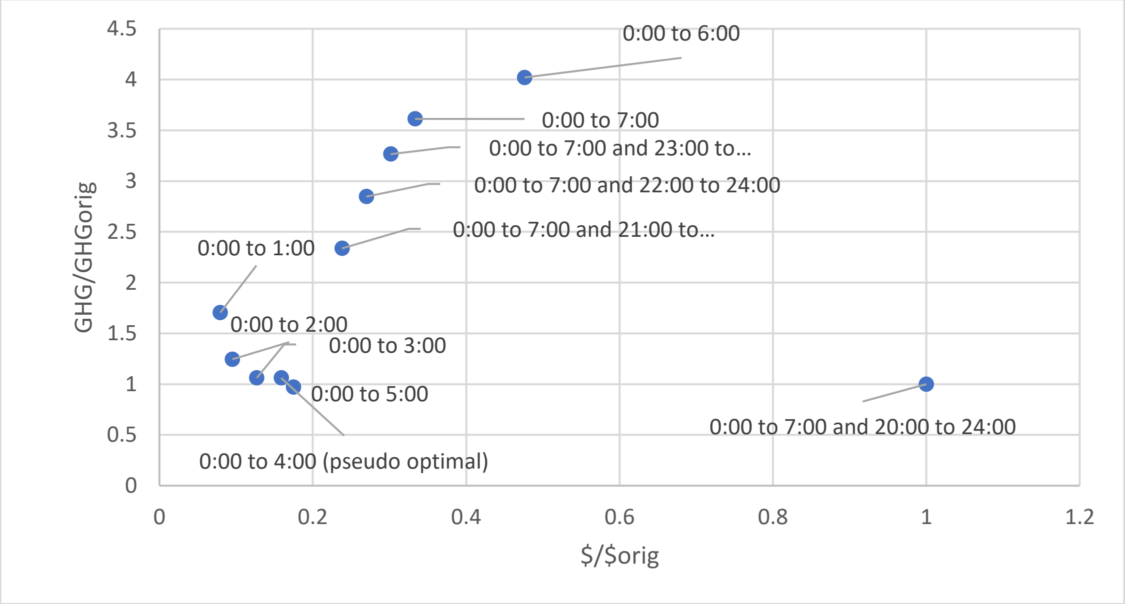

Figure 4 Tradeoff curve for System 2 (S2).

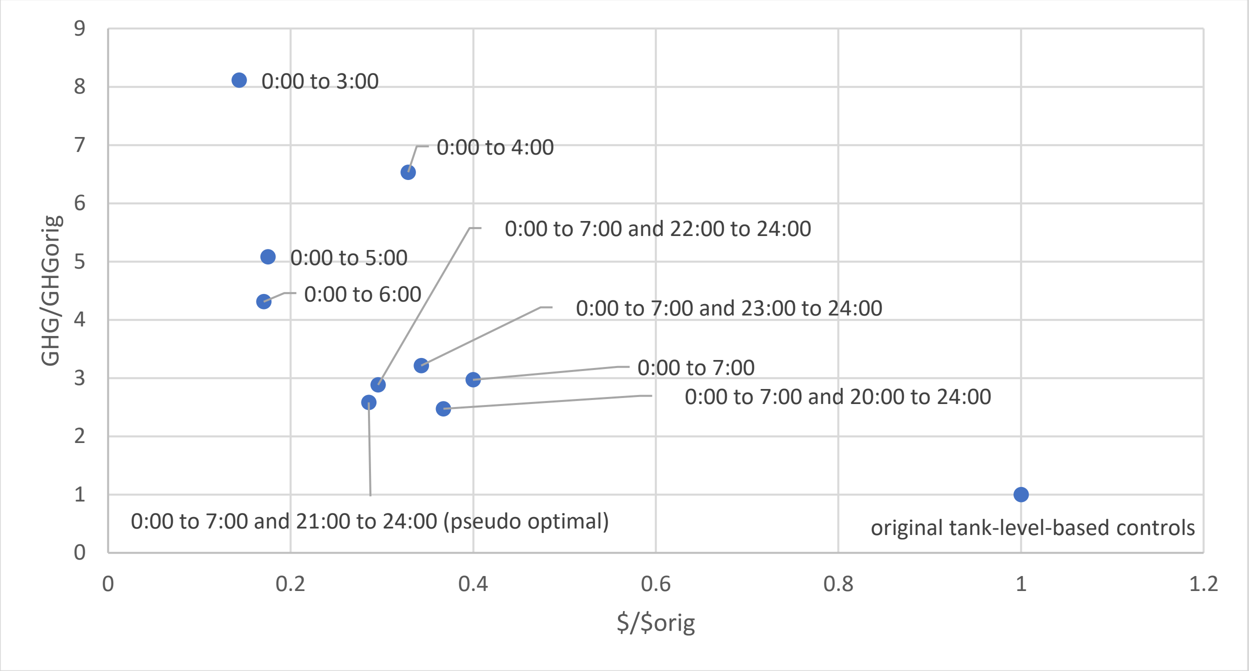

Figure 5 Tradeoff curve for System 3 (S3).

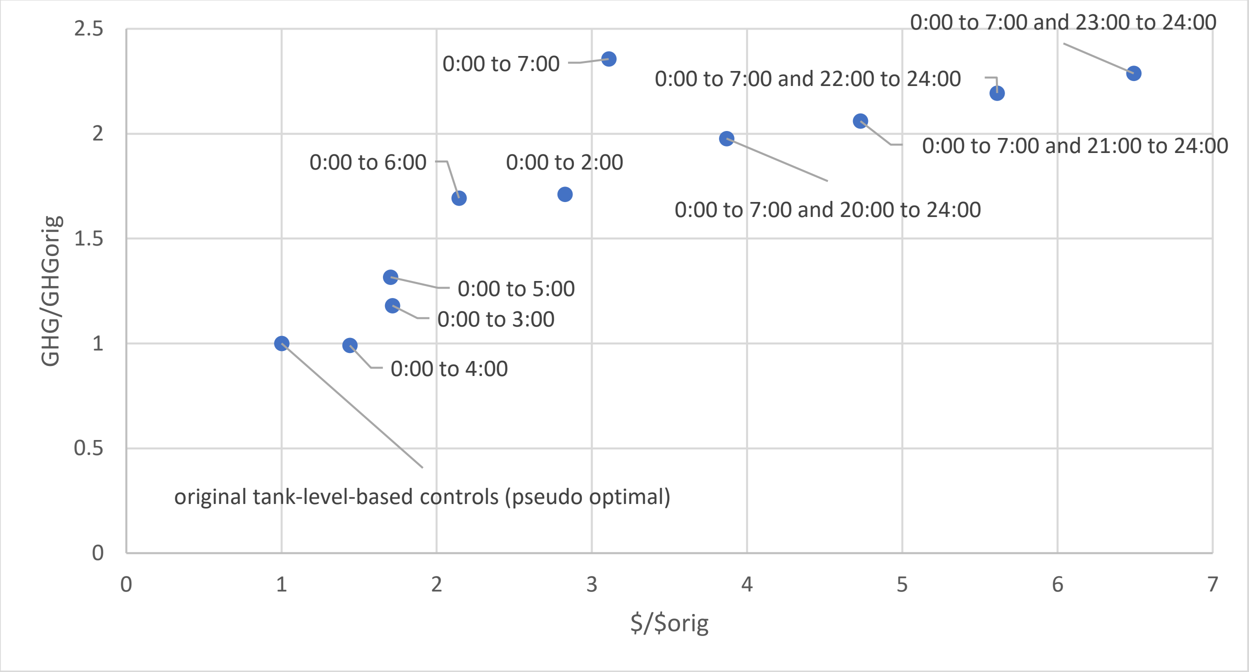

Figure 6 Tradeoff curve for System (S4).

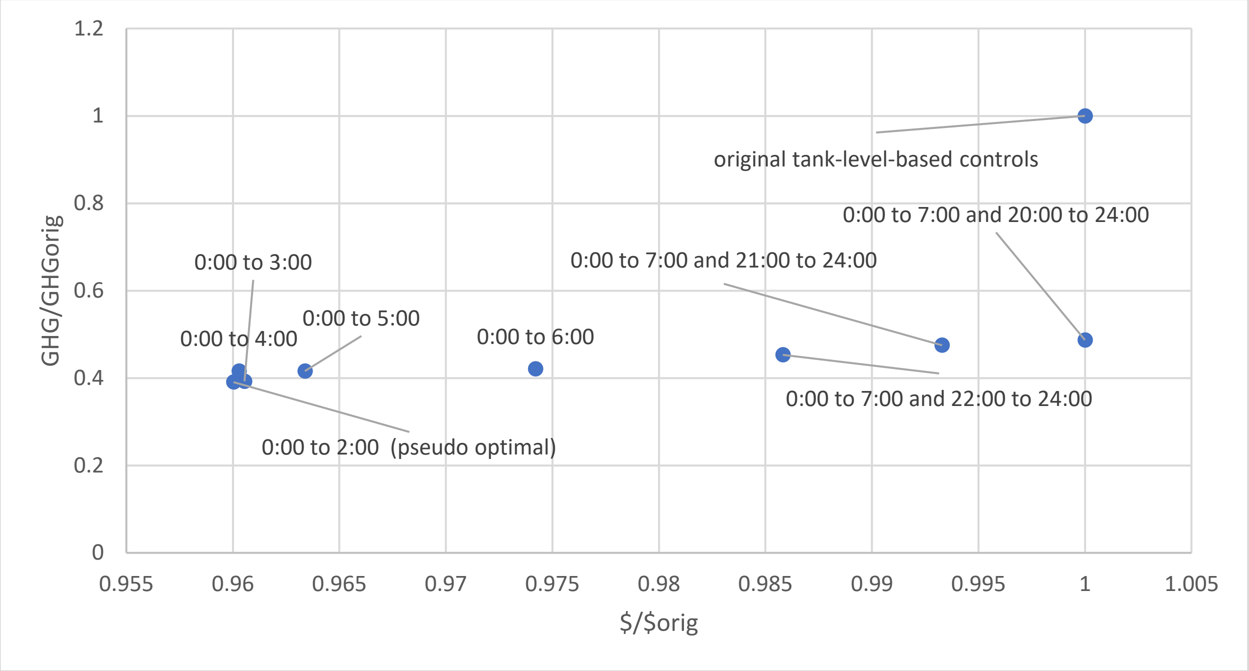

Figure 7 Tradeoff curve for System 5 (S5).

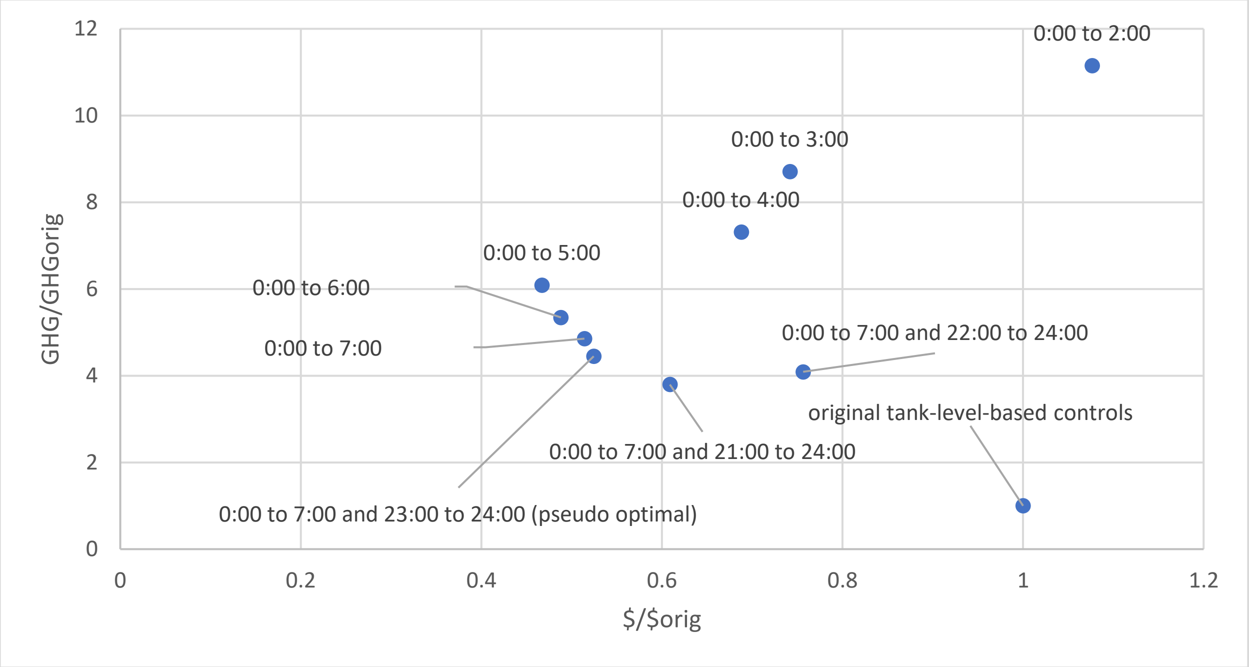

Figure 8 Tradeoff curve for System 6 (S6).

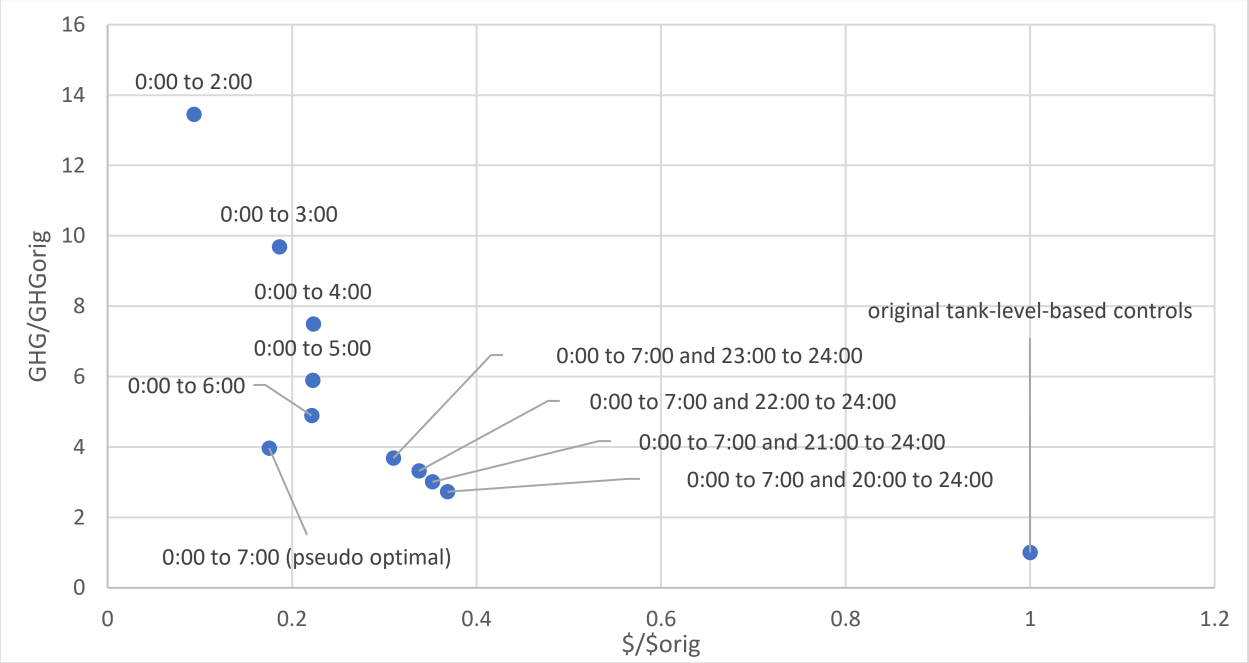

Figure 9 Tradeoff curve for System 7 (S7).

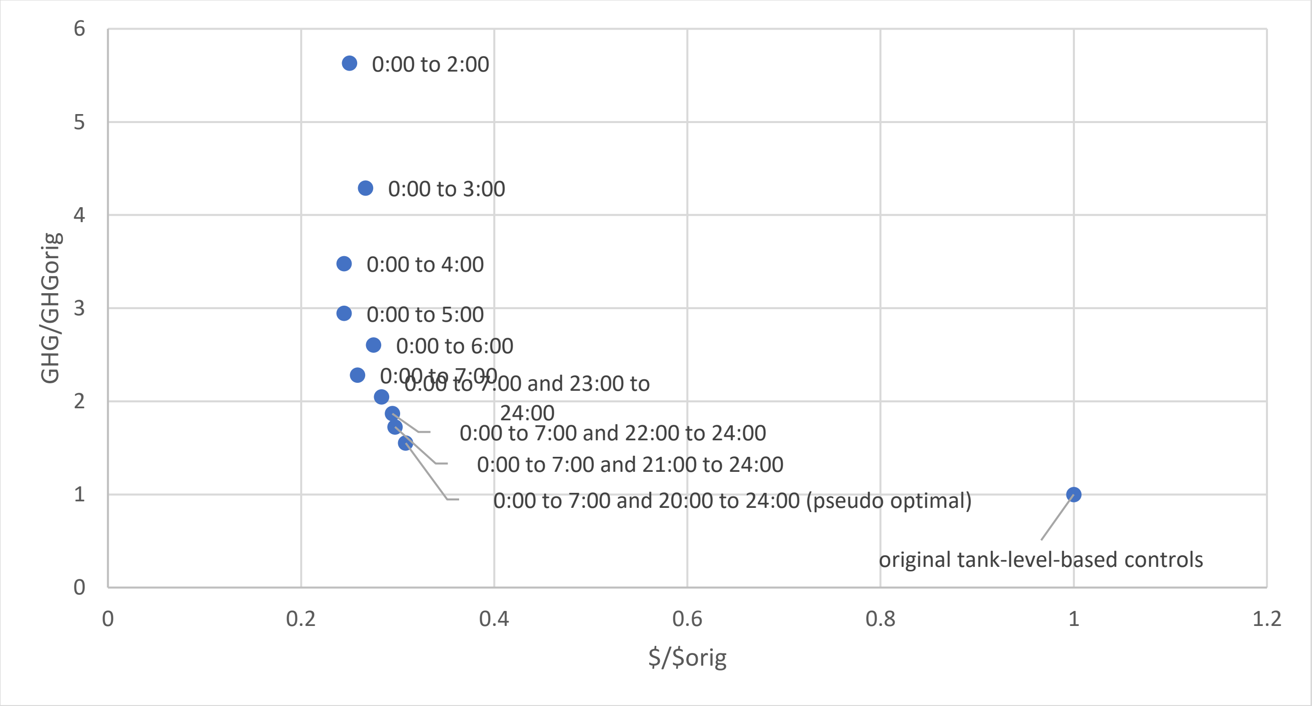

Figure 10 Tradeoff curve for System 8 (S8).

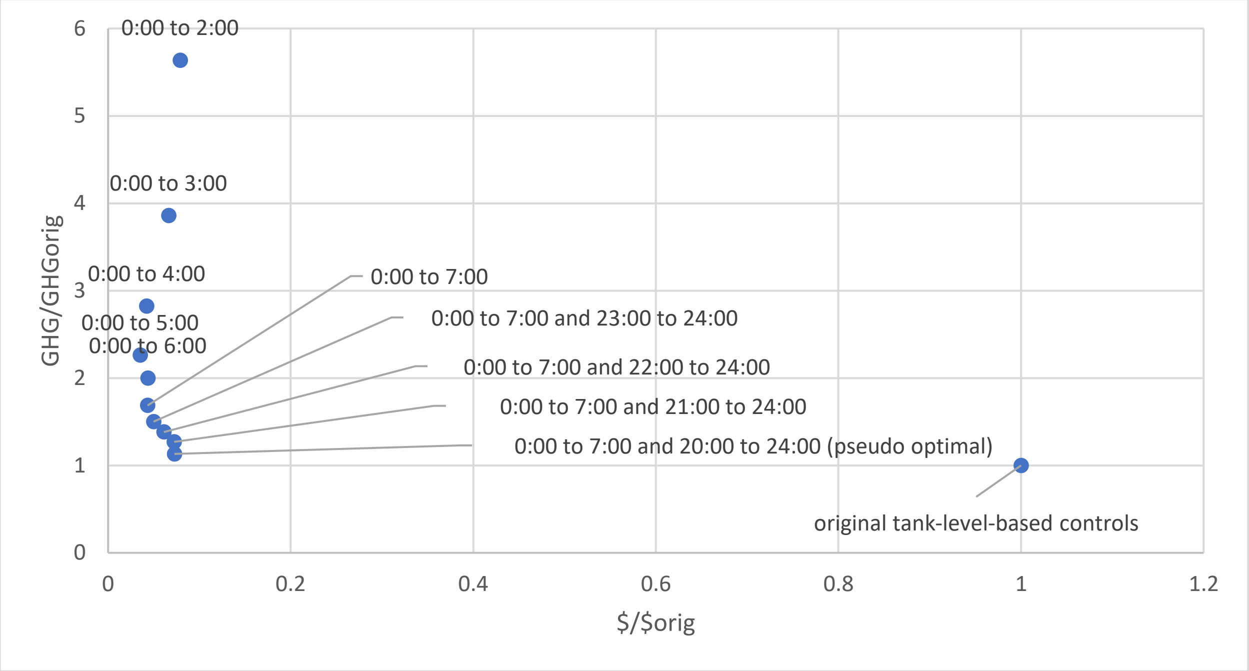

Figure 11 Tradeoff curve for System 9 (S9).

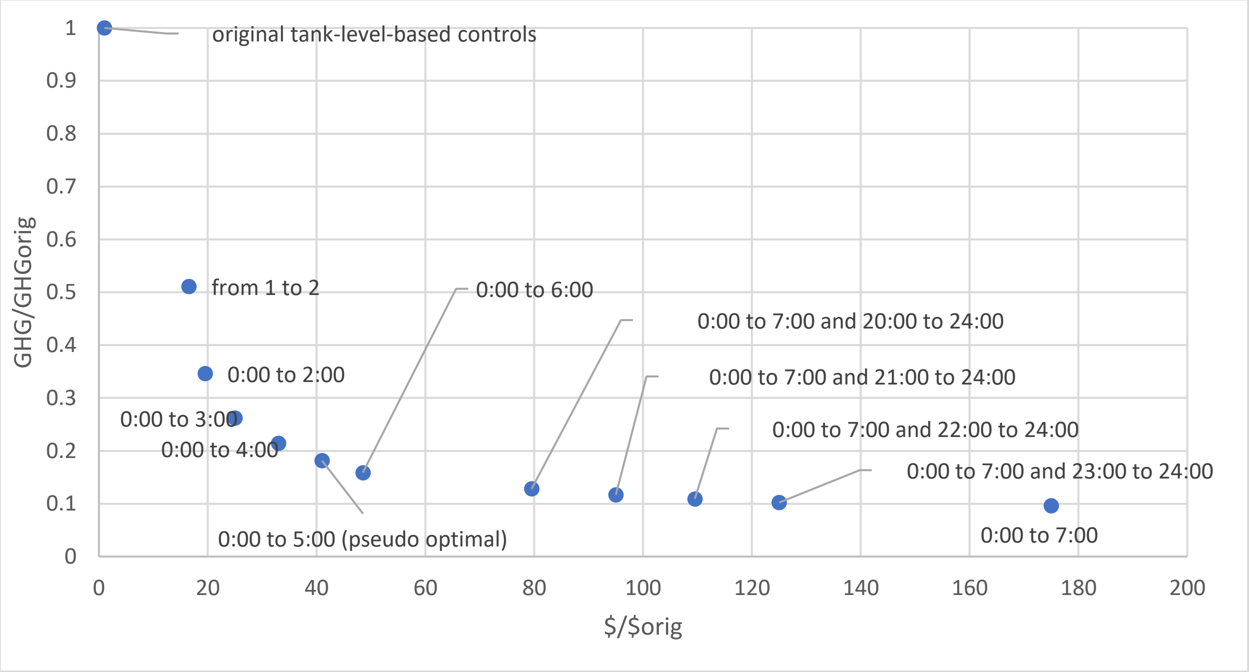

Figure 12 Tradeoff curve for System 10 (S10).

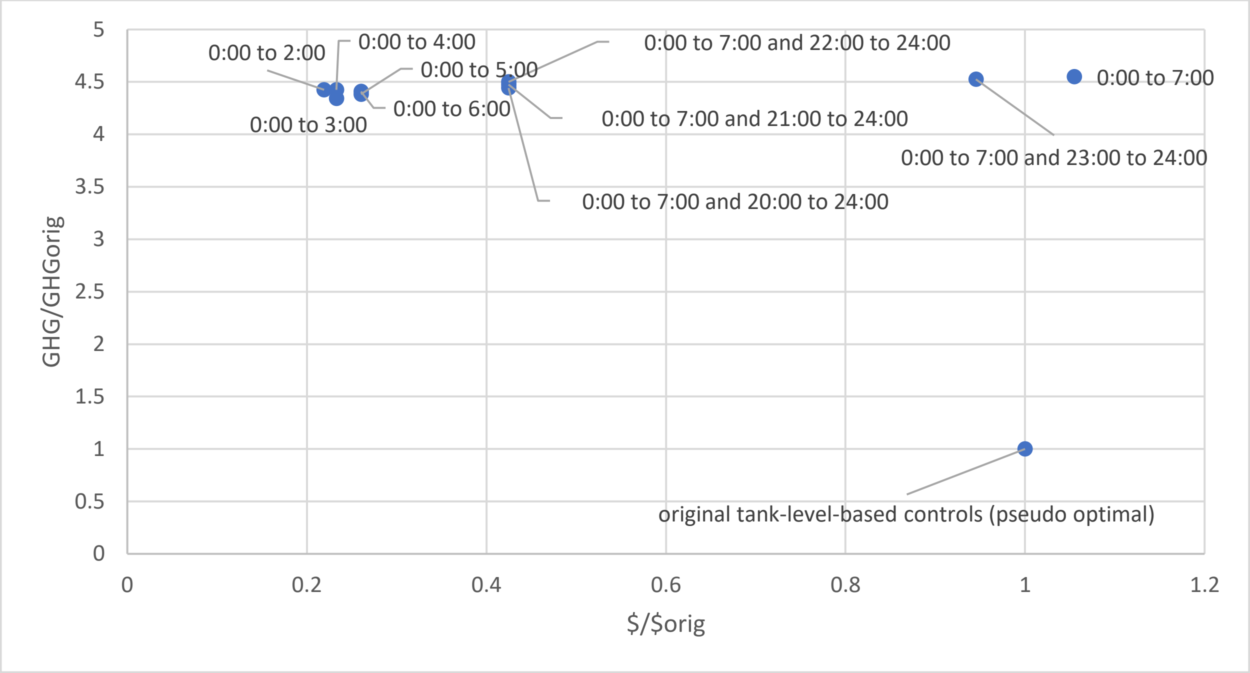

Figure 13 Tradeoff curve for System 11 (S11).

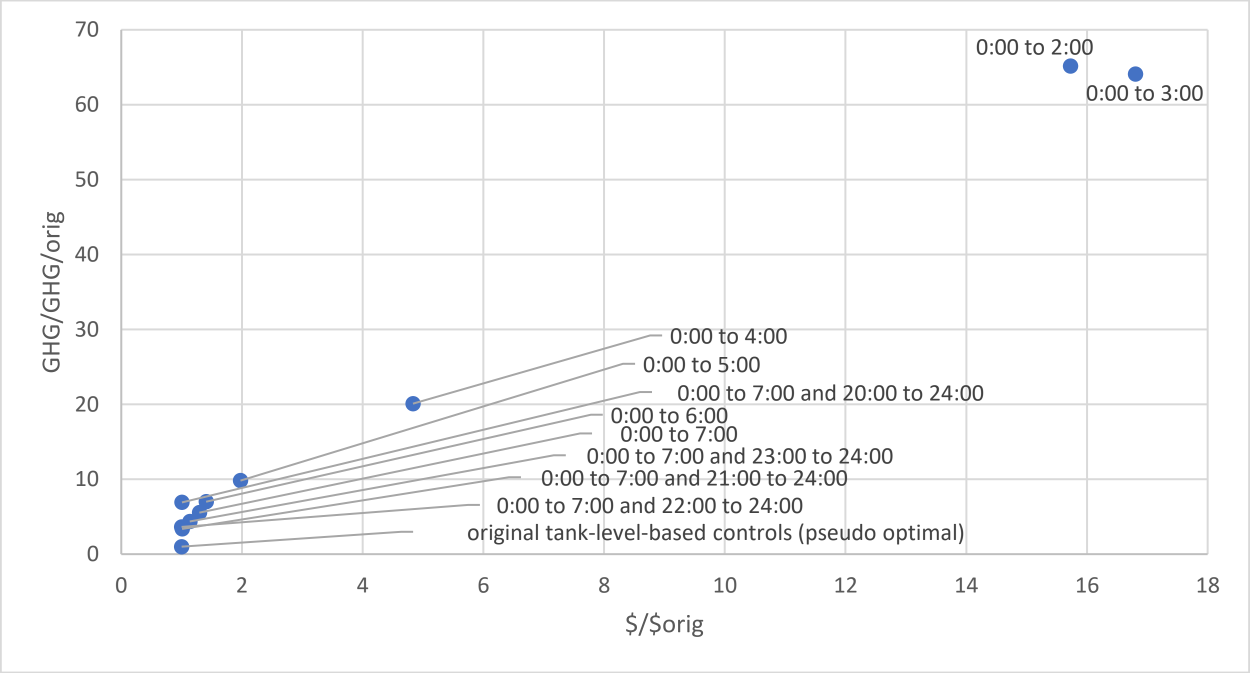

Figure 14 Tradeoff curve for System 12 (S12).

Table 3 Results of tradeoff curves for all systems.

System	Type	Curve Shape	Pseudo Optimal Pumping Schedule	# WDSs where this pumping schedule was optimal	Pumping Hours
S1	Far System	Inversely Proportional	0:00 to 6:00	1	6

	Looped				
S2	Far System Branched	C-Shaped	0:00 to 4:00	1	4
S3	Far System Looped Booster	Inversely Proportional	0:00 to 7:00 and 21:00 to 24:00	2	10
S4	Far System Looped	Proportional	original then 0:00 to 4:00	3	5
S5	Near System Looped Booster	Proportional	0:00 to 2:00 ≈ 0:00 to 4:00	1 3	5
S6	Near Direct Looped	C-Shaped	0:00 to 7:00 and 23:00 to 24:00	1	8
S7	Near Direct Looped Booster	Inversely Proportional	0:00 to 7:00	2	7
S8	Near System Branched	Inversely Proportional	0:00 to 7:00 and 20:00 to 24:00	2	10
S9	Far System Looped	Inversely Proportional	0:00 to 7:00 and 20:00 to 24:00	2	11
S10	Near Direct Branched	Inversely Proportional	original then 0:00 to 5:00	3	5
S11	Near Direct Branched	Proportional	original then 0:00 to 7:00	2	7
S12	Far System Looped Boosters	Proportional	original then 0:00 to 7:00 and 21:00 to 24:00	2	10

Far = tank is far from the source. Near = tank is near the source. System = water pumped into the system. Direct = water pumped directly into the tank. Branched = no loops in the system piping. Looped = loops exist in the system piping. Booster = there are booster pumping station(s).

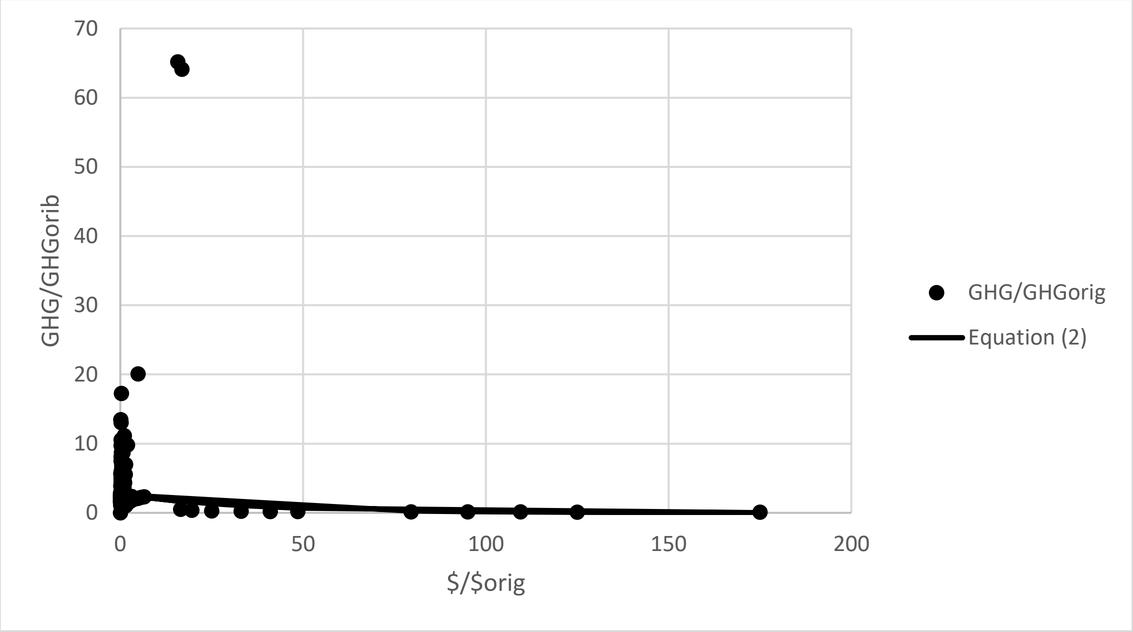

Figure 15 Tradeoff plot for all twelve systems.

To examine whether or not it is worth it for utilities to use a pump schedule that minimizes GHG emissions, even though it might cost more, the increased cost to use a pumping schedule that minimizes GHG emissions was calculated for each system (Table 4). It can be seen that cost increases ranged from 0 to 1,653% for GHG reductions ranging from 0 to 87%, and a system-averaged cost increase of 348% for a 34% GHG emissions reduction. The most advantageous is for System S6 with a cost-benefit ratio (Cost Increase/GHG Reduction Ratio) of 1.2. The system with the most cost increase per GHG reduction is System S9 with a value of 109.3. The average cost increase per GHG reduction was 10.3.

$$\frac{GHG}{GHG_{orig}} = 2.679e^{-0.028\left(\frac{\$}{\$_{orig}}\right)} \tag{2}$$

Table 4 Cost increase to minimize GHG emissions by pump scheduling choice.

System	Pseudo-Optimal Cost	GHGmin Cost	% Cost Increase	Pseudo-Optimal GHG	GHGmin	% GHG Decrease	Cost Increase/GHG Reduction Ratio
S1	5.41	20.41	277	6,382	820	87	3.2
S2	0.08	0.11	38	1	1	9	4.3
S3	46.53	163	250	12,869	4,983	61	4.1
S4	23.26	33.5	44	87,608	86,744	1	44.6
S5	17.71	17.71	0	3,723	3,723	0	NA
S6	19.33	36.86	91	4,088	918	78	1.2
S7	23.28	408	1,653	12,797	3,225	75	22.1
S8	1.11	3.6	224	5,976	3,851	36	6.3
S9	6.36	87.58	1,277	3,887	3,433	12	109.3
S10	0.82	3.5	327	2	1	47	7.0

S11	0.73	0.73	0	1	1	0	NA
S12	96.96	96.96	0	0	0	0	NA
			348			34	10.3

4. Discussion

The study [22] used a small, looped, far, pumped-into-system WDS with three reservoirs and found an inversely proportional relationship on the GHG-cost tradeoff curve. The costs, however, in contrast to this study, included the capital costs to build the system. The current study assumes an existing WDS with only the pumping schedule being studied. Electricity tariffs were applied in which the price of electricity increased each year to reflect inflation, not changing hourly, as in the current study. Wu et al. (2013) [23] studied three case study WDSs. Case Study 1 comprises a single pump, pipe and tank. This system had a C-shaped tradeoff curve. Case Study 2 had a single pump and tank with 35 pipes and was looped, pumped into the system, and had a far tank. It had a proportional tradeoff curve. Case Study 3 was a real branched system with a single pump, tank, and reservoir with nine pipes. It also used a yearly-increasing electricity tariff. It also displayed a proportional tradeoff curve. All three studies, however, included the capital costs for a new system, unlike this study for existing systems. This does show, however, that the tradeoff curve is system specific.

Changing the pump schedule is an operational matter, so in a way, operations is included here. Most systems use SCADA equipment to automatically turn pumps off and on, so manual operations are minimal. As far as maintenance, pumps are usually in parallel, so if one pump malfunctions, the other pump(s) can handle the required flow until repairs can be made. It is unclear if changing the pump schedule, as suggested here, will make the pumps break more often or not. The pump switch contacts wear out with more use. So, if a pump schedule results in the pump turning off and on more often, it could result in repair costs increasing as well. It is unclear how much, however. Pipes and tanks would not be affected by a change in pump scheduling.

5. Conclusions

This modelling study on twelve real WDSs with twelve pumping schedules to analyze the effect of an hourly-varying electricity tariff on GHG emissions resulted in the following conclusions:

1. The effect of pumping schedule is system specific.
2. Most of the studied system had an inversely proportional relationship between cost and GHG emissions.
3. In these systems, spending more on electricity results in less GHG emissions.
4. The optimal pumping schedule that minimizes both cost and GHG emissions is usually a longer pumping time that can pump at lower flowrates and thereby minimize friction head.
5. This can many times be the tank-level-based controls that pump whenever needed and with no regard of the electricity tariff higher-cost times.

Acknowledgments

None.

Author Contributions

The single author did all aspects of this study.

Funding

There was no funding in this project.

Competing Interests

The author has declared that no competing interests exist.

Additional Materials

The following additional materials are uploaded at the page of this paper.

1. Appendix: System Maps.

References

1. Seneviratne SI, Nicholls N, Easterling D, Goodess CM, Kanae S, Kossin J, et al. Changes in climate extremes and their impacts on the natural physical environment [Internet]. Cambridge, UK and New York, NY, USA: Cambridge University Press; 2012. Available from: https://www.ipcc.ch/site/assets/uploads/2018/03/SREX-Chap3_FINAL-1.pdf.
2. EPA. Sources of greenhouse gas emissions [Internet]. Washington, DC: Environmental Protection Agency; 2023. Available from: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.
3. UN. For a livable climate: Net-zero commitments must be backed by credible action [Internet]. New York, NY: United Nations; 2022. Available from: https://www.un.org/en/climatechange/net-zero-coalition.
4. Mays LW. Water distribution system handbook. New York, NY: McGraw Hill; 2000.
5. EPA. Energy efficiency for water utilities [Internet]. Washington, DC: Environmental Protection Agency; 2023. Available from: https://www.epa.gov/sustainable-water-infrastructure/energy-efficiency-water-utilities.
6. Babamiri AS, Pishvaee MS, Mirzamohammadi S. The analysis of financially sustainable management strategies of urban water distribution network under increasing block tariff structure: A system dynamics approach. Sustain Cities Soc. 2020; 60: 102193.
7. Ulanicki B, Kahler J, See H. Dynamic optimization approach for solving an optimal scheduling problem in water distribution systems. J Water Resour Plan Manag. 2007; 133: 23-32.
8. Dai PD, Viet NH. Optimization of variable speed pump scheduling for minimization of energy and water leakage costs in water distribution systems with storages. Proceedings of the 2021 13th International Conference on Electronics, Computers and Artificial Intelligence; 2021 July 1-3; Pitesti, Romania. Piscataway: IEEE.
9. Salomons E, Housh M. Practical real-time optimization for energy efficient water distribution systems operation. J Clean Prod. 2020; 275: 124148.

10. Wang Y, Too Yok K, Wu W, Simpson AR, Weyer E, Manzie C. Minimizing pumping energy cost in real-time operations of water distribution systems using economic model predictive control. J Water Resour Plan Manag. 2021; 147: 04021042.
11. Vieira BS, Mayerle SF, Campos LM, Coelho LC. Optimizing drinking water distribution system operations. Eur J Oper Res. 2020; 280: 1035-1050.
12. Maskit M, Ostfeld A. Multi-objective operation-leakage optimization and calibration of water distribution systems. Water. 2021; 13: 1606.
13. Stokes CS, Maier HR, Simpson AR. Effect of storage tank size on the minimization of water distribution system cost and greenhouse gas emissions while considering time-dependent emissions factors. J Water Resour Plan Manag. 2016; 142: 04015052.
14. Stokes CS, Simpson AR, Maier HR. A computational software tool for the minimization of costs and greenhouse gas emissions associated with water distribution systems. Environ Model Softw. 2015; 69: 452-467.
15. Azuatalam D, Chapman AC, Verbič G. Probabilistic assessment of impact of flexible loads under network tariffs in low-voltage distribution networks. J Mod Power Syst Clean Energy. 2020; 9: 951-962.
16. Menke R, Kadehjian K, Abraham E, Stoianov I. Investigating trade-offs between the operating cost and green house gas emissions from water distribution systems. Sustain Energy Technol Assess. 2017; 21: 13-22.
17. Menke R, Abraham E, Parpas P, Stoianov I. Demonstrating demand response from water distribution system through pump scheduling. Appl Energy. 2016; 170: 377-387.
18. Barkdoll BD, Murray K, Sherrin A, O’Neill J, Ghimire SR. Effective-power-ranking algorithm for energy and greenhouse gas reduction in water distribution systems through pipe enhancement. J Water Resour Plan Manag. 2016; 142: 06015001.
19. Ghimire SR, Barkdoll BD. Sensitivity analysis of municipal drinking water distribution system energy use to system properties. Urban Water J. 2010; 7: 217-232.
20. Kraft L, Barkdoll BD. Effect of reservoir elevation on energy consumption in water distribution systems. Urban Water J. 2020; 17: 266-272.
21. Wang M, Barkdoll BD. A sensitivity analysis method for water distribution system tank siting for energy savings. Urban Water J. 2017; 14: 713-719.
22. Wu W, Simpson AR, Maier HR. Sensitivity of optimal tradeoffs between cost and greenhouse gas emissions for water distribution systems to electricity tariff and generation. J Water Resour Plan Manag. 2012; 138: 182-186.
23. Wu W, Maier HR, Simpson AR. Multiobjective optimization of water distribution systems accounting for economic cost, hydraulic reliability, and greenhouse gas emissions. Water Resour Res. 2013; 49: 1211-1225.
24. Sabzkouhi AM, Lee J, Keck J. Energy and water quality management in water distribution networks considering variable speed pump and tank flush scheduling. Proceedings of the World Environmental and Water Resources Congress 2022; 2022 June 5-8; Atlanta, GA, USA. Reston: American Society of Civil Engineers.
25. Darweesh MS. Impact of optimized pump scheduling on water quality in distribution systems. J Pipeline Syst Eng Pract. 2020; 11: 05020004.

26. Choi YH. Development of optimal water distribution system design and operation approach considering hydraulic and water quality criteria in many-objective optimization framework. J Comput Des Eng. 2022; 9: 507-518.
27. Cantu-Funes R, Coelho LC. Simulation-based optimization of pump scheduling for drinking water distribution systems. Eng Optim. 2023; 55: 841-855.
28. Bonvin G, Demassey S, Lodi A. Pump scheduling in drinking water distribution networks with an LP/NLP-based branch and bound. Optim Eng. 2021; 22: 1275-1313.
29. Abdallah M, Kapelan Z. Fast pump scheduling method for optimum energy cost and water quality in water distribution networks with fixed and variable speed pumps. J Water Resour Plan Manag. 2019; 145: 04019055.
30. Dini M, Hemmati M, Hashemi S. Optimal operational scheduling of pumps to improve the performance of water distribution networks. Water Resour Manag. 2022; 36: 417-432.
31. Archer A, Barkdoll BD. Energy savings using biofuel in a developing-country water distribution system. Water Sci Technol Water Supply. 2018; 18: 1554-1563.
32. EPA. EPANET, Application for modeling drinking water distribution systems [Internet]. Washington, DC: Environmental Protection Agency; 2023. Available from: https://www.epa.gov/water-research/epanet.