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Integrated Graphical Approach for Selecting Industrial Water Conservation Projects

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Abstract

Sustainable water management is key to achieving sustainable development goals. Increasing water consumption prompts industrial plants to implement water conservation projects (WCPs) and improve the utilization efficiency of water resources. In this paper, we develop an integrated graphical method for the implementation of water conservation projects by considering both water-saving targets and investment costs with or without government subsidies. First, cost-benefit analysis for different projects is carried out. The unit water savings cost diagram is employed to rank the priority of implementation of each project. Then, the project combination that meets the expected water-saving goal is determined via water-saving pinch analysis. Finally, the water conservation potential and cost-benefit of the optimal project combination are estimated using the marginal cost curve diagram. Two scenarios are considered for the proposed graphical approach: with and without government subsidies. A chlor-alkali/polyvinyl chloride complex is used as an illustrative case study. The results indicate the proposed method can be used to screen out the feasible project under the constraints of water-saving target and financial fund.

Keywords

Water savings, cost-effectiveness, Marginal cost curve, Pinch analysis, Subsidies

1. Introduction

Water resources play an important role in population, economy, and social development (Sun et al., 2016; Liu et al., 2017). Water is a resource that is essential to a wide range of human activity, and is critical for achieving nearly all sustainable development goals (World Bank, 2016). However, water is in short supply in many countries due to the increasing demand and uneven temporal and spatial distribution of water resources. Furthermore, global water demand has increased nearly eight times from 1900 to 2010 (Wada et al., 2016). Over two billion people live in water-stressed areas (Oki and Kanae, 2006).

China is one of the countries experiencing water scarcity as the per capita available water resources are only a quarter of the world average (Sun et al., 2017). The shortage of water has severely limited sustainable development in many areas in China, especially in northern regions (Cai et al., 2017). The uneven spatial distribution and inadequate water quality, rapid economic development and urbanization, and growing population, have combined to aggravate the scarcity of water resources in China (Liu and Yang, 2012; Ma et al., 2020). Medium and high scenario forecasts of non-agricultural water demand project an increasing global withdrawal (1930–2876 km^3/y) and consumption (537–694 km^3/y) by 2100 with especially dramatic increases in developing regions (Bijl et al., 2016). The shortage of water resources is one of the biggest challenges to China's sustainable development (Jiang, 2015).

The growing regional and sectoral water shortage has led the Chinese government to invest heavily in the construction of hydraulic engineering facilities to relieve water pressure in water-scarce areas (Zhao et al., 2015). These projects include the world's largest hydropower project (i.e., the Three Gorges Project) and the largest water transport project (i.e., the South–North Water Transfer Project). As seawater desalination is an important supplement to water resources and strategic reserves, the Chinese government is also actively promoting desalination in the coastal cities. According to the National 13th Five-Year Plan for Seawater Utilization, the total scale of seawater desalination is expected to reach 2.2 Mt/d by 2020. However, the high cost of seawater desalination technology leads to a prohibitively high price of desalinated water. Therefore, the government must establish a subsidy scheme to promote seawater desalination. The optimal amount of government subsidies can be determined by pinch analysis (PA) (Jia et al., 2019a).

In addition to water transfer and seawater desalination to increase external water sources, the Chinese government, companies, and scholars are actively exploring sustainable water demand management interventions to reduce internal water use. Water management strategies play an important role in water shortage alleviation (Xiong et al, 2020). An operational definition of water demand management comprises five components: (1) reducing the quantity or quality of water required to accomplish a specific task; (2) adjusting the nature of the task so it can be accomplished with less or lower quality water; (3) reducing usage losses from the source to disposal; (4) shifting usage time to off-peak periods; and (5) increasing the ability of the system to operate during droughts (Brooks, 2006). Based on water pollution data collected for 51 cities in China from 2011 and 2013, 73.4 kt of industrial wastewater is discharged per billion gross domestic product (Wang and Yang, 2016). Water pollution exacerbates China's water scarcity. The North China suffers water scarcity throughout the year, whereas South China, experiences seasonal water scarcity due to inadequate quality. (Ma et al., 2020). Therefore, water conservation and wastewater reuse are two important aspects of industrial policies to ensure the water supply (Wang et al., 2015). The objective of water conservation and wastewater reuse in the industrial plant is to implement water conservation projects (WCPs) which prevent pollution at the source and reduce the freshwater consumption while at the same time contributing to economic goals.

In China, water intensity dropped to 6.68 L/CNY in 2018, attaining a reduction of 18.9 % compared with that in 2015 (NDRC, 2019). However, there is still a big difference compared with the average water intensity level in developed countries (Mao, 2019). This has prompted industrial sectors to select and implement WCPs for water intensive industries. As water demand is expected to increase in the future due to increased freshwater consumption, sustainable water management requires an integrated approach, which will consider not only the end-of-pipe treatment of effluents but also water conservation, reuse, regeneration, and recycling. In many cases, the potential problems are magnified by the prospect of water resource reduction due to climate change (Tan and Foo, 2018).

Cleaner production (CP) is one of the important environmental tools and policies used to address sustainable consumption and production for the industries. The increase in water demand and wastewater discharge, the economic benefit of wastewater reuse, and the related wastewater reuse policy promulgated by the government have promoted the development and implementation of CP technology (Lyu et al., 2016). However, the CP technology employed in the plants are considered separately, not in a systematic manner. Jia et al. (2015) extended pinch analysis technique to water management of chemical processes from life cycle perspective through the decomposition of total water footprint into external and internal footprint components. Different WCP strategies were considered to meet the water saving target. Zhang and Guo (2016) evaluated water savings potential under water integrated optimal management for agriculture and the economic effects of agriculture water savings. Basupi (2019) proposed a multi-objective optimization method for the design of sanitary sewer by implementing different WCPs with the objective of minimization of total cost of sewers and WCPs and maximizing cost benefits of employing WCPs. Wang et al. (2020) used adaptive water management plans for the evaluation of water saving potential from both supply and demand side. The proposed method facilitates developing effective policy for different groups of water users. Wang et al. (2021) investigated water consumption for the main units in coal-to-synthetic natural gas process. Water-saving potential is evaluated for the key operation units. The results indicate if all the water-saving measures are employed, about 60% of water consumption in recirculating cooling water system can be achieved. The limitation of this work is that it did not consider the economic feasibility of these WCPs.

Water is a basic public resource, which makes it important for government to ensure its equitable use. Financial assistance has been identified as an important policy tool by governments for promoting water conservation in the plants. Government financial support thus seeks to stimulate investment of limited funds to obtain a good return on the investment, i.e., rapid deployment of cleaner technologies. The government is one of the key stakeholders in sustainable water management and may use calibrated subsidies to influence decisions of targeted companies (Aviso et al., 2010). In practice, not all the WCPs are feasible, or economically viable. Detailed feasible analysis is needed to assess the applicability of each of WCPs. Therefore, the management and continuous optimization of industrial water use are essential climate change adaptation strategies to achieve sustainable growth (Jia et al, 2019b). The biggest challenge for developing countries is managing to retrofit the industrial processes, which are sometimes based on obsolete technologies, despite financial, institutional, and legal constraints (Gumbo et al, 2003).

The chlor-alkali/polyvinyl chloride (PVC) industry is a major basic chemical industry. China now accounts for approximately one-third of the global PVC output and consumption. This sector is also a very water-intensive industry (Wang et al., 2019). In 2017, the capacity and output of the PVC industry in China ranked in the first place globally. This inevitably leads to large water consumption (China Chlor-Alkali Industry Association, 2017). Furthermore, most PVC plants are located in water-scarce areas, thus leading to water stress both for the companies themselves and the neighboring communities (Wang et al., 2019). Deploying WCPs to alleviate water shortage in the installation regions of PVC industries is critical. The present work focuses on an integrated graphical approach to determine the optimal WCP mix that considers water-saving targets and limited investment funds with/without subsidies from local governments. It provides a systematic method for the manager to screen out the feasible water-saving options under the constraint of funding and water target.

2. Methods

The proposed methodology addresses the selection problem of water-saving projects in the plants. The problem statement can be stated as follow. A set of *N* independent projects is given. Each project has an initial investment with an expected water-saving. A set of *M* funds is given. The fund is associated with a given budget and an expected water-saving target. The objective of the problem is to screen out the feasible combination of water-saving projects, subject to financial constraints and water-saving targets. This is a crucial process for the decision makers because the utilization of limited economic resources needs to be optimized and the amount of water-saving for all the projects should be satisfied. Net present value (NPV) is chosen to check the economic feasibility of the projects, since it considers the time value of money and the incremental wealth from undertaking a project.

2.1. The general framework of the method

This work presents an integrated framework of screening WCPs considering simultaneously the benefits, cost, and waster saving potentials, as shown in Fig. 1. This framework contains system boundary definition, feasible analysis, targeting process, and potential analysis for WCPs. First, the water system boundary is defined, and candidate water-saving options are determined based on water consumption data. Next, the benefit and cost of the candidate options are analyzed according to the obtained information. The NPV per unit water-saving diagram and marginal water-saving curve diagram are plotted. Some water-savings projects with negative values in these two diagrams are removed from the alternative options. The remaining projects flow into the targeting process. Finally, a water-saving pinch analysis is performed to screen out the optimal project options. The best water conservation path is determined based on the financial constraints and water-saving targets. During the targeting process, if the cumulative investment of all the alternative options is more than the fund, the optimal projects are determined from the project options obtained by the NPV analysis. Otherwise, the options removed in the NPV analysis should be readded into the water-saving project pool in order to fully utilize the fund. The priority of the projects adding to the project pool is determined by the NPV per unit water-saving.

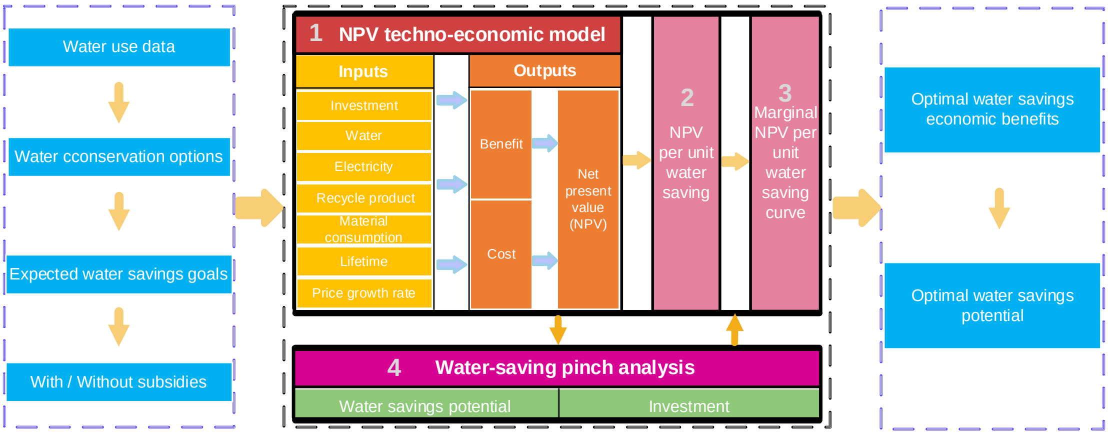


Fig.1. The framework of water conservation path

2.2. Techno-economic model

When implementing water conservation projects, plant managers often seek to maximize the project revenue while minimizing investment risks. The main risk factors are changes in government policies and fluctuations in water prices. In addition, the choice of WCPs is limited by the investment availability of the company, and the water-saving affordability is affected by the income and expenditure of the company. Based on the investigation and analysis of investment subjects, such as the government, companies or individuals, the policy makers decide on the implementation of possible investment project plans.

In this study, net present value (NPV) is chosen to measure the economic activities of the projects and evaluate their benefits. NPV is considered a reliable standard for measuring economic benefits (Marchioni and Magni, 2018). Within the project lifetime, the sum of the present value of the net cash flow per year is calculated at the industry benchmark discount rate. The net present value refers to the difference between the discounted net cash flow generated by the investment plan and the discounted value of the original investment. NPV > 0 means the project is profitable. The greater the net present value, the more profitable the project option. After considering the benefits and costs, the investment decision objective function is established as follows.

$$NPV = P(B) - P(C) \tag{1}$$

$$P(B) = \sum_{t=1}^{t_{option}} \frac{WS_t \times WP_t + VP_t \times PP_t}{(1+r)^{t-1}} \tag{2}$$

$$P(C) = INV + \sum_{t=1}^{t_{option}} \frac{EC_t \times EP_t + MC_t \times MP_t}{(1+r)^{t-1}} \tag{3}$$

P(B) represents the total revenue generated during the project's life cycle, including the water-saving revenue and recycled product revenue. *P(C)* represents the total cost consumed during the project cycle, including the initial transformation and operating costs (i.e., electricity costs, chemical consumption costs). Because the NPV model considers the time value of money, the remaining costs may change every year, but the initial investment costs will remain the same. Table 1 shows the evaluation process of the price of each category involved in water conservation processes.

Table 1 The parameter variables for each year ($t^{th} = t_{\_project}$)

Year	**0**	**1st y**	**…**	**tth y**
Investment INV	INV	-	…	-
Water saving WS_t	–	VS	…	VS
Water price WP_t	–	WP_1	…	$WP_1 \times (1+r1)^{t-1}$
Recycled product VP_t	–	VP	…	VP
Recycled product price PP_t	–	PP_1	…	$PP_1 \times (1+r2)^{t-1}$
Electricity consumption EC_t	–	EC	…	EC
Electricity price EP_t	–	EP_1	…	$EP_1 \times (1+r3)^{t-1}$
Material consumption MC_t	–	MC	…	MC
Material price MP_t	–	MP_1	…	$MP_1 \times (1+r4)^{t-1}$

2.2.1. Quantification of the water savings potential and marginal water savings cost of each project

The quantitative formulas of water savings potential and unit water savings cost of each project are shown in Eqs. (4-5). The input parameters of the project options include the project lifetime ($t_{\_project}$), annual water savings (WS), water price (WP), annual increase in water price (r1), annual recovered product amount (VP), unit price of recovered product (PP), annual price increase of recycled products (r2), annual electricity consumption (EC), electricity price (EP), annual increase in electricity price (r3), annual raw material consumption (MC), material price (MP), and annual increase in chemical price (r4). The amount of recovered product (VP) in this work is estimated by the production of the concentration of the product being recovered calculated and the flowrate of the recovered wastewater.

$$WSP = \sum_{t=1}^{t_{project}} WS_t \tag{4}$$

$$MC = NPV/WP \tag{5}$$

2.2.2. Unit water savings cost and marginal water savings cost curve diagrams

The NPV per unit water-saving (in units of CNY/t) can be calculated from Eq. (5), and the NPV per unit water-saving diagram is plotted. The X and Y axes correspond to the project sequence number and unit water savings cost, respectively. Then, the total water saving potential (in units of kt) and unit water saving cost (in units of CNY/t) of each project during its life cycle can be calculated according to Eqs. (4-5), respectively. The marginal NPV curve diagram is plotted. According to the NPV per unit water-saving, the marginal NPV curve is ranked. The projects with the lowest and highest cost effectiveness are located on the far left and far right, respectively. The project's cost effectiveness gradually increases from left to right. A negative value of the unit water-saving cost indicates that the benefit is less than the cost, which means that the company will save water at the expense of money (i.e., unprofitable project). A positive value indicates that the benefit is greater than the cost, which means that there is a net profit (i.e., cost-effective project). The width of the column in the diagram corresponds to the total water savings potential over the life of the project, and the area of the column corresponds to the net present value.

2.3. Water-saving pinch diagram

Pinch Analysis is an insight-based methodology for process integration problems. It was originally developed to optimize heat recovery in process plants, but over four decades of development, applications have diversified to address different sustainability issues (Klemeš et al., 2018). Water pinch technology has been further developed and widely applied to minimize water targets using the water cascade analysis methodology (Manan et al,2004).

In this work, PA for WCPs is extended for selecting water conservation projects in the chemical plant. This method solves a specific type of problem in project valuation, subject to financial constraints. It focuses on the limited economic resources whose utilization requires optimization (Roychaudhuri et al., 2017). For the detailed mathematical formulation, the reader can refer to Tan et al. (2016). The procedure for plotting the water-saving pinch diagram is shown in Fig. 2

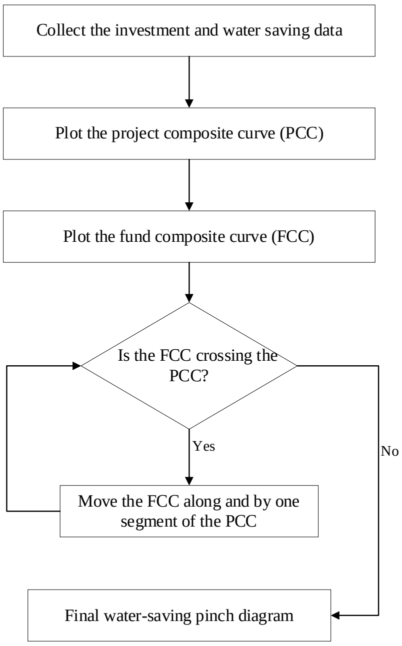


Fig. 2 The procedure of water-saving pinch diagram

The generation steps of the water-saving pinch diagram are as follows:

✓ Step 1: All WCPs are arranged in ascending order of the actual water savings intensity. Water savings intensity refers to the ratio between the magnitude of water savings and financial investment for a given project.

✓ Step 2: The magnitude of financial investment and water savings are used as the horizontal and vertical coordinates, respectively. Thus, a project composite curve is constructed based on the ascending order of the actual water savings intensity.

- ✓ Step 3: All financial resources are arranged in ascending order of the expected water savings intensity. Note that, in most cases, the company sets the expected water savings intensity of financial resources according to the expected water-saving goal.
- ✓ Step 4: Based on the ascending order of the water savings intensity, the composite curve of financial resources and projects is plotted in the same coordinate system. The project composite curve should completely be located above and to the left of the fund composite curve, implying that the water savings of the projects would be able to cover the water requirements of the funds. If not, the fund composite curve is to be moved along the project composite curve, one segment at a time, until the fund composite curve is completely below the project composite curve.

Regarding the water-saving pressure, priority is given to the project's water savings potential rather than economic benefits. Based on the expected water savings potential and maximum investment that the company can bear, a water-saving pinch analysis can be carried out to select the project portfolio that meets the expected water-saving target.

2.4. Sensitivity analysis

In the specific model calculation process, a large quantity of data is derived from existing data. The data that are closest to the actual situation are usually selected. In the case of uncertain data, a sensitivity analysis is required to test the sensitivity of the results to data changes. Sensitivity analysis is a method to study the sensitivity of a model's state or output to changes in the system parameters or surrounding conditions. It is often used to study the stability of the optimal solution when the original data are inaccurate or change. Sensitivity analysis can also determine which parameters have a greater impact on the system or model. By individually changing the values of related variables, we can explore the impact of changes of parameters on key indicators.

In this work, the impacts of subsidies on the water savings and costs are explored. The procedure for the sensitivity analysis is described as follows. First, the percentage of subsidies is determined. For example, in Scenario 2, 40% of the investment of the water-saving project is subsidized by the government. Next, the actual investment of the project afforded by the company can be determined by subtracting the subsidies from the initial investment. Thus, the actual investment and the amount of water-savings for all the water-saving projects can be identified. Finally, pinch analysis of water conservation projects is performed to screen out the feasible projects under the constraints of financial fund and water-saving targets. Based on the results of pinch analysis, the actual amount of water-savings for all the projects is determined. The same procedure is repeated for different percentage of subsidies.

3. Case study

A chlor-alkali/PVC complex is used in this work as an illustrative example. The system boundary of this case study is shown in Fig. 3. A detailed description of the production chain can be found in Wang et al. (2019).

There are many industrial water-saving techniques available for PVC plants. For example, cooling water systems are the most important contributors to water consumption. The water is usually evaporated into the atmosphere, and the quality of the blowdown water is better than the discharge of other processes. If water conservation techniques are employed in cooling water systems, the water-saving effects will be obvious. Additionally, water reuse techniques can be used to reduce the freshwater consumption. For example, steam systems can be transformed to closed circulation systems to recycle the steam condensate. Smart water monitoring systems can be installed in the living area of the plant to reduce the use of domestic water. A total of 11 WCPs were identified for the case study presented by Dai et al. (2015). The water-saving process involves PVC, acetylene, vinyl chloride, polymerization, and caustic soda workshops as well as public work and staff residential areas. Assuming that the water supply system of the case study runs steadily, 11 WCPs (i.e., P1 to P11) are specified. The corresponding data are summarized in Table 2 and the details for each project are summarized in Appendix A.

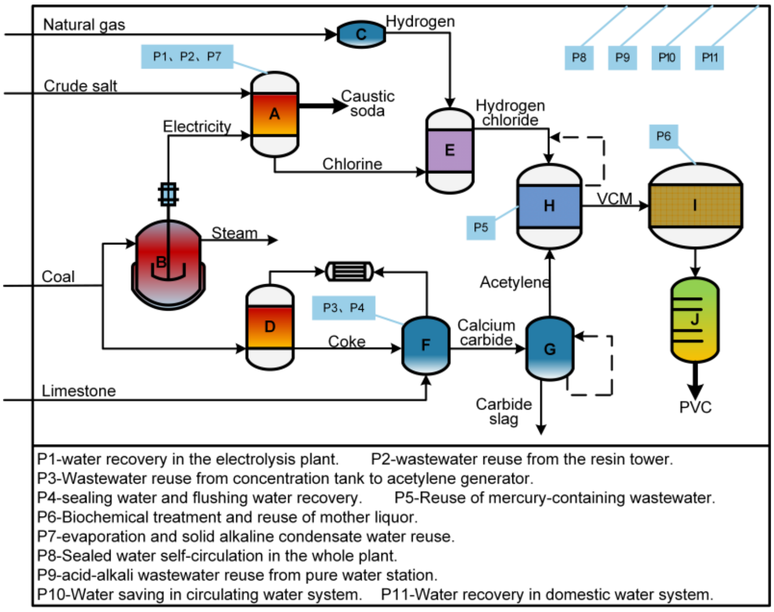


Fig.3 Schematic diagram of water conservation projects in PVC plant

If the local water resources are scarce, the chlor-alkali plant is required to save at least 2,500 kt/y of water, according to the industrial water-saving target set by the government. Currently, the largest water saving renovation project fund of the company is CNY 8 million, which is less than CNY 17.83 million needed to support all water saving project options. It is assumed that the life span of the water-saving projects is 10 years. According to the water-saving target and capital amount of the largest renovation project, the expected water saving intensity is I = 2500*10/8000 = 3.125. With limited funding, it is necessary to exclude some projects and screen out project portfolios that meet the expected water-saving goals. In Section 4, the selection of project options with or without government subsidies is discussed.

Table 2. Water conservation projects of chlor-alkali plant and input parameters

Location	No.	Project name	Transformation cost /kCNY	Water saving /(kt/y)	Recycled product /(kt/y)	Electricity consumption /(MWh/y)	Chemical consumption /(kt/y)
Chlor-alkali workshop	P1	Water recovery in the electrolysis process	40	100.4[a]	0	44[c]	0
	P2	wastewater reuse from the resin tower	1500	100[a]	5.9561[b]	200[c]	0
Acetylene workshop	P3	Wastewater reuse from concentration tank to acetylene generator	100	144[a]	0	56[c]	0
	P4	sealing water and flushing water recovery	50	96[a]	0	44[c]	0
Vinyl chloride workshop	P5	Reuse of mercury-containing wastewater	3000	26.4[a]	0	142.56[c]	9.6[d]
Polymerization workshop	P6	Biochemical treatment and reuse of mother liquor	5000	380[a]	0	1800[c]	0.228[e]
Caustic soda workshop	P7	Evaporation and solid alkaline condensate water reuse	1000	640[a]	0	216[c]	0
Utility area	P8	Sealed water self-circulation in the whole plant.	1080	224[a]	0	216[c]	0
	P9	Acid-alkali wastewater reuse from pure water station	250	216[a]	0	100[c]	0
	P10	Water savings in circulating water system	5600	1800[a]	0	738[c]	0
Staff living area	P11	Water recovery in domestic water system	210	360[a]	0	174.6[c]	0

a. water price is CNY2.7/t.
b. recycled product price is CNY388/t.
c. electricity price is CNY0.24/kWh.
d. the price of steam used in P5 is CNY40/t;
e. the price of chemical consumed in P6 is CNY3,000/t.

4. Results and discussion

4.1. Scenario 1: Without government subsidies

In order to evaluate the costs of the project options, the following assumptions are made: (1) According to the percentage growth rate of China's price index, the annual growth rate for water price, recovered product price, steam price, electricity price, and chemical price are assumed to be constant in this work, i.e., 2%, 3%, 3%, 2%, and 3%, respectively. (2) The discount rate of all projects is 5%; the life span of all the projects is set to 10 years. (3) All projects are technically feasible and can achieve the water savings potential described by the original data. (4) All projects are independent; there are no inter-project dependencies.

The techno-economic status of alternative projects without government subsidies is evaluated based on the water saving and the investment. First, the price of the relevant products consumed in the project for the specific year are evaluated according to the equations in Table 1. Based on the given growth rate in the above assumption and initial price in Table 2, the prices of water, electricity, recycled products, the steam and chemicals for each year during the lifetime can be obtained. Next, the benefits and costs of the water saving projects for each year are obtained according to during Eqs (1) – (3). The results are shown in the 2nd and 3rd column of Table 3. Noting that the benefit for each project are the summation of the discounted benefit of each year during the lifetime of the project. The costs are obtained in the same manner. Finally, the NPV results and marginal water-saving cost are calculated according to Eqs (4) – (5), as summarized in the 4th and 6th column of Table 3. In the 5th column of Table 3 presents the total amount of water saving during the lifetime of the project. The water-saving potential for all the projects is presented in Fig.4 and marginal water-saving cost curve is presented in Fig. 5.

Table 3 NPV results of the project options without subsidies

No.	Benefit /kCNY	Cost /k**CNY**	NPV /k**CNY**	Water saving /kt	NPV per unit water-saving /(**CNY**/t)
P1	2,387.54	133.01	2,254.53	1,004	2.2456
P2	23,604.20	1,922.76	21,681.44	1,000	21.6814
P3	3,424.36	218.37	3,205.99	1,440	2.2264
P4	2,282.91	143.01	2,139.90	960	2.2290
P5	627.80	6,828.38	-6,200.58	264	-23.4870
P6	9,036.51	15,087.37	-6,050.86	3,800	-1.5923
P7	15,219.38	1,456.58	13,762.80	6,400	2.1504
P8	5,326.78	1,536.58	3,790.20	2,240	1.6921
P9	5,136.54	461.38	4,675.16	2,160	2.1644
P10	42,804.50	7,159.99	35,644.52	18,000	1.9803
P11	8,560.90	579.07	7,981.83	3,600	2.2172

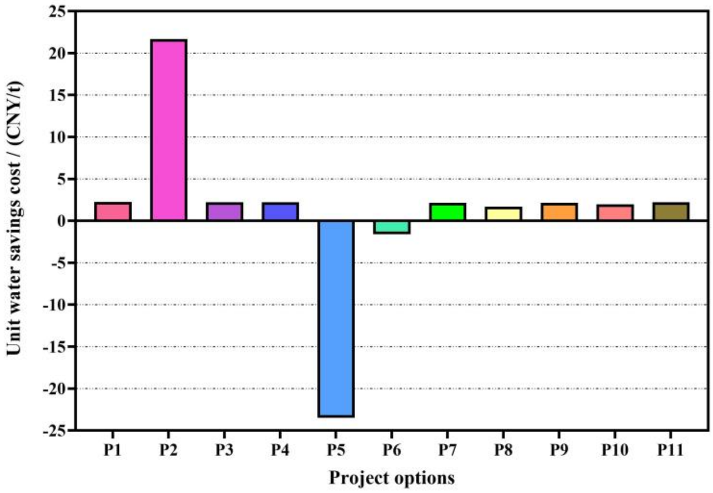


Fig.4 The NPV per unit water-saving diagram without subsidies

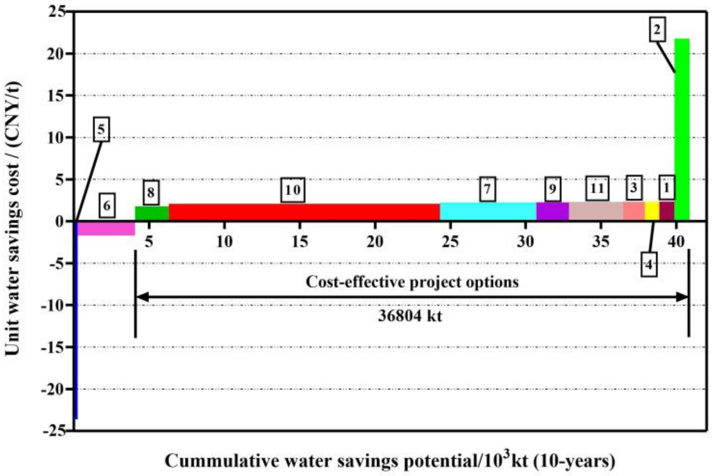
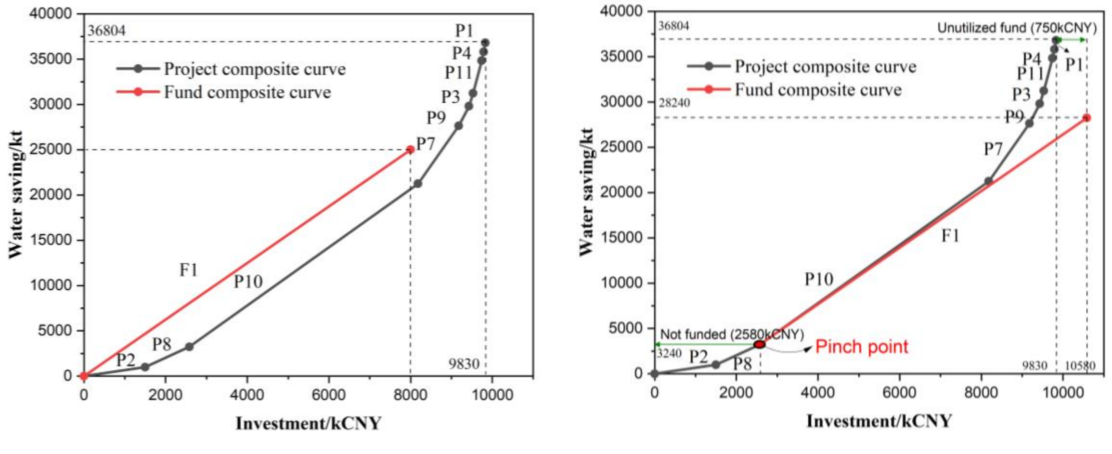


Fig. 5 Marginal NPV curves diagram without subsidies

As shown in Fig.4, P5 and P6 are located below the X axis, which indicates that sacrificing money for water conservation is unprofitable. The operation of plants consumes not only electricity but also high-priced steam and chemicals. The operating costs far exceed the benefits of water conservation. Therefore, these projects with high operating cost should be implemented at last. The remaining projects are located above the X axis, indicating that the benefits are greater than the costs. P2 is the highest in the bar chart, with a value of 21.68 CNY/t. Implementing acid-base waste-water recovery reduces the hydrochloric acid and liquid base consumption. In terms of the company's economic benefits, the funds should be allocated to P2 first. Besides P2, P5, and P6, the other projects do not involve the recovery and use of chemical substances, and the calculated unit cost of water saving is almost the same, which is also in line with the actual operating situation.

It can be deduced by Fig. 5 that the order of priority of funds flowing into alternative projects is P5, P6, P8, P10, P7, P9, P11, P3, P4, P1, P2. The total water saving potential of cost-effective projects over a 10-year period is 36,804 kt. The area of P10 is the largest. Although its unit water-saving cost-effectiveness is not the highest, the water-saving potential of circulating water in public works is huge. Furthermore, its NPV is the largest, meaning that the project not only saves a lot of water resources but also brings a net income of CNY 35.644 million to the company. In terms of the economic benefits of the company, this work evaluates and prioritizes WCPs according to the unit water savings cost. However, Fig. 5 shows that P2 has an excellent unit cost-effective, and its water-saving potential is not large. Thus, from the point of view of water savings potential, the project is not advantageous over other projects. Finally, to study the intensity of water saving under the condition of fund shortage and water-saving target, the water-saving pinch diagram without subsidies is used. The results are shown in Fig. 6. In Fig. 6a, water-saving pinch diagram is infeasible because the fund composite curve is located above the project composite curve. The projects covered by the fund cannot meet the water target. Therefore, the fund composite curve should be shift along the project composite curve until the fund composite curve is completely below project composite curve. The results of shifting fund composite curve are presented in Fig. 6b.



(a) (b)

Fig. 6 Water-saving pinch diagram for WCPs without subsidies

The pinch point for WCPs without subsidies is (2580, 3240). Below the pinch point, the project options are not funded by the fund because of low water saving intensity. Above the pinch point, the projects in the project composite curve covered by the fund composite curve are chosen to implement in the plant. In this scenario, P10, P7, P9, P3, P11, P4, and P1 on the right side of the pinch point are located above the fund composite curve F1, which has a higher water savings potential/investment ratio. These projects will receive funds for water conservation. An investment of CNY 7.25 million can achieve cumulative annual water savings of 3,356.4 kt, which is the sum of the water-saving of the selected projects. Funding for F1 is greater than the cost of the selected portfolio projects, with the remaining CNY 0.75 million unutilized. The projects on the left of the pinch point are P2, P8. The total water savings potential is 3,240 kt, which has not been supported by funds (i.e., CNY 2.58 million). Obviously, in terms of water savings potential/investment point, the projects above the pinch point is far better than the projects below the pinch point. The combination of WCPs selected by this standard includes P10, P7, P9, P3, P11, P4, P1. The investment of the company does not exceed the expected maximum amount of CNY 8 million, and the annual water savings potential exceeds the target of 2,500 kt. The water-saving per unit investment is 4.6295 t/CNY. The chosen projects can meet the financial requirement and water-saving target.

4.2. Scenario 2: With government subsidies

If local water resources are very limited and the government can provide financial support for water conservation, WCP subsidies can be set up. In this work, it is assumed that 40% of the initial costs are subsidized. Depending on the actual investment of individual projects, the subsidies amount is determined. At this point, the company bears 60% of the initial cost. The NPV for each project is calculated again according to the Eqs. (1) – (5). The parameters and procedures for the NPV analysis are the same as the Scenario 1. The results are shown in Table 4. The NPV per unit water-saving is analyzed and plotted in Fig. 7. The marginal NPV curve is shown in Fig. 8.

Table 4 Results of the project options with 40% subsidies

No.	**Benefit /kCNY**	**Cost /kCNY**	**NPV /kCNY**	**Water saving /kt**	**Unit cost /(CNY/t)**
P1	2387.54	117.01	2270.53	1004	2.26149
P2	23604.20	1322.76	22281.44	1000	22.28144
P3	3424.36	178.37	3245.99	1440	2.25416
P4	2282.91	123.01	2159.90	960	2.24990
P5	627.80	5628.38	-5000.58	264	-18.94160
P6	9036.51	13087.37	-4050.86	3800	-1.06602
P7	15219.38	1056.58	14162.80	6400	2.21294
P8	5326.78	1104.58	4222.20	2240	1.88491
P9	5136.54	361.38	4775.16	2160	2.21072
P10	42804.50	4919.98	37884.52	18000	2.10470
P11	8560.90	495.07	8065.83	3600	2.24051

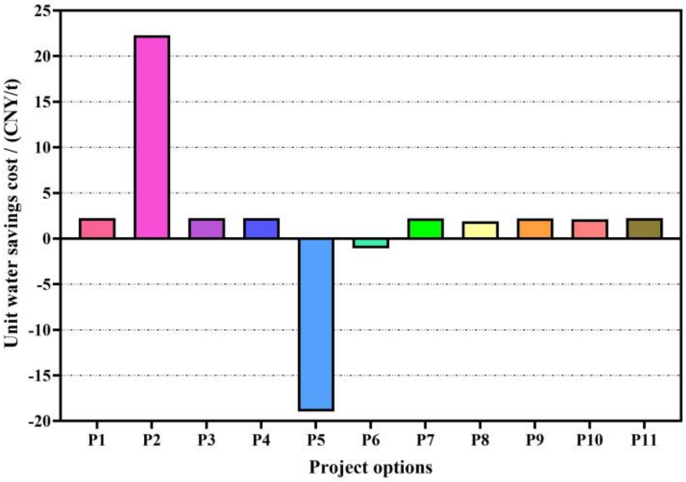


Fig.7. The NPV per unit water-saving diagram with 40% subsidies

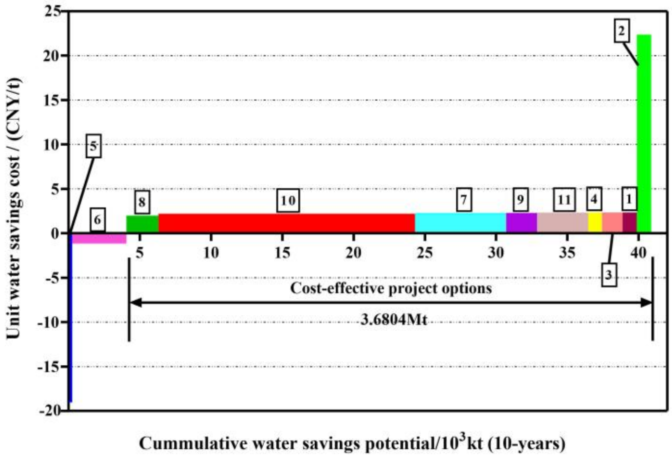
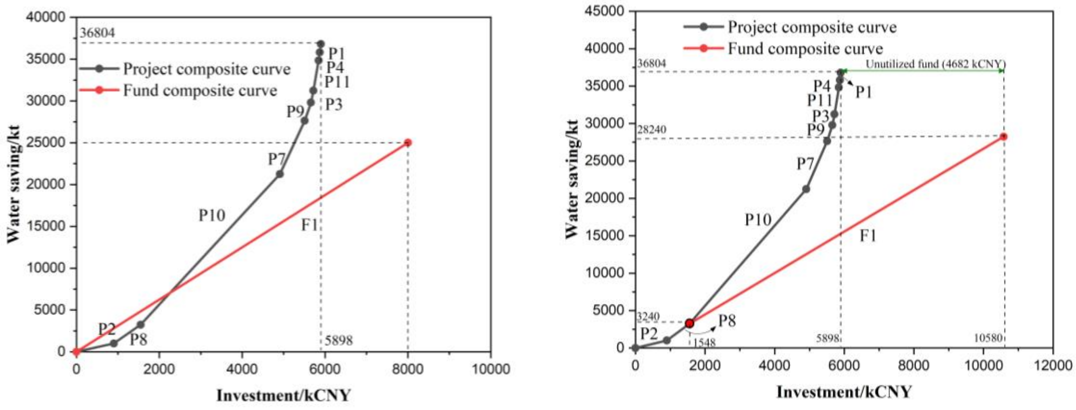


Fig.8. Marginal NPV curves diagram with 40% subsidies

Compared to the results of scenario without subsidies, shown in Fig. 4, the NPV per unit water-saving for each project option in the scenario with subsidies increases (Fig. 7). However, P5 and P6 still remain below the X axis and are not cost-effective. This is because these two projects have high investment and less revenues. Therefore, P5 and P6 are removed from the project pool. As can be seen from Fig. 7, in terms of economic benefits, the order of priority of WCPs is P2, P1, P3, P4, P11, P9, P7, P10, and P8. Additionally, unlike Fig. 5, P3 has a higher priority than P4. This is because although the investment of these two projects are subsidized by 40%, the NPV per unit water saving of P3 is higher than P4. The water savings potential of the cost-effective project remains 3680.4 kt.

The initial water-saving pinch diagram for the remaining WCPs with 40% subsidies is presented in Fig. 9a. The fund composite curve crosses the project composite curve. Therefore, the fund composite should be moved along project composite curve until it is completely located below project composite curve. The shifted results are shown in

Fig.9b. The pinch point is (1548, 3240). The unutilized fund is CNY4.682 million and the amount of water-saving is 33.564 Mt. The water-saving per unit investment is 10.1157 t/CNY. The selected projects are P10, P7, P9, P3, P11, P4 and P1. From the Fig. 9a and 9b, it can be seen that the fund could cover the financial requirement of the project composite curve and the water-saving requirement is also satisfied. However, the fund has a low utilization efficiency because CNY4.682 million of the funds (CNY8 million) is not used. In order to increase the efficiency of the fund, the project removed by NPV analysis should reenter the project pool.

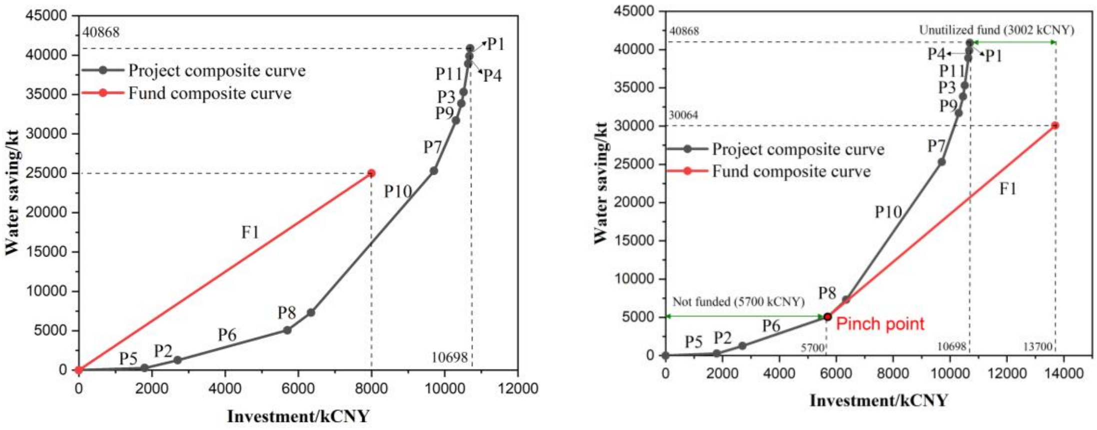


(a) (b)

Fig. 9 Initial water-saving pinch diagram for WCPs with 40% subsidies

After adding P5 and P6 in the alternative options, the initial water-saving pinch analysis diagram is shown in Fig. 10a. In Fig.10a, the fund composite curve is completely located above the project composite curve, implying the water-saving pinch analysis diagram is infeasible. Thus, the fund composite curve is shifted along the project composite curve until it is below the project composite curve. The shifted diagram is shown in Fig. 10b. The pinch point is (5700, 5064). Below the pinch point, the project with low water-saving intensity is not funded. Above the pinch point, the project composite curve is fully covered by the fund composite curve. The segment beyond the project composite curve is the unutilized fund. The projects above the pinch point are P8, P10, P7, P9, P3, P11, P4 and P1.

Compared with the results of Fig.9b, P8 has also been successfully selected into the project portfolio as it can achieve an annual cumulative water saving of 3,580.4 kt. The company funds CNY4.998 million for the water conservation project, and the remaining CNY 3.002 million are not used. The water saving per unit investment is 7.1637 t/CNY. The selected WCPs are P8, P10, P7, P9, P3, P11, P4, and P1. The investment does not exceed the expected maximum amount of CNY8 million, and the annual water-saving amount exceeds the target of 2,500 kt. Although the initial water-saving pinch diagram has a higher water saving intensity (10.1157 t/CNY), the fund has a low utilization efficiency. In the final water-saving pinch diagram, the utilization efficiency of the fund and water-saving has increased. However, the water-saving per unit investment is decreased. The decision maker can consider the tradeoff between the financial constraint and water scarcity. If the plant is located in the water scarcity region, the most important factor considered by the decision makers is the amount of water savings. The projects selected by the Fig. 10b will be implemented. If the plant is located in the region with less water scarcity, the main factors considered by the decision makers is the water-saving per unit investment. The incentive of water-saving projects is to achieve the standard set by the government, i.e., the recycling ratio of water in the plant. To this end, the solution obtained by Fig. 9b will be deployed.



(a) (b)

Fig. 10 The final water-saving pinch diagram for WCPs with 40% subsidies

Figure 11 shows the relationship between the cost, subsidy percentage, and water saving. When the subsidies ratio is below 33.6%, the water savings potential in this range is 3,356.4 kt. When the subsidies ratio is between 33.6% and 75.7%, P8 is selected, and 224 kt of water savings potential is added annually. When the subsidies ratio is between 75.7% and 78.7%, P6 is selected, and 380 kt of water savings potential is added annually. When the subsidy rate is between 78.7% and 97.2%, P2 is selected, and 100 kt of water savings potential is added annually. When the subsidy rate exceeds 97.2%, P5 is selected, and 26.4 kt of water savings potential is added annually.

When the government subsidies increase, the company’s financial burden is greatly reduced. Whenever a new project is selected, the input costs of both the government and business rise. When the subsidy rate exceeds 75.7%, the government subsidies rise sharply, but the potential of water savings does not increase much. This would greatly increase the financial burden on the government; therefore, subsidies should not exceed 75.7%. When the subsidy rate is less than 33.6%, the investment decrease with the increase of subsidy rate and the water savings are constant. For the subsidy rate between 33.6% and 75.7%, although the investment decrease, the total subsidy increases, and the water savings are the same as the 33.6% subsidy rate. The water savings at 33.6% subsidy rate have satisfied the water-saving requirement. Therefore, in order to reduce the burden on the government, the optimal government subsidy rate is determined as 33.6%.

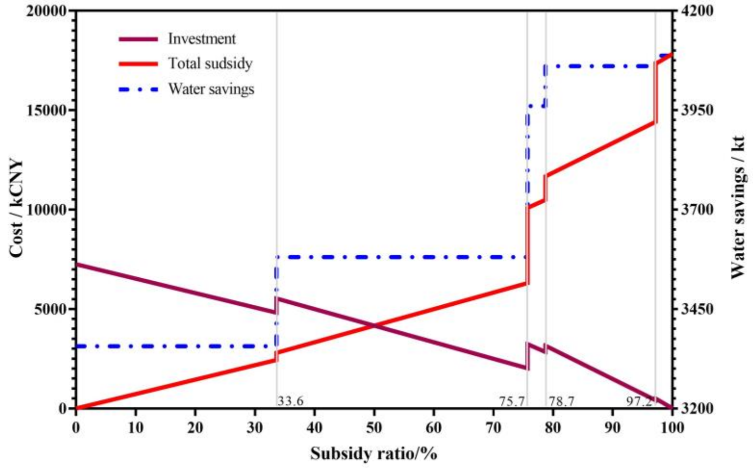


Fig.11. Relationship among investment, subsidies, water savings and subsidy rate

Table 5 Comparison the parameters with and without government subsidies

Scenarios	Without subsidies	With 33.6% subsidies
Project portfolio	P10、P7、P9、P3、P11、P4、P1	P8、P10、P7、P9、P3、P11、P4、P1
Investment/kCNY	7250	5531.12
Subsidies/kCNY	0	2798.88
Water savings/(kt/y)	3356.4	3580.4
NPV /kCNY(10y)	69664.73	76253.81
Total unit cost /(CNY/t)	2.08	2.13

Table 5 compares the output parameters for the scenarios with and without government subsidies. In the subsidized model, the subsidies ratio is 33.6%, and the initial investment of the company decreases by CNY1.719 million compared to that of the unsubsidized model; this corresponds to a decline of approximately 23.7%. Subsequently, the government subsidies increase by CNY.2.799 million. The annual water savings of the selected project portfolio increase by 224 kt, up to approximately

6.7%. The NPV increases by CNY3.79 million, up to approximately 5.4%. The total unit cost increases by 0.054 CNY/t, up to approximately 2.6%.

In this work, a 50% subsidy rate was selected as the practical limit for studying the relationship between the subsidy rate and unit water savings cost. Figure 12 shows the unit water savings cost of each project as a function of the subsidy rate. As the subsidy rate increases, the unit water savings cost presents an upward trend; P5 exhibits the sharpest increase. For every 10% increase in the subsidy rate, the unit water savings cost of P5 increases by 1.136 CNY/t. However, independent of the ratio of the total subsidies to the initial investment of the project, the unit water savings cost can be positive. This occurs because the annual operating costs of P5 exceed its operating income. From the local magnification graph, we observe that P8 and P10 increase rapidly. P1, P4, P3, P11, P9, and P7 increase at almost the same rate. Additionally, the location of concurrency of curves (P1, P4, P7, P9 and P3) and of curves (P7 and P9) changes depending on the subsidy rates. This is consistent with the fact that the unit water savings cost of P4 exceeds that of P3 without subsidies, and the unit water savings cost of P3 exceeds that of P4 with a 40% subsidy rate.

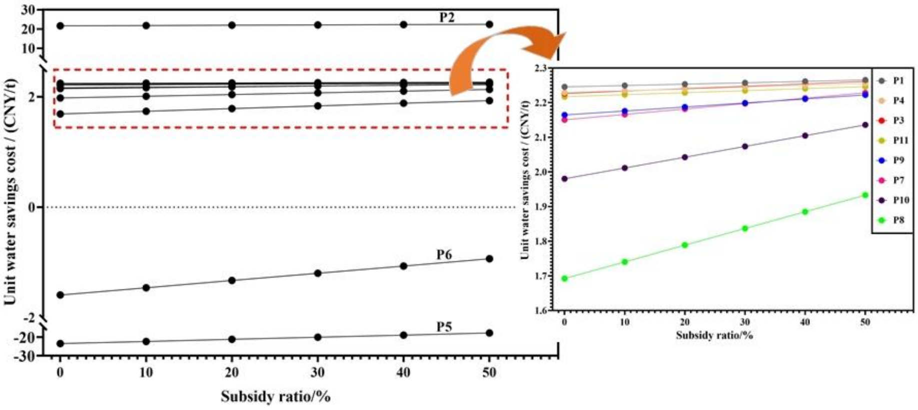


Fig.12. Unit water savings cost under different subsidy rates

4.3 Sensitivity analysis

Sensitivity analysis was performed to determine the impact of an input parameter on the unit water savings cost of an alternative project. Before performing the sensitivity analysis, a representative project was selected. P2 corresponds to the production of the recovered product, P10 has the greatest water savings potential, and P5 and P6 require the consumption of chemical substances. These projects all have a certain representativeness. P5 and P6 were not selected for the water conservation portfolio, neither in projects of economic benefit nor in projects of water conservation potential. Therefore, only P2 and P10 were selected for the sensitivity analysis, as shown in Fig. 13.

The sensitivity analysis diagram shows the range of output results for all input parameters varying by ± 50%. The analysis shows that the unit water savings cost is more sensitive to the life of the project, the price of the recovered products, and the price of water. For example, in the course of operation, which only involves the electricity expense and water-saving income of ordinary process P10, the higher the price of water is, the higher the unit water savings cost is, and the sensitivity of water price is much higher than the initial investment. It is also found that ordinary WCPs are more sensitive to water prices, i.e., they can increase water prices and further promote the water conservation ability.

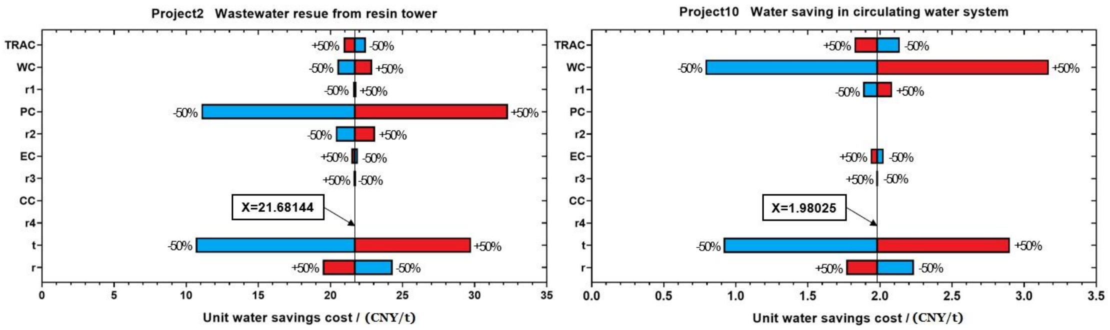


Fig.13 Sensitivity diagrams for P2 and P10（fluctuation of input parameters ± 50%）

4.4. General implications

As discussed in the previous section, water conservation technologies become the necessary foundation of CP technologies. WCPs provide the opportunity to alleviate water stress by decreasing freshwater demand. The decision to WCPs, particularly the extent of the implementation of WCPs, is dictated largely by economic factor (i.e., feasibility and affordability) and specific water saving targets (e.g., allocated by the company's decision-makers or the local government according to water management strategies).

One of the disadvantages is substantial investment in WCPs program. Furthermore, the incremental costs involved in every capital project might be offset by freshwater and regulatory compliance costs. Byers et al. (2003) reported financial incentives (e.g., pollution control tax credit, rebate, etc.) offered by local governments could largely stimulate investment in environmentally beneficial projects. In China, NDRC (2019) released national action plan to vigorously promote water conservation in the whole society to improve the utilization efficiency of water resources. NDRC (2019) pointed out expand investment and financing channels to provide services for water-saving management. According to these issues, financing incentives became useful means, even though these incentives vary from province to province and even within industrial sectors. For example, the company receives a subsidy of part of the capital cost for a project directly from local government in Zhejiang province, China. The total subsidy received can be up to 30 percent of equipment cost, and the maximum amount of subsidy for a single project shall not exceed CNY 1 million (Hanzhou Daily, 2018).

The purpose of this integrated work is to provide technical support for the design of qualification requirements for the subsidy from the local government. This type of financial incentive should be clearly investigated to guide and standardize the selection of WCPs combination. CBA is to estimate the overall cost and value implications of a project. Water-saving pinch analysis is to determine the expected water-saving goal. Then, we might determine the optimal subsidy based on the relationships among investment, subsidies, water savings and subsidy rates.

5. Conclusions

In this work, an integrated framework of screening WCPs is proposed to select WCPs subject to financial constraints. First, the benefit and cost of the water saving project options are estimated based on the expected price and utility consumption. The NPV for each project is calculated. The NPV per unit water-saving and marginal NPV diagram is selected to screen out the alternative projects for further analysis. Next, water-saving pinch analysis is used to determine the optimal water projects under the constraint of the fund and water-saving target. Finally, the water-saving roadmap for water conservation is obtained. The integrated framework can be used as a decision-making tool for selecting and ranking WCPs. The proposed approach can account for government subsidies for WCPs that can effectively promote water-saving project implementation. In the absence of water-saving incentive, the integrated framework can assist policy makers in selecting profitable water conservation projects and maximizing financial gains. Thus, the same investment can result in greater economic benefits. Although the method is used here to screen WCPs in chlor-alkali/PVC plants, the framework of the marginal cost curve and pinch analysis for WCPs decision-making can be extended to various industrial sectors as well as to urban water management.

In future work, chemicals recovery in WCPs needs to be considered. Co-benefit analysis should urge industrial managers to examine every possible means of conserving both water and chemicals. Sensitivity analysis should also be performed to examine the effect of techno-economic uncertainties on our findings.

Acknowledgement

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Appendix

Table A1 The description of the project options in the case study

Processes	No.	Description
Chlor-alkali process	P1	The project collects the drainage of the electrolysis device and reuses it to primary brine process in the salt preparation system. The reuse water can replace fresh industrial water as salt water. In the project, a pump with 5.5 kW is deployed. The reuse water flowrate is about 8.1~17.0 m^3/h. Therefore, in this work, an average flowrate of 9.1 m^3/h is chosen.
	P2	This project collects the wastewater from the secondary brine chelating tower and sends the wastewater to regeneration process for the recovery of hydrochloric acid and liquid alkali. The recovered acid and alkali can be used in the neutralization process before and after dechlorination process. In the acid wastewater, the flowrate of acid wastewater is 160 m^3/d and the mass faction of hydrochloric acid in the wastewater is 3%. The pump installed is 12.5 kW. The hydrochloric acid solution purchased from other plants has a mass faction of 31%.
Acetylene process	P3	In the project, the supernatant wastewater from the concentration tank is sent to the acetylene generator for reaction and reuse. It can replace fresh industrial water as supplement water for the acetylene generator. The pump for transferring the water has a power of 7 kW. The amount of recovered wastewater is 18 m^3/h.
	P4	The sealing water of the acetylene slurry pump and the washing water of plate-and-frame filter press are collected to be recycled to the thickening tank in order to replace the fresh industrial water as the supplementary water of the acetylene system. The power of the pump for the wastewater transfer is 5.5 kW. The amount of wastewater recovered is 18 m^3/h.
Vinyl chloride process	P5	The project collects an average flowrate of 3.3 m^3/h of mercury-containing wastewater in the vinyl chloride process. The wastewater is treated by the newly installed mercury-containing wastewater treatment device and reaches the standard of the water for alkali washing tower and makeup water for preparation of alkali solution. The regenerated water can be used as the makeup for the alkali washing tower system instead of freshwater. The energy consumption of the regeneration process is 5.4 kWh/m^3. The consumption of1.0 MPa steam is 1.2 t/h.
Polymerization process	P6	The mother liquor water of the polymerization unit is collected and treated to reach the reuse standard after biochemical treatment. The treated water can be used as the makeup water for the circulating water system. The energy consumption of the device is 225 kWh. The chemical consumption for the regeneration process is 0.15 kg per ton wastewater. The flowrate of the water is 47.5 t/h.
Caustic soda process	P7	The project collects the evaporation and solid alkali condensate from the caustic soda process. The collected water is reused to the ion-exchange membrane electrolysis system and the pure water station system to replace desalinated water and industrial water. The power of the pump for transferring the condensate is 27 kW. The flowrate of the wastewater is 80 m^3/h.
Utility area	P8	In this project, the machine-sealed water in the 6 processes is recovered separately for self-circulation transformation. It is used to replace the demineralized water as supplementary water for the machine-sealing. The flowrate of the wastewater is 28 m^3/h and the power of the pump is 4.5 kW.
	P9	The reclaimed wastewater from the water purification station is used

		in the neutralization pool of the water purification station to reach neutrality. The neutralized water is then transported to the primary saltwater tank to partially replace the industrial water in salt dissolving process. The power of the installed pump is 12. 5kW. The average amount of recycled wastewater is 27 m^3/h.
	P10	The backwash drainage from circulating water system and water purification station is collected and purified to reach the water reuse requirement in the circulating water system. The power of the installed pump is 12. 5kW. The average amount of recycled wastewater is 12.5 m^3/h.
Staff living area	P11	The wastewater for the residence area is 55 t/h. This wastewater has simple contaminants and is easy to be treated. It is estimated that about 45 t/h of wastewater from residence area can be recovered as the water for the plants in the plant.