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Economic feasibility analysis of variable-speed pumps by simulating 15 multiple water distribution systems

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ABSTRACT

The UN Sustainability Goals address measures to reduce environmental pollution. Water distribution systems (WDSs) use electric energy, which pollutes the atmosphere through, at least partly, the burning of coal. This study simulates, through modeling, variable-speed pumps (VSPs) on 15 different real WDSs on the network solver EPANET and analyzes the payback period. An algorithm is introduced here to select the optimal pump speed pattern to save the most energy while satisfying the constrain of sufficient pressure at all times and all locations. It was found that five of the 15 systems operated unsuccessfully using a VSP, due to the VSP operating at lower speeds causing a lower pressure than normal, thereby causing the pressure to become negative. Additionally, a new chart that compares the payback period, project life, and energy costs between the base case and the VSP case was developed and different regions on the chart reflect different decision criteria.

Key words: economics, energy, engineering, public health, water supply

HIGHLIGHTS

- VSPs can save energy in a water system.
- However, VSPs does not always save energy.
- Thus, do not install VSPs if there is not enough pressure everywhere in the system.
- Installing a VSP may or may not pay for itself over the lifetime of the pump.
- Saving energy may be worth considering it for reducing climate change, effects even though the costs are not recovered.

INTRODUCTION

The United Nations Sustainable Development Goals point to ways to improve our world and include goals that are related to improving the environment and providing clean drinking water for improved public health. Specifically, Goal 3 Good Health and Well-Being talks about the importance of clean water for drinking, Goal 6 Clean Water and Sanitation talks about the importance of water distribution to provide clean water close to people's homes, Goal 7 Affordable and Clean Energy speaks to using clean energy for all uses, including water distribution pumping, Goal 11 Sustainable Cities and Communities involves using less energy, and Goal 13 Climate Action relates to using less coal-based electricity (United Nations 2021).

Global climate change (GCC) results from the burning of fossil fuels to generate electricity, thereby trapping in the sun's heat due to the release of greenhouse gasses such as carbon dioxide and methane (IPCC 2021). Since coal is widely used for electricity generation, reducing the amount of energy consumption can slow down climate change.

Water distribution systems (WDSs) involve pumping water from lower elevations such as a river, lake, or groundwater aquifers, up to a higher elevation where users need the water. Water is pumped through pipes, stored in tanks for storage when users consume water in varying amounts throughout the day and night in a user-demand pattern. Pumps can operate at a constant speed and be turned off and on when storage tank's water levels reach specified set points, both maximum and minimum. Typical controls specify turning the pump(s) off when the tank water level approaches the tank top and off when the tank is almost empty. These operational controls can impact system performance, water quality, and energy efficiency (Jones

& Sowby 2014), especially with demand charges and electricity tariffs (McCormick & Powell 2003). Pumps use electricity that can be charged at a constant rate or at a variable rate by the electricity provider (Walski & Vitter 2017). Users typically use more water during the daytime when they are awake and almost no water at night when they are sleeping. In contrast to constant-speed pumps, variable-speed pumps (VSPs) change the speed of the pump as needed throughout the day and night to match demand. They have been recommended to reduce the amount of energy used since there are times when the pump speed is lower and, therefore, saving energy (Steger & Pierce 2018; Qandil *et al.* 2019; Cimorelli *et al.* 2020). VSPs can be used to match desired pressure values at various locations and times in the WDS (Wu *et al.* 2009).

Payback period (PP) is an econometric method of quantifying whether or not an action is worthwhile. PP is quantified by calculating how long it takes for the savings realized from an action to payback the initial financial investment. If the PP is less than the time to make an additional investment, then the action results in a financial profit. Conversely, if the initial investment is not paid off before another financial investment is required, the action never pays for itself and, therefore, is not worth it. In the context of WDSs and VSP, if the energy cost savings from installing a VSP is not realized within the lifetime of a VSP, then installing a VSP is not worth it and vice versa.

Page *et al.* (2019) studied VSPs in a system in a single WDS in South Africa and showed that pressure values were kept low and relatively constant. Cimorelli *et al.* (2020) used a genetic algorithm to optimize pump speeds on two portions of a WDS and found that VSPs could save energy in that system but do not always justify the costs. Abdallah & Kapelan (2019) studied a VSP optimization method for a single system to optimize both energy cost and water quality but not the economic aspects of whether or not the initial investment pays off and found that VSPs can save energy and improve water quality. Briceño-León *et al.* (2021) investigated different control strategies for fixed and VSPs and found that the number and type of pumps affect the control system and is, therefore, system-specific. No mention was made, however, if the installation of a VSP paid off economically. Darweesh (2018) investigated using VSPs for reducing energy costs and leakage on a single simplified system and found that a 20% reduction is possible. Bonvin *et al.* (2021) used a linear programming/non-linear programming (LP/NLP)-based branch and bound algorithm to optimize pump scheduling. In addition, rotational speed related to pumps used as turbines (Alberizzi *et al.* 2018; Tahani *et al.* 2020; Ebrahimi *et al.* 2021) is a related and emerging idea but separate in scope from the present study. Energy savings in WDSs can also result from changing reservoir level (Kraft & Barkdoll 2020), tank location (Wang & Barkdoll 2017), using biofuel (Archer & Barkdoll (2017), pipe enlargement (Barkdoll *et al.* 2015), and tank parameters pumping station properties (Ghimire & Barkdoll 2010).

The purpose of this study is to determine what factors determine when VSPs are more efficient than constant-speed pumps and are economically profitable for a large number and variety of WDSs. In addition, if VSPs are more energy-efficient, then this could reduce energy use and reduce environmental impacts related to energy use and, therefore, help attain the United Nations Sustainable Development Goals.

System description

Fifteen WDSs were chosen to test whether VSPs improved the energy costs of the systems. The WDSs ranged from branched to loop systems, those with and without valves and tanks (Table 1 and Figures A1 through A15 in Appendix A). All systems had time-varying user demand patterns at most junctions and pump on/off controls related to elevated storage tank water levels. All the systems' modeling information was obtained through personal communications with various researchers. The town identities are removed for security purposes. They all represent realistic WDSs. Energy costs and demand charges were already included for the region in which the WDS is located and remained unaltered during this study.

Simulation procedure

All simulations were extended-period simulations (Duan *et al.* 2020) in the network solver EPANET, which takes values of reservoir level, pipe diameter, lengths, roughness values, junction elevations, and tank size and location and calculates the flow in every pipe and the pressures at every junction for all times steps (EPA 2021). Simulations were performed in which the demands, flows, pressures, and tank levels changed every time step. First, to get the base case energy cost, the simulation was run for an unaltered system with pump speed factors of 1.0 for every time step and the energy cost was recorded. A speed value of 1.0 denotes a speed unchanged from the base case.

The pump speed factor determination algorithm used here was based on the logic that the pump speed should be proportional to the demand pattern (Georgescu *et al.* 2014), since EPANET uses a demand-driven modeling approach. First, the pump speed pattern was exactly proportional to the user demand pattern but was then adjusted to save the most

Table 1 | System characteristics

System	Junctions (#)	Pipes (#)	Pumps (#)	Reservoirs (#)	Tanks (#)	Valves (#)
1	6	8	1	1	1	0
2	41	41	1	1	1	0
3	126	168	2	1	2	8
4	118	135	3	1	1	4
5	348	395	8	1	2	1
6	874	958	3	1	1	6
7	12,525	14,824	6	2	4	5
8	93	118	2	2	3	0
9	25	25	1	1	1	0
10	44	62	1	1	1	0
11	115	115	1	1	1	0
12	19	40	1	3	0	0
13	504	551	4	7	0	3
14	15	15	1	1	1	0
15	388	429	11	1	7	4

energy and ensure adequate pressures at all nodes at all times. Adequate pressures were considered to be greater than 20 psi, (Nowak *et al.* 2018). This was accomplished using Equation (1). The x value from Equation (1) is a chosen value for each system and the lower the x value the closer the speed multiplier will be to the base case value of 1.0. Therefore, the algorithm starts with the pump speed factors equal to the user demand patterns factors. For each subsequent attempt at choosing the pump speed factors, each factor is adjusted toward the 'all 1.0' base case values by some proportion, as denoted by x in Equation (1). If the pressure at any junction or any time goes negative, then the pump speed factor for that time step is increased to bring the pressure back to a positive value. The set of pump speed factors that result in the minimum energy usage, subject to the positive-pressure constraint is selected.

$$\text{Pump speed factor}\,_i^{j+1} = F_i^j - (F_i^j - 1)x; \tag{1}$$

here i is the time step, 1–24 h, j is the algorithm iteration until the minimum energy cost is found, and F is the pump speed factor.

Several speed patterns with varying values of x were run with each system to determine which would give the lowest energy cost. Once these simulations were run on all the systems, the PP of installing VSPs into the systems was calculated. A price for a variable-speed drive box was determined from research on manufacturers' websites (Grainger 2021) and some systems needed new, larger pumps to run a variable-speed pump pattern (Pump Products 2021). For the PP calculation, the initial cost for a VSP is either the initial cost for the drive box and/or the new pump. The savings is determined by the cost of running the base case minus the cost of running a VSP. Then the amount of time to payback the investment of a VSP can be found. Inflation of 5% was added for each year of economic costs (Cimorelli *et al.* 2020). The lifetime of the pump was assumed to be 12 years (Hydraulic Institute 2001). If the VSP cost was not recovered within the VSP lifetime, then installing a VSP is not worth it because it will never payback the initial investment and lose money. Additionally, the amount of time the pumps are on for both the base case and the VSP case were recorded, since using a VSP may slow down the pump enough so that it can never fill the tank and trigger the control command to shut off the pump, thereby potentially using more energy. The algorithm was applied to the existing pump(s) with no more or fewer pumps added or removed, for simplicity, although this would affect the results. Altering the number and locations of pumps, or the operations would require a more comprehensive framework and should be considered for future work.

The initial cost for all the systems when determining the PP was either the cost of a drive box to make a VSP pumping schedule or some systems needed to upsize the pump(s) size to run a variable pumping schedule. The drive box is a Variable Frequency Drive: 480 V with a 50 hp maximum output. 50 hp pumps can operate most of the systems and some can operate on lower horsepower. The four systems that needed a pump upsize are Systems 5, 6, 7, and 8. System 5 had three pumps that needed to be upsized and 20 hp pumps were sufficient to run the system. Each pump costs $9,352. System 6 had one pump that needed to be upgraded and that system needed a size of 50 hp at a cost of $20,100. System 7 also needed a 50 hp pump for the upsize. System 8 needs a 0.33 hp pump upsize which will cost $1,683. The pumps compared for the PP analysis were centrifugal booster pumps and the maximum cost was used for the PP calculations.

RESULTS

After running the 15 systems, it was found that VSPs are not always the best option for all systems, i.e., there are some systems where it costs more energy to run a VSP than it would be for a single-speed pump. This was determined by the PP calculations and the annual costs to run the pumps (Appendix B). The energy costs were found from the EPANET simulation of the systems. Ten of the systems had a PP shorter than the VSP lifetime of 12 years, thereby indicating that installing a VSP would be worth it, while the other five systems never paid back within the pump lifetime. The five systems that did not payback soon enough were all systems where VSPs were less cost-effective than a normal pump system. In short, counterintuitively, sometimes installing a VSP results in *increased* energy usage. Four of the pumping systems had to have new pumps installed because when the system switched to VSP it was no longer able to provide the requisite pressure that the system needed. The costs of the new pumps were included in the calculation of the PP and one of those four systems will not payback during the pump lifetime. From looking at the systems, one of the criteria for not installing a VSP is that if the pressure is slightly over 20 psi at any junction at any time in the system, then the pump should not be changed out for a VSP because the pump will need to be upsized to meet the demand of the system. If a pump is already being swapped out in a regular maintenance schedule, then this may no longer apply if the cost of upsizing can be paid off in time.

As stated previously, an interesting result from running the simulations is the fact that some of the pumps did not reduce PP when running on a VSP schedule. To investigate this, different factors were studied to see what could be affecting the energy use to increase the cost (Table 2). The first to be considered is the difference between the time the pump is on between the VSP case and the base case. The reason was that if the VSP was turned on longer than a normal pump, then that would lead to an increase in energy cost. However, the percent of time being turned on for all the VSP systems was greater than the normal case and several reached 100% time on for the VSP, and those cases all paid off. There was no correlation between the percent of time the VSP was on and whether it would be cost-effective or not. Another attribute of the systems was the size of the storage tanks with the thought the larger the diameter of the tank the longer it would take to fill and, therefore, have the pump running longer to reach the upper set point at which the pump would switch off. There was also no correlation between tank sizes and if a system would fail to payback or not. The five systems that could not payback had a variety of tank sizes and number of tanks and Systems 12 and 13 both had no tanks at all. One final parameter of the systems that was considered to determine what caused the failure in the PP was the average flow being pumped into the system for both the base case and the variable-speed trial. For most of the systems, the variable-speed schedule generated a greater average flow than the base case average flow. Additionally, Systems 10, 12, and 13 had an average flow for the VSP trial less than the average flow for the base case. No conclusions can be drawn from this result since there are differences between the three systems that make comparison difficult.

DISCUSSION/CONCLUSION

This study found that not every system is more cost-effective when using a VSP, which concurs with Cimorelli *et al.* (2020). From these results, guidelines of when to install VSPs and when not to were investigated by looking at different parameters of the systems. One aspect determined is that if the pressure in a system is slightly above 20 psi anytime or anywhere, then a VSP should not be installed. Additionally, factors such as tank size, percent time the pumps are on, and the average flow from the pumps do not influence if a pumping system will payback the VSP investment or not. The recommendation for water managers thinking about installing a VSP would be to perform an analysis of their own system. First, make a pump speed schedule using the equation developed in this paper and apply different variations to find the optimal conditions of the VSP. From there, conduct a PP analysis, then plot the results on the graph below (Figure 1). The quadrants are divided along the 1.0

Table 2 | VSP and base case comparison

System	Payback period (years)	Use VSP?	% Time on, base case	% Time on, VSP	Tank diameter/s (ft)	AVG flow, base case (GPM)	AVG flow, VSP case (GPM)	Upsize pump?
1	2	Yes	75	100	50	293	645	No
2	18	No	16	66	4	1	2	No
3	Infinity	No	50	100	186 106	2,388	37,041	No
4	1	Yes	27	100	58	368	476	No
5	8	Yes	48	100	35	1,037	3,148	Yes
6	Infinity	No	47	92	14	843	6,145	Yes
7	1	Yes	36	87	100	16,314	61,439	Yes
8	Infinity	No	8, 100	100, 87	85, 50, 164	3,397	12,995	Yes
9	12	Maybe	65	82	25	36	51	No
10	3	Yes	64	100	80	621	597	No
11	93	No	17	99	3	5	86	No
12	Infinity	No	100	57	None	4,211	3,844	No
13	Infinity	No	100	100	None	316	204	No
14	7	Yes	6	44	5	1	6	No
15	1	Yes	100	100	31, 21, 14, 12, 12, 8, 7	166	299	No

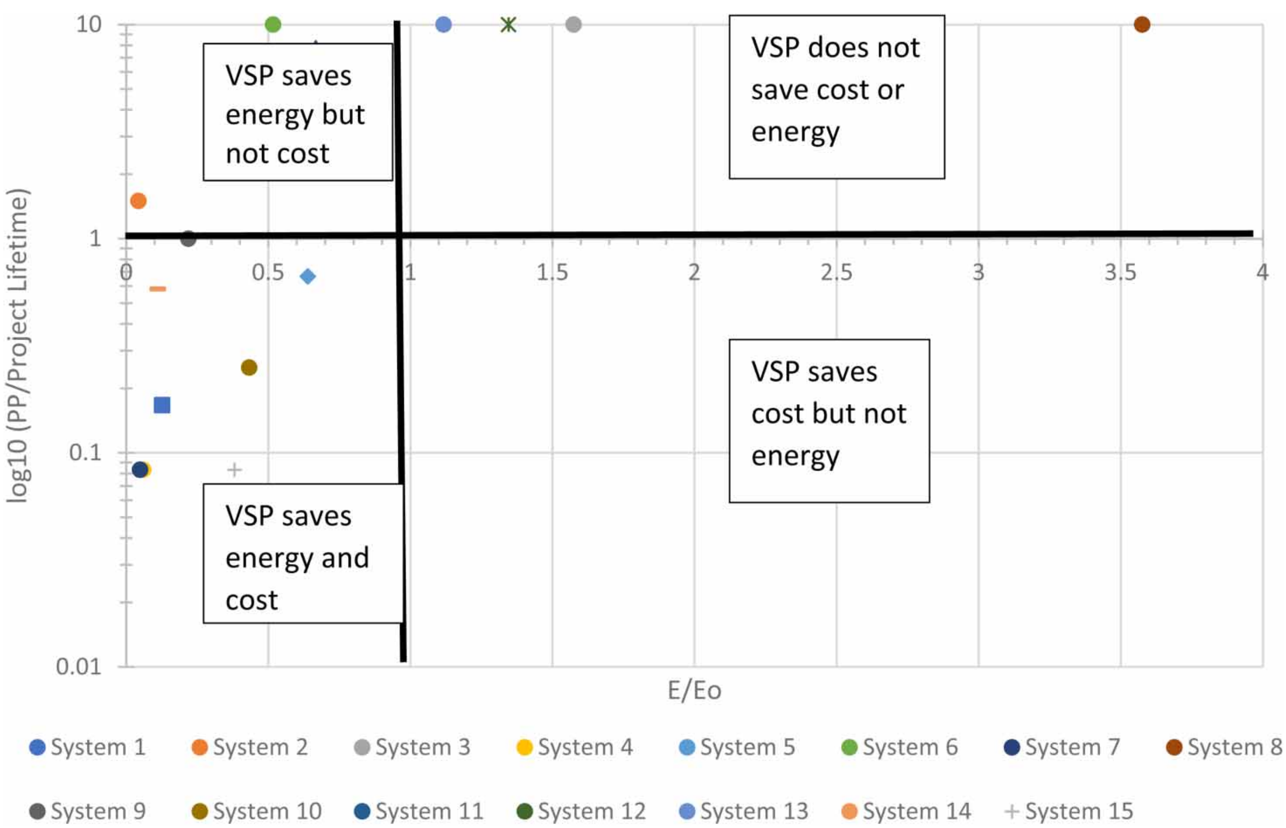

Figure 1 | Graph of PP/project lifetime vs. E/E_o to aid in deciding whether to replace a constant-speed pump with a VSP. Systems that plot closer to origin with E/E_o and PP/project lifetime values <1.0 indicate the efficacy of installing a VSP.

line for both axes. The lower left quadrant denotes a system in which a VSP will pay off and also reduce greenhouse gas emissions. The lower left is where the PP is short and the energy of running the pump is also low. This is the ideal section of the chart for a system installing VSP to be. The upper right quadrant has long PPs and higher energy costs for running the pumps. This section is when a VSP should never be installed because both factors are non-ideal. The upper left quadrant is where there are long PPs but the energy cost of running the pumps is low. This section may not be the best economically but since the pump will require less energy to run, the environmental impacts of high energy use will be reduced; thus, depending on the goals of the system managers installing the pump, VSPs may be considered. The lower right quadrant is where there are short PPs and high energy costs. Systems in this quadrant will save money but use more energy which will increase environmental impacts. This is another decision that the managers of the system will need to make. However, none of the tested systems ended up in this section, so this may be a rare section due to the relationship between energy cost and energy usage. More energy usage will lead to more costs, making a PP less than the VSP lifetime harder to attain.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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