

Article

Energy Cost Optimization for Water Distribution Networks Using Demand Pattern and Storage Facilities

Yungyu Chang ¹, Gyewoon Choi ², Juhwan Kim ³ and Seongjoon Byeon ^{4,*}¹ Seohae Environmental Science Institute, Jeonbuk 54817, Korea; ravage@nate.com² Department of Civil and Environmental Engineering, Incheon National University, Incheon 22012, Korea; gyewoon@inu.ac.kr³ K-Water Institute, Water Research Center, Daejeon 34045, Korea; juhwan@kwater.or.kr⁴ International Center for Urban Water Hydroinformatics Research & Innovation, Incheon 21999, Korea

* Correspondence: seongjoon.byeon@gmail.com; Tel.: +82-32-851-5731; Fax: +82-32-851-5730

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Abstract: Energy consumption in water supply systems is closely connected with the demand for water, since energy is mostly consumed in the process of water transport and distribution, in addition to the energy that might be needed to pump the water from its sources. Existing studies have been carried out on optimizing the pump operations to attain appropriate pressure and on controlling the water level of storage facilities to transfer the required demand and to reduce the energy cost. The idea is to reduce the amount of the water being supplied when the unit price of energy is high and to increase the supply when the unit price is low. To realize this scheme, the energy consumption of water supply systems, the amount of water transfer, the organization of energy cost structure, the utilization of water tanks, and so forth are investigated and analyzed to establish a model of optimized water demand management based on the application of water tanks in supplied areas. In this study, with the assumption that energy cost can be reduced by the redistribution of a demand pattern, a numerical analysis is conducted on transferring water demand at storage facilities from the peak energy cost hours to the lower energy cost hours. This study was applied at the Bupyeong 2 reservoir catchment, Incheon, Korea.

Keywords: energy costs; genetic algorithms; water pipe network analysis; water storage facilities; demand pattern optimization; water distribution systems

1. Introduction

These days, it is always necessary to make big efforts to save energy costs. In addition, energy savings in South Korea are always an important matter. Nationwide, South Koreans were reminded of this issue after suffering traumatic damage from a major blackout throughout the country in 2011. In addition, energy issues relating to climate change and emission reductions are currently treated as part of the national competitiveness strategy (IEA, Paris, France, 2012) [1].

In terms of water distribution networks (WDNs), water saving strategies (e.g., water demand control and water efficient design) are generally implemented as part of energy saving efforts by water saving company projects, water saving utilities, and different campaigns. These programs are favorably progressing since water use is naturally connected with energy consumption.

Previous studies on demand management have established various data sets on water consumption patterns for different purposes of water use. Furthermore, several strategies have emerged and have been tested in previous studies [2–7]. In addition, Kim et al. (2007) and Kanakoudis and Tsitsifli (2013) monitored water demand patterns and their side effects in terms of hours in

the day, days in the week, season, and weather [8,9]. Myeong et al. (2011) studied water demand with spatial patterns, such as the house type, number of rooms in the house, house area, and population in the house, by statistical analysis [10]. In addition, Kim et al. (2012) studied leakage as one of the reasons for energy overconsumption and developed a strategic model of leakage detection by demand pattern analysis [11]. Kanakoudis and Gonelas (2016) studied the economic leakage level in a water distribution system [12], and the same authors (2015) studied the joint effect of cost and water pressure. Seo (2011) developed a water savings index to evaluate strategies driven by local authorities and Kanakoudis and Gonelas (2015) studied water price changes based on pressure management [13,14].

Several preliminary studies on water storage facilities have been conducted. Previous studies have mainly focused on assessing storage facilities throughout the country [15,16]. The results have provided data on water tanks and their hydraulic characteristics, downtime, and water quality. Generally, the downtime averaged 0.3–3.9 days, and generally only 37.6% of total storage capacity was used.

Most of the studies on WDNs have focused on water safety (quality), stable distribution (quantity), future water demand estimates, and efficient management [17–20]. To date, however, the primary subjects of the current study (e.g., control of water demand patterns and energy savings) have not been extensively researched.

The major purpose of the current study is to develop a strategy of controlling the hourly patterns of water consumption by using storage facilities in order to reduce water use during high energy price hours (peak time) by distributing water use from peak times to low energy price hours. The purpose and scope of this study include the following: (a) investigate storage facilities in South Korea and especially Incheon, which is a metropolitan city; (b) develop a MATLAB (MATLAB R2013a, MathWorks, Natick, MA, USA) optimization model with a genetic algorithm (GA) for energy cost minimization; (c) apply an EPANET (EPANET 2.0, US EPA, Cincinnati, OH, USA) model to assess WDNs; and (d) apply an EPANET model as a variable of a MATLAB optimization model to finalize the results.

2. Materials and Methods

2.1. Energy Consumption

Generally, energy costs reflect geomorphological conditions from the source to the consumers; however, energy consumption in WDNs varies in location and process [21]. For instance, most energy consumption at a water treatment plant (WTP) is for facility operation, as it uses gravity-dominant flow, while water distribution pipelines use most of the energy for pumping using pressure flow. Energy consumption at a WTP will remain unconditionally compulsory and uncontrollable until new energy efficient machines are developed. However, pumping energy can be varied and reduced by its cost optimization. In addition, pumping energy, which uses electricity, incurs variable costs by the season and hour of the day; therefore, it is necessary to understand the electricity price system when investigating how to minimize the energy cost [22,23]. It is essential to secure stable electricity in the daytime as higher consumption is needed, and this phenomenon is connected with high-cost materials for power generation and high costs for energy consumption [24]. For example, in South Korea, unit cost per kilowatt-hour (Kw h) varies from 0.059 US dollar (USD) to 0.193 USD depending on the time of day (the cost is approximately 3.25 times higher at peak versus low usage times), and it could be possible to reduce around 69.2% of the energy cost by optimization. Table 1 shows an example of the energy consumption at the peak, intermediate, and low cost levels of water supply systems.

According to the characteristics of the price of electricity, it is necessary to consider the hour of the day, demand distribution, and storage facility type (tank or reservoir). In terms of the hour of day, the peak hour varies depending on the season, and hourly energy consumption patterns also vary according to the season. However, seasonal water consumption patterns are similar to one another unless demand patterns are properly managed for energy cost savings by using a storage facility, such as a water storage tank at an apartment complex. The storage facility could be filled with water during low-cost hours and could supply water during high-cost hours from the facility

without (or partially) using the main water supply [9]. Furthermore, WDNs with different WTPs might have distinct differences, and each WDN has its own storage facilities. Therefore, energy cost can be minimized through optimal operations of demand pattern control, WTPs, and storage facilities [25,26]. Although the price of water supply does not vary with time, the minimized, by optimization, energy cost can affect the improvement of water pricing policy [27].

Table 1. Energy consumption at a water supply system (example of South Korea).

Year	Cost Level	Unit Price US Dollar/kW h	Intake St. (%)	Pumping St. (%)	Water distribution Networks (WDNs) (%)
2011	High	0.193	47.9	47.9	46.2
	Middle	0.112	35.5	35.5	36.8
	Low	0.059	16.6	16.6	17.0
2012	High	0.193	47.0	47.2	45.1
	Middle	0.112	35.5	35.4	36.7
	Low	0.059	17.5	17.4	18.2

2.2. Water Storage Facilities

Water supply by WDNs is occasionally operated by different supply methods, such as (1) direct water supply (i.e., water coming directly from the water supply); (2) indirect water supply (i.e., through storage facilities such as a tank); and (3) combinations of direct-indirect water supplies. In general, storage facilities are used to ensure a stable water supply with constant water supply through securing water pressure. Table 2 presents the current state of installed water storage facilities in Incheon metropolitan city.

Table 2. Water distribution storage facilities (water tank) in Incheon city.

Building Type and Minimum Criteria of Water Storage Facility Necessity	No. of Storage Facilities
General buildings larger than 5000 m ²	816
Commercial buildings larger than 3000 m ²	334
Complex buildings larger than 2000 m ²	450
Theaters	2
Private academies over 2000 m ²	2
Large shops at individual buildings	6
Wedding halls over 2000 m ²	12
Indoor gyms	4
Apartment complexes	1067
Total	2693

Most of the storage facilities are installed in the apartments or in large buildings with areas greater than 2000 m². The storage facilities are operated by individual buildings, and there is no special code on storage facility operations; therefore, the operation of facilities occasionally depend on the practically based rule of meeting water demand. Kwak et al. (2005) studied the hydraulic characteristics of water storage facilities [16]. In their study, downtime averaged 0.3–3.9 days and the water level average was 37.6% of height. At this level, and operating inefficiently, less than 40% of the storage facility is being used. However, water demand is typically less than 40% of the capacity of a water storage facility, and the rest (60% of storage) of the capacity can be used as research capacity for this study.

2.3. EPANET

Since the EPANET model was developed by the US Environment Protection Agency in 1994, hydraulic simulations of WDNs have been routinely implemented. EPANET has been extensively used

as a tool for research implementation in terms of network design optimization [28,29]. EPANET can be used through a graphical user interface (GUI) as standalone software or can be used through a toolkit library using open source user-specific software. The library and source code can be called through external programming language [29]. In this study, the MATLAB toolkit for the EPANET model was used [30]. MATLAB allows connections to external software libraries, which can help researchers use tools and simulators developed originally in a different language. The EPANET source code was originally formulated in C language.

2.4. Genetic Algorithms

GAs are widely used for the optimization of water-related problems [28,31–33]. This optimization technique searches for a solution with minimum costs given as the objective goal of the target problem [33]. Prasad et al. (2003) presented a GA with multivariable functions for an optimal design of WDNs using a Pareto-optimal approach [34]. Prasad and Park (2004) outlined a multi-objective GA for an optimal WDN design [35]. Deb and Jain (2014) developed a nondominated sorting approach for Multi-objective Genetic Algorithm (MOGA) for multi-objective optimization [36]. The considered objectives minimize the error among real and simulated values and maximize reliability. In this study, a GA was selected and coded by simple revision. The GA, based on Deb and Jain's (2014) work [36], included the following considerations: (1) minimum and maximum values for mutation and cross-over; (2) the EPANET model as its variable; (3) many variables with multiple objectives; and a (4) simultaneously fixed bug at mutation with 10+ variables. The GA model was applied for emitter calibration by minimizing errors because the number of variables to be calibrated in WDN was the same as the number of junctions in the network. The EPANET model was applied as the general solver for variables to be calibrated in conjunction with GA. The Pareto front (known as the nondominated solution set) is the fully optimal solution in a multi-objective sense, and the GA is a robust optimization approach for multi-objective purposes with the Pareto front [37].

3. Development of the Optimization Tool

3.1. Objective Function

A formula was developed based on the concept of energy costs for water transfer in WDNs. Energy costs are closely related to water flow and its unit energy cost, and water flow is generated based on water consumption, which has occasionally similar patterns in terms of the energy cost hourly patterns. A possible assumption is that the energy cost could be minimized by redistributing pattern within the concept of GA optimization. The basic concept for optimization is described in Figure 1.

As shown in Figure 1, the demand pattern is considered as a variable, and they become input variables for EPANET to produce the variation of water flow rate. Produced water flow rate as an hourly pattern becomes a new water consumption pattern, and the calculation is iterated through GA optimization. In addition, the energy cost by each pattern is calculated, and the iteration continues until the tool finds the minimum cost as specified.

The water consumption at peak cost time can be classified by consumption through a direct water supply or an indirect water supply (by tank). A direct water supply cannot control the consumption pattern, while an indirect water supply can control it by storage operation. A water supply with high-cost pumping energy during peak price hours can be moved to low-cost hours through tank storage operations. Thus, the daily water supply can be expressed through the summation of a controllable water supply and an uncontrollable water supply, and the energy cost is the summation of hourly water supply multiplied by hourly energy cost, as depicted in Equations (1) and (2):

$$Q_{day} = \sum_{i=1}^{24} [Q_n \cdot P_n(i) + Q_u \cdot P_u(i)], \quad (1)$$

$$\text{Energy Cost} = \sum_{i=1}^{24} [Q_n \cdot P_n(i) + Q_u \cdot P_u(i)] \cdot E_{\text{cost}}(i), \quad (2)$$

where Q_{day} is the daily total water consumption, Q_n is the daily water consumption by direct water supply (without a storage facility), Q_u is the daily water consumption by the indirect water supply (with a water storage facility), $P_n(i)$ is the dimensionless pattern of water consumption for the direct water supply (uncontrollable) at time step i and can be determined through hourly water consumption by direct water supply divided by the Q_n , $P_u(i)$ is the dimensionless pattern of water consumption for the indirect water supply (controllable) at time step i and can be determined by hourly water consumption (indirect with a water storage facility) divided by Q_u , and $E_{\text{cost}}(i)$ is the energy cost for water transfer at time step i . P_n and P_u are dimensionless hourly patterns of daily water consumption and they vary within a range from zero to one and the sum of 24 h value should be one, respectively. In Equations (1) and (2), Q_n and Q_u are fixed daily value and P_n is also a fixed value; therefore, Q_n , Q_u and P_n are variables out of design space while P_u is a variable that varies within the range from zero to one. In addition, unit cost of electricity also varies with time and season. Therefore, the water consumption designed by the P_u and the energy cost designed by the unit price of electricity were used as the bi-objective Pareto front objective function. By Equations (1) and (2), the objective function for optimization can be defined as Equation (3):

$$\text{Objective Function for Minimum cost (OF)} = \text{Minimize} \sum_{i=1}^{24} D_i C_i, \quad (3)$$

where D_i is the water consumption at time step i , and C_i is the unit price of electricity at time step i . The energy cost optimization should also consider the stability of water consumption by securing the necessary water pressure; therefore, there must be two constraints. In the optimization model, we tried to find the lowest objective function value as the energy cost for the water supply through designing a P_u variable. However, some of chromosomes that are produced through GA can lead to unexpected or infeasible values. Previous studies on GA recommend defining a penalty for them to guide algorithms to avoid infeasible values through defining penalty functions [38,39]. Therefore, the first constraint applies a penalty function throughout the WDNs at junctions, and the other constraint defines the pressure range constraint at specified junctions. Therefore, the penalty function is defined as Equation (4):

$$\text{Penalty Function (PF)} = \alpha \cdot \sum_{i=1}^{24} P_t(i), \quad (4)$$

where $P_t(i)$ is the pressure at all junctions within total WDNs, and α is a coefficient to determine relativeness among OF and PF. The value of α is zero when the pressure at the junction is in the range of specified minimum and maximum pressure by user specification. Thus, the OF can be revised within the consideration of PF as Equation (5):

$$\text{OF} = \sum_{i=1}^{24} D_i C_i + \alpha \cdot \sum_{i=1}^{24} P_t(i). \quad (5)$$

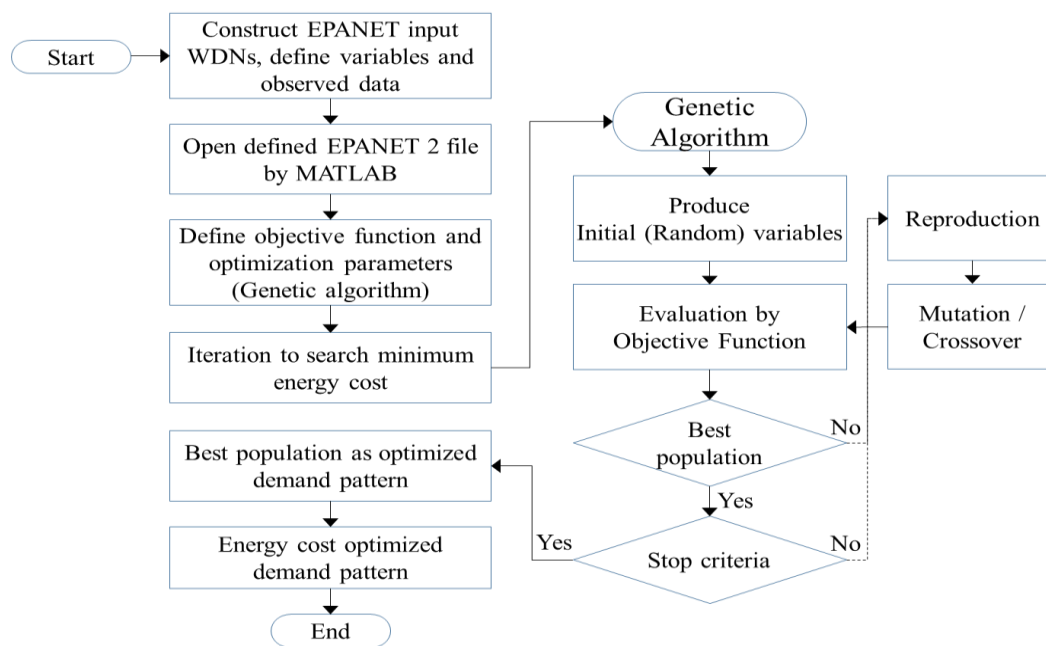


Figure 1. General framework for energy cost optimization.

3.2. Study Area

In this study, the study area is chosen in the effluence area of Bupyeong's second water supply reservoir since there are several different types of storage facilities and different types of land use (e.g., residential, commercial, public, and an apartment complex). In addition, data about WDNs, electricity, and hydraulic data (flow rate and pressure) could be secured. Figure 2a shows the boundary and land use data of the study area, and Figure 2b shows the pipeline on the block.

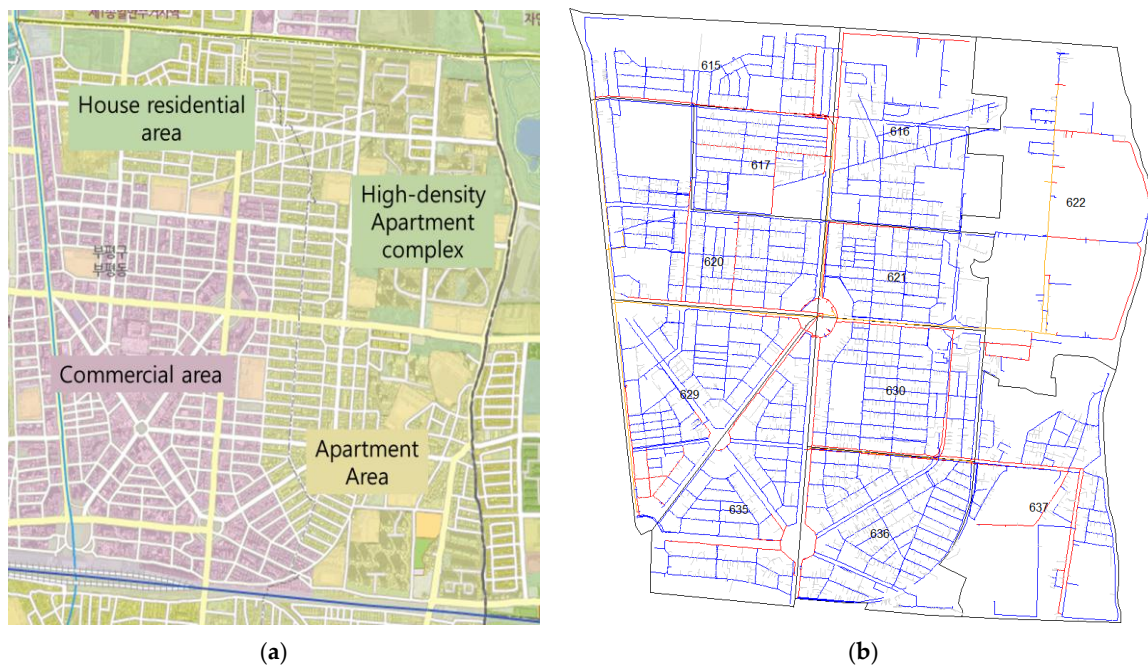


Figure 2. Maps of study area: (a) land use map; and (b) pipeline map.

In the study area, the daily maximum water supply is 46,000 m³/day, and the water supply is generally coming from Bupyeong's second water supply reservoir, which has 20,000 m³ of capacity, 59.5 m at the high-water level, and 55 m at the low-water level. The maximum water use pattern occurs between 6:00 p.m. and 7:00 p.m., and the water use pattern for the high energy cost time frame (peak hours) and the intermediate high cost time frame (mid hours) is high while the pattern for the low energy cost time frame (low hours) is low. Thus, it is possible to lower energy costs by redistributing the water use pattern. The water use pattern is shown in Figure 3.

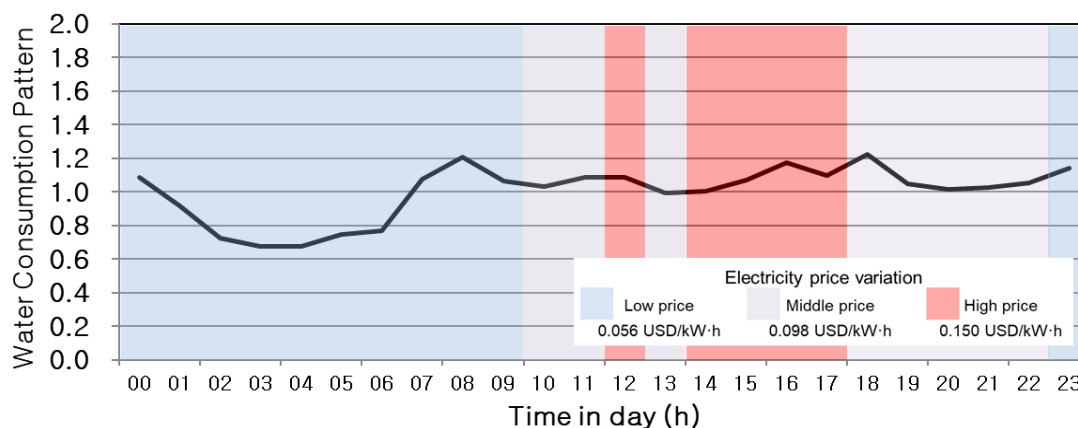


Figure 3. Water demand pattern of the study area.

In Figure 3, the water demand pattern is high during peak cost and intermediate cost hours, while the pattern is low during low energy cost hours. In this study, we assumed that the high water demand pattern can be moved to the low energy cost hours by using the water storage facilities (which are not actively used), and the use of facility can be determined by the optimization process.

The study area has 122 storage facilities and 11,321 m³ of capacity in total storage facilities. The total capacity of the storage facilities is approximately 24% of the daily maximum water supply (46,000 m³/day). Seven storage facilities have greater than 500 m³ of capacity, and they represent about half the total capacity of all the storage facilities, as shown in Table 3.

Table 3. Number of storage facilities and their water demand in study area.

Storage Capacity (m ³)	No. of Facilities	Sum of Daily Mean Water Demand (m ³ /day)
1–10	18	106
11–50	70	1718
51–100	14	890
101–500	13	2976
501–1000	7	5631
Total	122	11,321

The official GIS provided from Incheon city authorities was used as the major input for EPANET modeling, and the water use pattern data was included in the model for an extended period simulation. The completed set of EPANET data was validated by test simulation and added as a variable of Matlab GA optimization. Table 4 shows the summarized parameters for GA optimization.

The parameters were determined through several test implementations. Moreover, the main variable for optimization was the WDN's pipe network problem, which was also quite complicated to solve. The length of chromosome was set as 24 since there were 24 real number coding for each hour pattern (24/day). The population was set as 50 after several practice runs. The linear ranking was selected as 1.7 for higher selective pressure. In addition, random selection for crossover and a 0.1 mutation ratio were selected.

Table 4. Main parameters for genetic algorithm optimization.

Procedure	Parameter Name	Value	Remarks
Real number coding	Length of chromosome	$L = 24$	
Population	Population	50	
Linear ranking	Crowding degree of crossover	$\eta_{\max} = 1.7$	
Crossover	Crossover ratio	0–50%	Randomly varying in generations
Mutation	Maximum generation	0–10%	Randomly varying in generations
Scaling window	Scaling window	$W_s = 1.0$	
Elitist selection	Survived generation	1	

The model simulation consisted of five different cases for each season. The first case shows the current state of operation without any application of energy saving strategies. The second, third, and fourth cases depict the redistribution of water demand to the low energy cost hours at 60%, 80%, and 100% of water use, respectively. The last case applies the GA optimization. Table 5 shows detailed descriptions of the simulation cases.

Table 5. The classification of cases.

Season	Case Name	Description
Summer	SP	Current State
	S1	Uniform distribution of 60% demand of storage facility at low price hours
	S2	Uniform distribution of 80% demand of storage facility at low price hours
	S3	Uniform distribution of 100% demand of storage facility at low price hours
	SGA	Distribution optimization by genetic algorithm
Winter	WP	Current State
	W1	Uniform distribution of 60% demand of storage facility at low price hours
	W2	Uniform distribution of 80% demand of storage facility at low price hours
	W3	Uniform distribution of 100% demand of storage facility at low price hours
	WGA	Distribution optimization by genetic algorithm
Spring and Autumn	FP	Current State
	F1	Uniform distribution of 60% demand of storage facility at low price hours
	F2	Uniform distribution of 80% demand of storage facility at low price hours
	F3	Uniform distribution of 100% demand of storage facility at low price hours
	FGA	Distribution optimization by genetic algorithm

4. Results and Discussion

4.1. Model Sensitivity and Convergence

To choose the value of α , a coefficient to determine relativeness among objective function and penalty function as described in Equation (4), the sensitivity of α was examined. The result is shown in Figure 4.

The pattern of $P_u(i)$ (the dimensionless pattern of water consumption for the indirect water supply, which is controllable, at time step i) in Figure 4 is similar to all cases since the GA is calculated based on the rank of the generated population, and the extreme values in the population are excluded due to their low rank. However, the higher value of α distributes homogeneous pressure, which could provide less fluctuation since the penalty function reflects the pressure in the pipe network. In addition, the simulation time, from start to convergence, with the value of higher α was shorter than lower or the zero value of α . To summarize, the penalty function affected the convergence in determining the optimized value of the objective function; however, the sensitivity itself was not high. The value of α

was determined as 10% by the analysis. The convergence of the objective function with the value of α as 10% is shown in Figure 5.

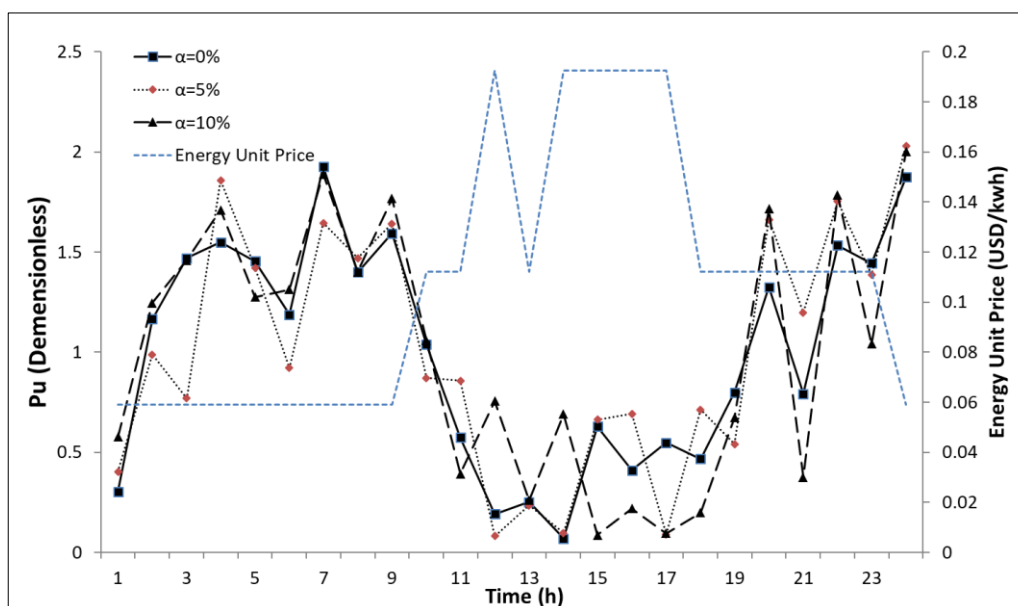


Figure 4. Demand pattern change by the penalty function coefficient.

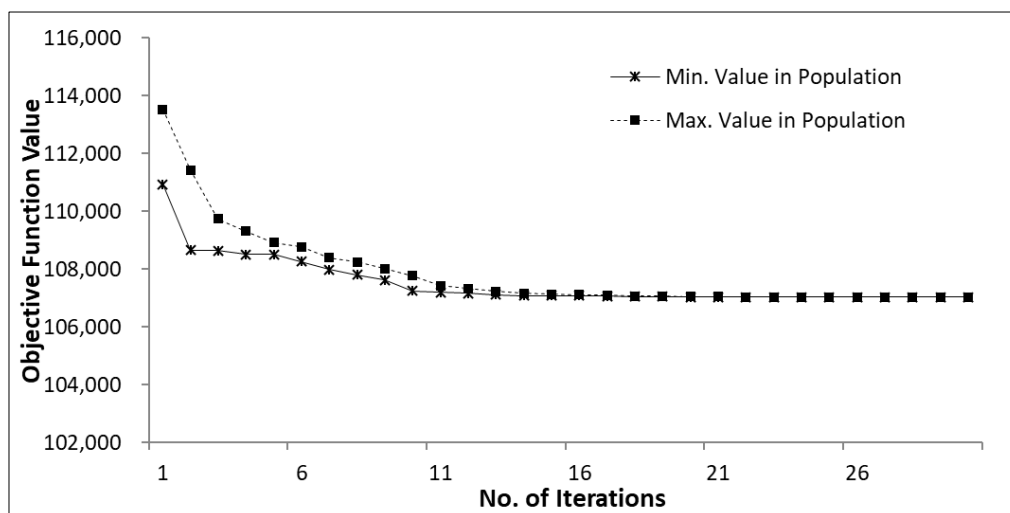


Figure 5. Convergence of objective function value with summer season data.

The convergence was tested with the result of the objective function value in the summer season. The convergence was completed at the 22nd generation. Fast convergence can show the lack of diversity; however, this fast convergence could be made by the effect of the penalty function, which can provide a strong exploration capacity for the model. The total number of pipe networks with iterations was 1100 times, and the convergence made a slow improvement, which can be appropriate for optimization. In addition, the convergence patterns in the other seasons were similar to the example of the summer season.

To optimize the energy cost, we examined cases by uniform distribution and optimization in different seasons; however, the spring and autumn seasons were treated as the same case since the energy cost in the spring and autumn are the same. The classification of cases is shown in Table 5.

4.2. Summer Season

In the summer season, the flow rate between 10:00 a.m. and 11:00 p.m. (peak and mid hours) is high, while water consumption for the low energy cost hours is comparably low, as shown in Figure 6.

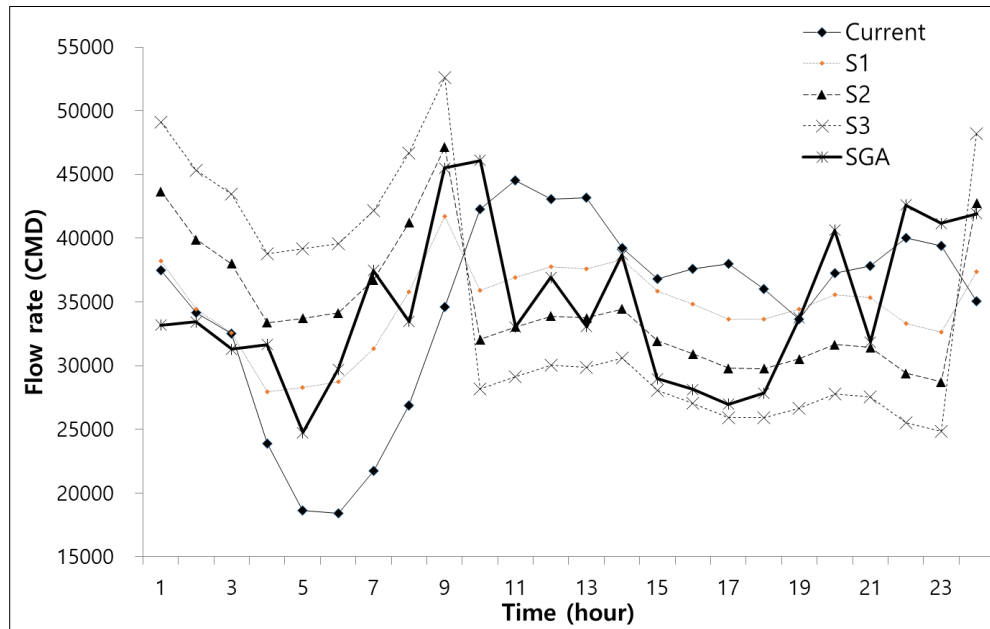


Figure 6. Resulting comparison for the summer season.

In Case S1, water consumption from the storage facilities was increased during the low energy cost hours, while it decreased during peak and mid hours. Bigger variations occurred in Case S2 and S3, with an almost reversed pattern from the current state. In addition, the results of S1, S2, and S3 showed different scales of variations by the different proportions of storage usage but showed similar variation patterns since the distribution method was almost the same. In the case with GA optimization (SGA), the pattern was between the patterns of S1 and S2 during the low energy cost hours, while the pattern was similar to the S3 pattern during peak hours. It is clear that the water demand during peak hours and mid hours was transferred and distributed for low cost hours, as shown in Table 6.

Table 6. Hourly variation of flow rate patterns for the summer season.

Time	Cost Level	Hourly Flow Rate (m ³ /h)					Difference with Current (m ³)			
		Current	S1	S2	S3	SGA	S1	S2	S3	SGA
1	Low	1563	1593	1819	2046	1363	−30	−257	−483	200
2		1422	1436	1662	1889	1409	−13	−240	−466	13
3		1355	1358	1584	1810	1232	−3	−229	−456	123
4		996	1164	1390	1617	1151	−168	−394	−621	−155
5		777	1179	1405	1631	1237	−401	−628	−854	−460
6		767	1197	1423	1649	895	−430	−656	−883	−128
7		905	1305	1531	1758	1542	−400	−626	−853	−637
8		1120	1491	1718	1944	1674	−371	−598	−824	−554
9		1441	1738	1964	2191	1918	−297	−523	−749	−477

Table 6. Cont.

Time	Cost Level	Hourly Flow Rate (m ³ /h)					Difference with Current (m ³)			
		Current	S1	S2	S3	SGA	S1	S2	S3	SGA
10	Mid	1761	1497	1335	1173	1552	264	426	587	209
11		1854	1538	1376	1215	1577	316	478	640	278
12	Peak	1794	1574	1412	1251	1255	220	382	543	539
13	Mid	1799	1568	1406	1244	1465	232	394	555	334
14	Peak	1634	1598	1436	1274	1397	37	198	360	238
15		1535	1493	1331	1169	1338	42	204	365	197
16		1567	1451	1289	1127	1247	117	278	440	320
17		1584	1403	1241	1080	1169	181	342	504	415
18	Mid	1500	1402	1241	1079	1206	97	259	421	294
19		1402	1434	1272	1110	1516	−32	130	292	−114
20		1552	1481	1320	1158	1853	71	232	394	−301
21		1575	1472	1310	1148	1626	103	265	427	−51
22		1667	1387	1225	1063	1767	281	442	604	−99
23		1641	1359	1197	1036	1500	282	444	606	141
24	Low	1460	1556	1782	2009	1784	−96	−322	−549	−324
Summary	Low	11,806	14,015	16,279	18,544	14,265	−2209	−4474	−6738	−2459
	Mid	14,752	13,138	11,682	10,227	13,751	1614	3070	4525	1000
	Peak	8114	7518	6709	5901	6655	596	1404	2213	1459

As shown in Table 6, the transferred water from intermediate hours to low hours is higher in cases S1, S2, and S3 than for SGA, while the transferred water from peak hours to low hours is higher in the SGA case than in the rest of the cases. Therefore, in the cases for the summer season, the SGA case shows higher efficiency for energy savings. Figure 7 shows the transferred water demand from the peak and mid hours to the low hours.

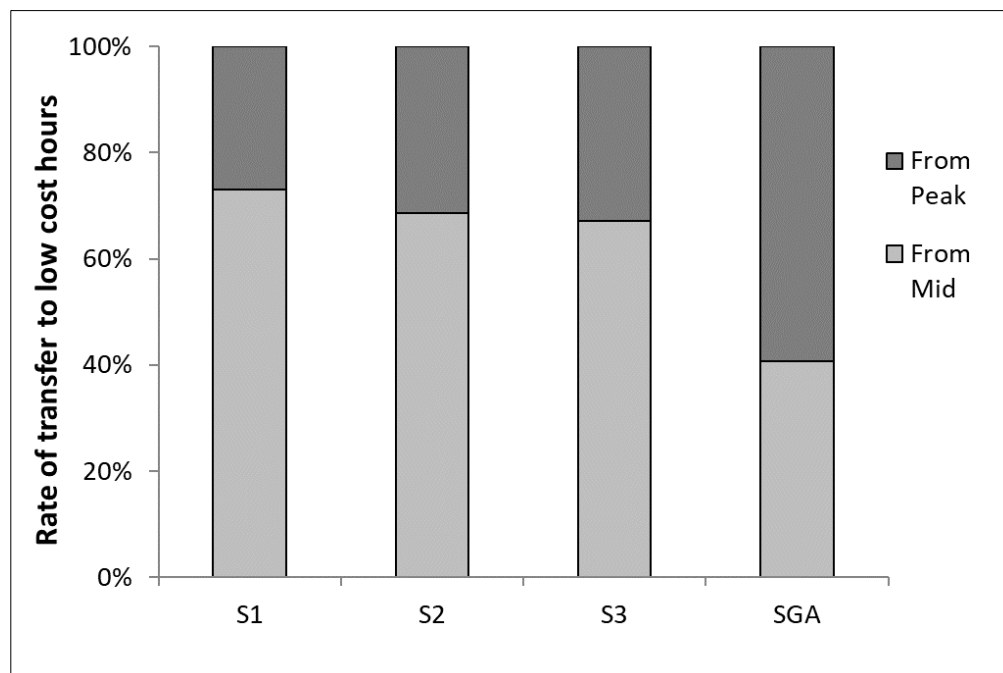


Figure 7. Flow rate transferred to low cost hours by summer season simulation.

In Figure 7, the water demand transferred from peak hours to low hours in cases S1, S2, and S3 was approximately 27–33%, while it was approximately 60% in the SGA case, as the GA tries to give priority for water demand during peak hours. The saving effect in case S1 and SGA was approximately 33.3%.

4.3. Winter Season

In the winter season, unlike the summer, the flow rate is very high in the evening time, especially between 6:00 p.m. and 9:00 p.m. and 10:00 p.m. and 11:00 p.m., as shown in Figure 8.

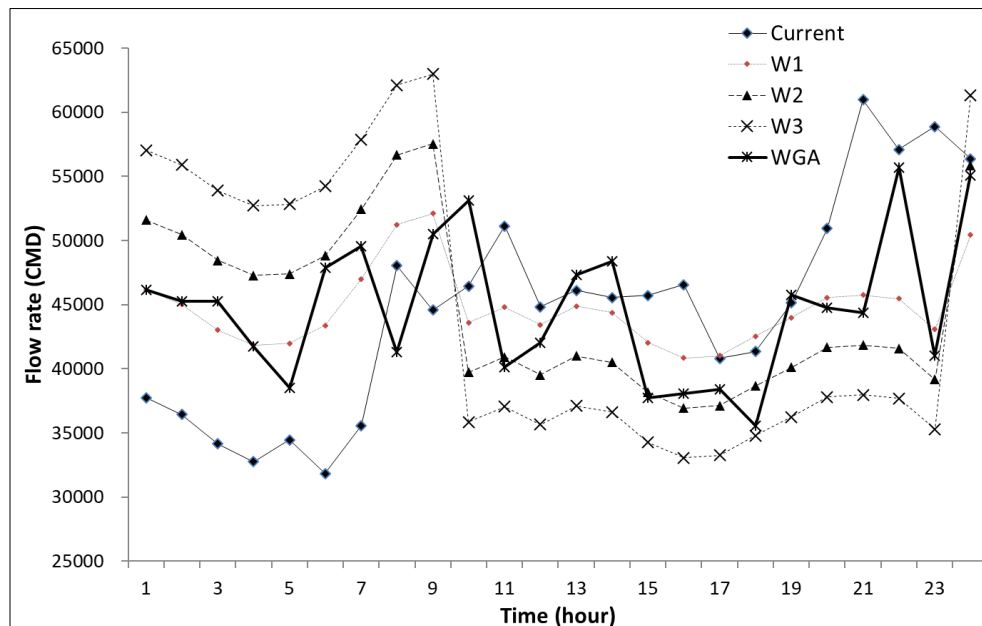


Figure 8. Result comparison for the winter season.

In cases W1, W2, and W3, the variations of water demand pattern from the current state were similar to the cases for the summer season. In addition, the pattern revised by case W1 was similar to the WGA case. W1, W2, and W3 at 11:00 p.m. were close to one another, with the highest variations in the day. Demand pattern changes in the W1, W2, and W3 cases were similar to the results of the summer season in S1, S2, and S3, respectively, with the reversed demand, while the WGA case showed very low demand between 5:00 p.m. and 6:00 p.m. and at 11:00 p.m. It is clear that the water demand during the peak and mid hours was transferred and distributed to the low hours, as shown in Table 7.

Table 7. Hourly variation of flow rate pattern for the winter season.

Time	Cost Level	Hourly Flow Rate (m ³ /h)					Difference with Current (m ³)			
		Current	W1	W2	W3	WGA	W1	W2	W3	WGA
1	Low	1573	1924	2150	2376	1923	−351	−577	−804	−351
2		1518	1876	2102	2329	1885	−357	−584	−810	−366
3		1422	1793	2019	2246	1886	−371	−597	−823	−464
4		1364	1744	1970	2197	1740	−380	−606	−833	−376
5		1436	1749	1975	2202	1605	−313	−539	−766	−169
6		1326	1807	2033	2260	1994	−481	−708	−934	−668
7		1482	1958	2185	2411	2064	−477	−703	−929	−582
8		2002	2135	2362	2588	1721	−133	−360	−586	281
9		1858	2171	2398	2624	2105	−314	−540	−766	−248

Table 7. Cont.

Time	Cost Level	Hourly Flow Rate (m ³ /h)					Difference with Current (m ³)			
		Current	W1	W2	W3	WGA	W1	W2	W3	WGA
10	Mid	1935	1817	1655	1493	2213	118	280	441	−278
11		2130	1867	1705	1544	1671	263	425	587	459
12	Peak	1868	1809	1647	1486	1751	59	220	382	117
13	Mid	1921	1870	1708	1547	1971	51	213	374	−50
14	Peak	1898	1849	1687	1526	2016	49	210	372	−118
15		1904	1751	1590	1428	1572	153	315	477	333
16		1940	1701	1539	1378	1585	239	401	563	355
17		1700	1709	1547	1386	1599	−9	153	314	101
18	Mid	1722	1773	1611	1449	1482	−50	112	273	241
19		1880	1833	1672	1510	1907	47	209	371	−26
20		2122	1898	1737	1575	1866	224	385	547	256
21		2541	1906	1744	1582	1849	635	797	958	692
22		2379	1894	1733	1571	2,321	484	646	808	58
23		2454	1794	1632	1471	1,710	660	821	983	744
24		2349	2102	2328	2554	2,295	248	21	−205	54
Summary	Low	16,330	19,258	21,523	23,787	19,218	−2928	−5193	−7457	−2888
	Mid	16,217	14,498	13,204	11,910	15,126	1720	3014	4308	1091
	Peak	12,177	10,974	10,004	9034	10,386	1202	2173	3143	1791

As shown in Table 7, the transferred water from mid hours to low hours is higher in the W1, W2, and W3 cases than the WGA, while the transferred water from peak hours to low hours is higher in the WGA case than in the rest of the cases, which was similar to the case for the summer season. Therefore, in the cases for the winter season, the WGA case shows higher efficiency for energy savings. Figure 9 shows the transferred water demand from the peak and mid hours to the low hours.

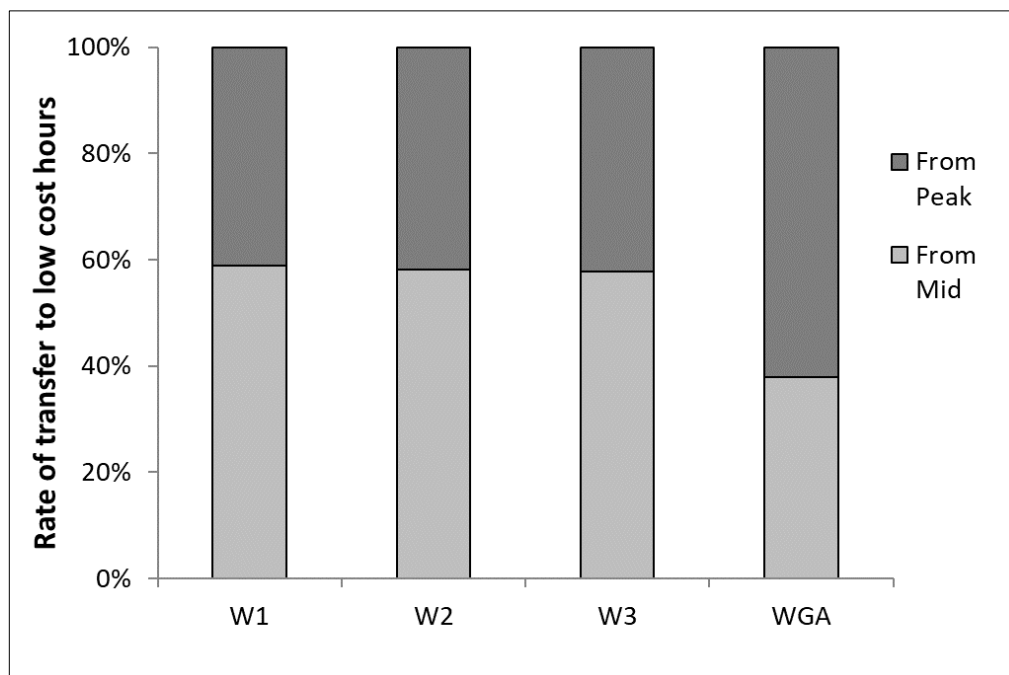


Figure 9. Flow rate transferred to low cost hours by the winter season simulation.

In Figure 9, the water demand transferred from the peak hours to the low hours in cases W1, W2, and W3 was approximately 40%, while it was approximately 60% in the WGA case, as the GA tries to give priority for water demand during peak hours. The saving effect by cases W(1, 2, and 3) and WGA was approximately 33.3%.

4.4. Spring and Autumn Seasons

In the spring and autumn seasons, unlike the summer or winter seasons, the flow rate was high during the daytime and continuous in the evening, as shown in Figure 10.

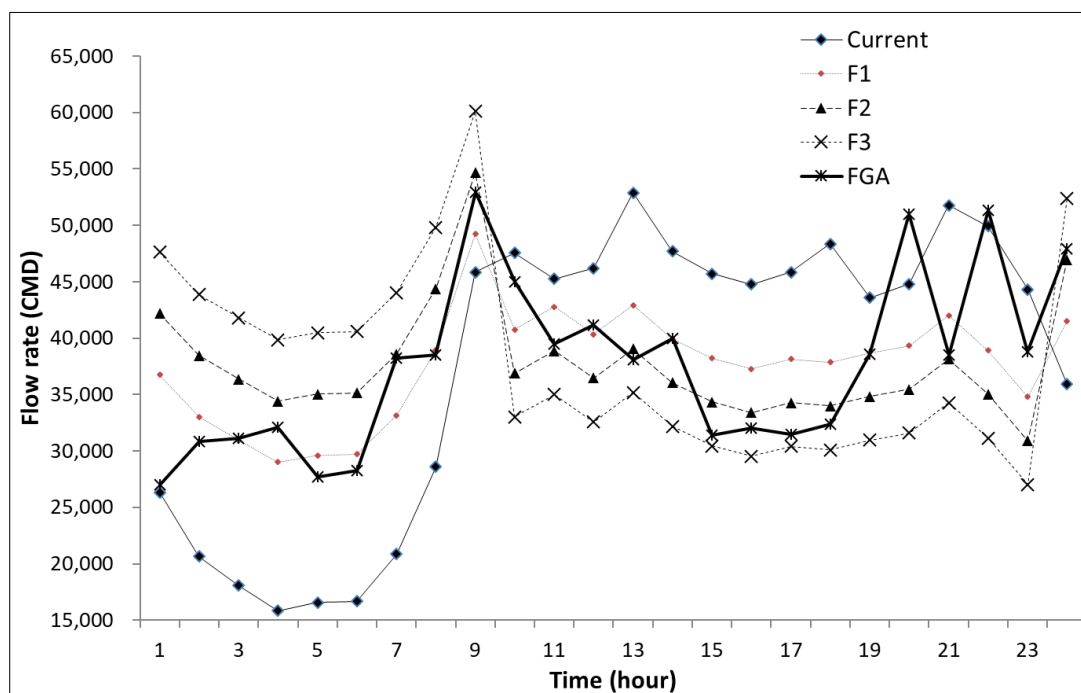


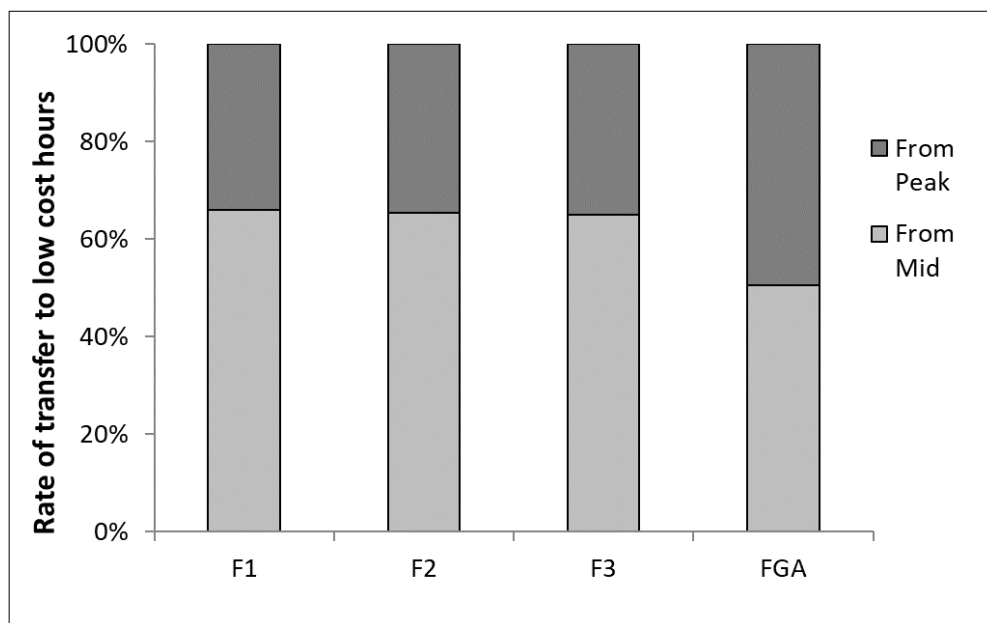
Figure 10. Result comparison for the spring-autumn season.

In the spring and autumn seasons, the shapes of the curves in Figure 10 are very different between the current state and the simulation cases. In the current case, no significant variation is observed between 9:00 a.m. and 9:00 p.m., while the simulation cases show an hourly varying curve as high demand during the morning and evening. F1, F2, and F3 show a similar variation as the S1, S2, and S3, respectively. However, the F1 and F2 cases do not show the reversed demand pattern in the morning and evening, while F3 shows a reversed pattern from the morning to evening. In terms of the FGA case with GA optimization, the curve is quite close to the SGA since the hourly energy cost in spring, summer, and autumn is constant. The differences between the current state and SGA are comparably small because of a fairly constant demand pattern in the current state. A comparison of energy costs is summarized in Table 8.

As shown in Table 8, the transferred water from the mid hours to the low hours is higher in cases F1, F2, and F3 than in FGA, while the transferred water from the peak hours to the low hours is higher in the FGA case than in the rest of the cases, similar to the case for the summer season. Therefore, in the cases for the winter season, the FGA case shows higher efficiency for energy savings. Figure 11 shows the transferred water demand from the peak and mid hours to the low hours.

Table 8. Hourly variations of the flow rate pattern for the spring–autumn season.

Time	Cost Level	Hourly Flow Rate (m ³ /h)					Difference with Current (m ³)			
		Current	F1	F2	F3	FGA	F1	F2	F3	FGA
1	Low	1097	1532	1758	1985	1125	−435	−662	−888	−28
2		861	1375	1602	1828	1284	−514	−741	−967	−423
3		752	1288	1515	1741	1298	−536	−762	−989	−545
4		660	1208	1435	1661	1336	−548	−775	−1001	−676
5		690	1234	1460	1686	1156	−544	−770	−996	−466
6		694	1238	1464	1691	1179	−544	−770	−997	−485
7		869	1382	1609	1,835	1594	−513	−739	−966	−725
8		1191	1623	1850	2076	1605	−432	−658	−885	−414
9		1911	2052	2278	2504	2206	−141	−367	−594	−296
10	Mid	1982	1699	1537	1375	1875	283	445	606	107
11		1885	1782	1620	1459	1644	103	265	426	241
12	Peak	1925	1681	1519	1357	1714	244	406	567	210
13	Mid	2204	1789	1627	1465	1588	415	577	738	616
14	Peak	1987	1664	1502	1341	1667	323	484	646	320
15		1904	1592	1430	1269	1309	312	474	635	595
16		1865	1554	1392	1230	1334	311	473	635	531
17		1910	1590	1428	1266	1312	320	482	644	598
18	Mid	2014	1578	1416	1254	1348	437	598	760	667
19		1816	1613	1451	1290	1608	204	365	527	209
20		1866	1639	1478	1316	2126	227	389	551	−259
21		2157	1751	1589	1428	1605	406	568	729	552
22		2080	1621	1459	1298	2139	458	620	782	−60
23		1846	1449	1288	1126	1617	397	558	720	228
24	Low	1497	1731	1957	2184	1996	−234	−461	−687	−499
Summary	Low	10,222	14,663	16,927	19,191	14,780	−4441	−6705	−8969	−4558
	Mid	17,851	14,921	13,466	12,010	15,550	2929	4385	5840	2301
	Peak	9591	8081	7272	6463	7336	1510	2319	3127	2255

**Figure 11.** Flow rate transferred to the low cost hours in the spring–autumn season simulation.

In Figure 11, the water demand transferred from the peak hours to the low hours in cases F1, F2, and F3 were approximately 35%, while it was approximately 50% in the FGA case, as the GA tries to give priority for water demand during peak hours. The saving effect in cases W(1, 2, and 3) and FGA was approximately 30%.

4.5. Energy Cost Savings

As discussed in the previous chapter, only 37.6% of the storage facilities are being used in the current state. Therefore, the realistic, available capacity to be used for energy cost optimization is approximately 60% of total storage facilities, and only the S1, W1, and F1 cases could be considered close to the real world scenario. The current seasonal simulations (S1, W1, and F1) and optimization cases (SGA, WGA, and FGA) compared in this chapter are summarized in Table 9.

Table 9. Comparison of energy cost by current state (base) and simulation cases for each season.

Hour	Summer Season				Winter Season				Spring–Autumn			
	Cost (USD)	Base	S1	SGA	Cost (USD)	Base	W1	WGA	Cost (USD)	Base	F1	FGA
1	0.059	92	94	82	0.065	103	126	126	0.065	65	91	66
2	0.059	84	85	82	0.065	99	122	123	0.065	51	81	76
3	0.059	80	80	77	0.065	93	117	123	0.065	44	76	77
4	0.059	59	69	78	0.065	89	114	114	0.065	39	71	79
5	0.059	46	70	61	0.065	94	114	105	0.065	41	73	68
6	0.059	45	71	73	0.065	87	118	130	0.065	41	73	70
7	0.059	53	77	92	0.065	97	128	135	0.065	51	82	94
8	0.059	66	88	82	0.065	131	139	112	0.065	70	96	95
9	0.059	85	103	112	0.065	121	142	137	0.065	113	121	130
10	0.112	198	168	216	0.110	214	201	244	0.110	163	140	155
11	0.112	208	173	154	0.166	353	309	277	0.166	155	147	135
12	0.193	345	303	296	0.166	309	300	290	0.166	216	189	193
13	0.112	202	176	155	0.110	212	206	218	0.110	182	147	131
14	0.193	315	308	310	0.110	210	204	223	0.110	223	187	187
15	0.193	295	287	232	0.110	210	193	174	0.110	214	179	147
16	0.193	302	279	226	0.110	214	188	175	0.110	210	175	150
17	0.193	305	270	216	0.110	188	189	177	0.110	215	179	147
18	0.112	168	157	130	0.166	285	294	245	0.166	166	130	111
19	0.112	157	161	158	0.166	311	304	316	0.166	150	133	132
20	0.112	174	166	190	0.166	351	314	309	0.166	154	135	175
21	0.112	177	165	149	0.110	280	210	204	0.110	178	144	132
22	0.112	187	156	199	0.110	263	209	256	0.110	171	134	176
23	0.112	184	152	192	0.166	406	297	283	0.166	152	119	133
24	0.059	86	92	103	0.065	153	137	150	0.065	88	102	118
Sum		3915	3750	3667		4873	4675	4645		3153	3004	2979
Reduce Rate (%)			4.22	6.33			4.06	4.69			4.71	5.51

In terms of the energy cost in the summer season, the cost reductions would be 4.22% for S1, 6.33% for SGA, 4.06% for W1, and 4.69% for WGA from the 3.92 USD/m³ cost at the current state. For spring and autumn, F1 and FGA can be reduced by 4.71% and 5.51%, respectively. It means that the energy efficiency reduction is best in the summer season, while the winter season does not show significant differences.

In this study, only WDNs were applied to reduce the energy cost in a water supply system; however, the cost reduction ratio could be applied to the whole process in the water supply system, including the water supply pump from the WTP to the reservoir, the intake pump, and the boost pump from the intake to the WTP. The monthly reduction ratio is determined as the reducing ratio of energy cost from SGA, WGA, and FGA, and the estimated reductions are summarized in Table 10.

Table 10. Estimated reduction of energy cost.

Month	Pumping Energy Cost (US Dollar)			Reduction Rate	Estimated Reduction (US Dollar)		
	Water treatment plant (WTP) to Reservoir	Intake to WTP	Intake Pump		WTP to Reservoir	Intake to WTP	Intake Pump
1	217,187	374,619	198,833	4.69	10,186	17,570	9325
2	204,927	368,949	195,837	4.69	9611	17,304	9185
3	163,857	295,386	159,691	5.51	9029	16,276	8799
4	158,186	284,807	152,206	5.51	8716	15,693	8387
5	161,967	265,562	143,691	5.51	8924	14,632	7917
6	162,426	277,781	150,808	5.51	8950	15,306	8310
7	208,737	363,752	194,557	6.33	13,213	23,026	12,315
8	231,201	392,057	209,807	6.33	14,635	24,817	13,281
9	178,433	288,754	157,592	5.51	9832	15,910	8683
10	187,814	314,747	177,283	5.51	10,349	17,343	9768
11	220,807	359,276	201,406	4.69	10,356	16,850	9446
12	224,347	343,844	189,648	4.69	10,522	16,126	8894
Total	2,319,890	3,929,535	2,131,360	-	124,322	210,852	114,311

5. Conclusions

In a water distribution system, the proportion of energy costs from using pumps at the WDN is high for the total cost. Energy cost (electricity) varies according to the season of year and the hours of a day. The water demand pattern is similar to the hourly energy cost curve, so high water demand occurs during high energy cost hours. In this study, under the assumption that energy cost reduction is possible through redistributing the demand pattern, a numerical analysis was conducted on transferring the water demand at peak energy cost hours to low energy cost hours by the storage facilities. This study was applied to a real facility, the Bupyeong 2 reservoir catchment, and produced the following conclusions.

The demand pattern was optimized using several methods, and the optimization was applied for the summer, winter, and spring–autumn seasons. The maximum energy cost savings from the optimization was 6.33% for the summer season. Only 37.6% of the total capacity of the storage facilities was being used, and 60% of storage capacity was still available for this study. This study confirms that it is possible to reduce energy costs by using electricity during the low-cost hours to fill storage facilities to be used during peak hours. In this study, the real capacity of the storage facilities in the study area was applied to redistribute the water demand from the peak hours to the low hours. The result of the energy cost reduction could be generalized throughout the water supply system and applied to the major procedures involved, such as pumping the water supply from the water treatment plant to the reservoir, using the water intake pump, and powering the boost pump to move water from the intake to the water treatment plant. In total, approximately 5.36% of energy cost could be reduced.

This study applied water demand patterns, pipe networks, storage facilities, and hourly varying electricity prices in a study area without special characteristics. An energy cost changes over time in many regions of the world and there are many water storage facilities that are not actively being used. Therefore, it is possible to apply this research to the other regions as a worldwide application for studies on energy savings, improvement of the water billing system or smart water grids. In addition, we studied energy costs and water demand among the water supply costs and, in further study, water tariffs can be an additional variable for energy savings since the low price of water tariffs can trigger over use of water.

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Seongjoon Byeon collected data and Yungyu Chang generated the result. All authors read and approved the final manuscript.

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