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Cost-effective Scheduling of Load and Microgrid in Wastewater Treatment Plant

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COST-EFFECTIVE SCHEDULING OF LOAD AND MICROGRID IN WASTEWATER TREATMENT PLANT

by

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ABSTRACT

COST-EFFECTIVE SCHEDULING OF LOAD AND MICROGRID IN WASTEWATER TREATMENT PLANT

By

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Under the Supervision of Dr. Lingfeng Wang

As a big consumer of energy, water and wastewater treatment used about 75000 to 100000 GWh electricity, which accounts for nearly 3% of U.S. annual energy [1]. Not only being energy-intensive, wastewater treatment plant (WWTP) also consumes a lot of electricity during peak hours, which makes WWTP a good candidate of DR (demand response). The main purpose of demand response is to improve the stability of the electric grid and reduce the use of electricity during peak period to lower the total system costs. Two kinds of strategies can be utilized to reduce electrical loads during peak periods, which are load shifting and load shedding. Load shedding strategy is to reduce the total electrical load during demand response event and load shifting is to reschedule the time of some electrical load to partial-peak or off-peak hours. In this work, both of them are used to reach a better financial benefit.

The process and energy consumption of WWTP have been analyzed. It is found that the aeration in secondary treatment and pumps for wastewater pumping and sludge pumping are two main processes which consume the majority of total electric power. Based on shifting loads of aerations and pumps, a load shifting model is formulated to shift load from on-peak hours

to off-peak hours. Several constraints have been taken into consideration such the storage capacity, maximum holding time of wastewater when it stays in storage tanks, maximum treatment capacity of WWTP, etc. This model can effectively reduce the annual electricity cost while the quality of effluent and the reliability of WWTP are not compromised. In the case study analysis, 22% cost reduction is achieved by using the load shifting model.

A software tool has also been developed to help users calculate the amount of cost they can save when the load shifting model is applied. The software tool is user friendly and easy to use. The influent data and electricity price data need to be loaded by users, and some kinds of parameters need to be typed in depending on different situations. For instance, the size of the WWTP and the capacity of storage tank need to be loaded.

In addition to demand response, WWTP can save more money with the help of a microgrid. A microgrid is a smaller version of traditional power grid which can provide backup power to WWTP so that the power generated by a microgrid can be used during on-peak hours or sold back to the main grid if possible. A microgrid can also increase the reliability of WWTP. As a discrete energy system with distributed energy sources, a microgrid can operate in parallel with or independently from the main power grid. This feature of the microgrid makes sure WWTP can still receive reliable energy when no electricity can be provided by the main grid.

A microgrid model is developed. A battery bank is also involved in the formulation. Constraints

including microgrid capacity, charge and discharge efficiency of battery bank, and battery capacity have been considered. The method used to solve this formulation is particle swarm optimization (PSO). A detailed description of the problem-solving process has been displayed step by step. The case study shows the microgrid model can increase the cost reduction further to 29% of total energy expense based on the load shifting model.

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LIST OF ABBREVIATIONS

WWTP	Wastewater Treatment Plant
PSO	Particle Swarm Optimization
PV	Photovoltaic
RAS	Return Activated Sludge
BOD	Biochemical Oxygen Demand
DO	Dissolved Oxygen
VSD	Variable Speed Drive
DR	Demand Response
DOE	Department Of Energy
HAWT	Horizontal Axis Wind Turbines
VAWT	Vertical Axis Wind Turbines
P_{pump}^{t}	Energy used for pumps (KW)
P_{blower}^{t}	Energy used for aeration blowers (KW)
M_{elec}^{t}	electricity price ($)
P_{expump}^{t}	extra pumping energy (KW)
W_{p}^{t}	the amount of wastewater need to be processed (MG)
T_{cap}^{t}	the treatment capacity (MG)
C_{a}^{t}	available capacity at time t. (MG)
C_{s}^{t}	storage capacity at time t. (MG)
W_{r}^{t-1}	the remaining wastewater at time t-1. (MG)

I^t	the amount of influent at time t. (MG)
$\lambda_{O\&M}^{n}$	operation and maintenance coefficient
$P_{out}^{n,t}$	power generated by microgrid (KW)
M_{elec}^{t}	the electricity price ($)
P_{load}^{t}	load power (KW)
P_{mc}^{t}	charged power from microgrid (KW)
P_{gc}^{t}	charged power from main grid (KW)
P_{D}^{t}	discharged power (KW)
P_{b}^{t}	battery storage at time t (KW)

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CHPTER 1 BACKGROUND OF WWTPS

1.1 MAIN PROCESS

The main function of WWTP is to meet the requirements for effluent quality and most importantly protect the health of citizens. However, the high energy cost makes WWTP a great financial burden placed on local government. It is necessary to improve the energy efficiency and energy management to reduce the energy cost [2].

The process of wastewater treatment can be divided into four parts: preliminary treatment, primary treatment, secondary treatment, tertiary treatment. Depending on different purpose, one or more processes can be added to achieve different effluent quality requirement.

The process is schematically presented in Figure 1-1, which includes four basic treatments and additional waste sludge treatment.

Preliminary treatment: the incoming wastewater called influent will go through screens in order to remove floating matter such as bottles, strips, sticks, papers,woods and other large pieces of trash which may cause operation and maintenance problem in the following process. When wastewater goes into the grit chamber, sand and grits are removed [3].

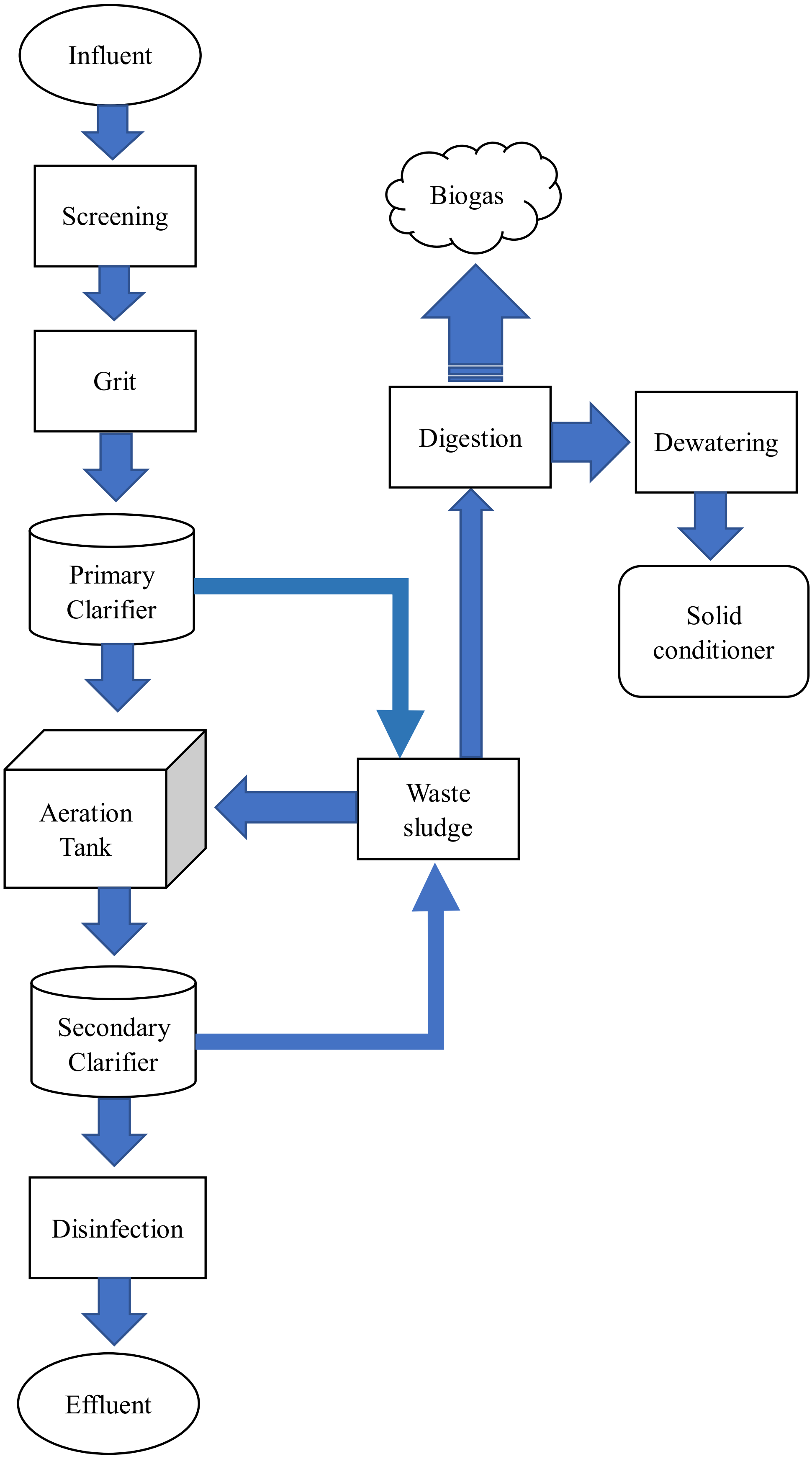

Figure 1-1 Process of wastewater treatment

Primary treatment: wastewater then enters the primary settling tank. The wastewater is just temporarily held in the tank and the wastewater gose slowly so that heavier solids settle to the bottom of the tank while softer and lighter matter float on the surface. The floating trash and the settled materials are removed from the tank[4]. The settled solids, called primary sludge, are sent to sludge handling facilities for further treatment after degritting. The rest of wastewater from the settling tank flows to the secondary treatment process[3].

Secondary treatment: this process is also known as the activated sludge process. The air is pumped by the aerator into the aeration tank and it mixes with incoming wastewater and sludge which increases the number of oxygen-consuming bacteria. The bacteria existing in the tank can consume most of the remaining organic materials which may pollute the water[3]. The aerated wastewater then flows into the secondary settling tank. The function of the secondary settling tank is similar to the primary settling tank. The heavier solids settled here are called secondary sludge. Some of the sluge from primary treatment and secondary treatment is reused in the aeration tank as return activated sludge (RAS). The rest of the secondary sludge along with primary sludge is then added to digestion process.

Tertiary treatment:The purpose of tertiary treatment is to further clean the wastewater to make sure all the indexs in effluent can meet the requirement. It can also remove some contaminants which cannot be removed in secondary treatment. However, if the quality of wastewater coming from secondary treatment is good enough, then this part can be skipped. Usually, the methods WWTP ultilizes are ultra violet and chlorine disinfection, membrane and sand filters[5]. If chlorine is used in disinfection, it must be removed by adding sodium bisulphite before it is discharged. Chlorine in high concerntration may be damaging to water body and lives in it[6]. After this process, the treated water is released to the river.

Sludge treatment: Since the sludge from primary and secondary treatment contain nearly 99% water, it is important to separate it from water to allow further treatment[3]. This first process is called thickening. The total volum of sludge can be decreased by more than 50%[7]. After thickening, the sludge is put into a tank without oxygen. This process is called anaerobic digestion which is used to further reduce the volume of sludge. In this process, the organic material is consumed by anaerobic bacteria and converted into carbon dioxide and biogas[8]. The biogas produced can be used as a source to generate electric power so the WWTP equipped with associated generators can store the biogas and use it to generate electricity when necessary.The treated sludge is pumped to a dewatering facility. In the dewatering process, three types of technologies, plate and frame filter press, centrifuge and belt press, are used to remove liquid from sludge[9]. The dried sludge can be used as solid conditioner.

1.2 ENERGY CONSUMPTION

Knowing the energy consumption of each piece of equipment in the wastewater treatment plant is essential for determining demand response strategies because the primary target for demand response is the energy-intensive equipment and it can lead to the greatest energy and demand savings. In most WWTP, aeration and pumping systems are often the largest energy consumers. Other equipment and processes such as lighting, trickling filters, anaerobic digestion and dissolved air flotation can also require a certain amount of electricity.

Plant Process	Energy Consumption (%)
Secondary treatment aeration	55.6
Primary clarifier and sludge pumps	10.3
Heating	7.1
Solids dewatering	7.0
Influent pumping	4.9
Effluent filters and process	4.5
Secondary clarifier and RAS (Return activated sludge)	3.7
lighting	2.2
Thickening and sludge pumping	1.6

Table 1-1 typical energy consumption for a WWTP[10]

1.2.1 AERATION

The largest energy use is aeration (55.6%). Facility energy use can be reduced if the air produced in aeration is decreased. Aeration provides oxygen to bacteria to break down the organic matter so that a normal biochemical oxygen demand (BOD) level can be achieved. BOD of wastewater and the aerator efficiency are the key factors to decide which size and how many aerators should be used in the wastewater treatment system. With the help of aeration equipment, adequate mixing in the tanks can be guaranteed and solids can be prevented from settling to make sure a certain solids retention time is achieved[11].

To maintain a specific level of dissolved oxygen (DO) in the wastewater effluent, several blowers are used in the aeration basin. Fine bubble diffusers are quite often used in the aeration basins compared to course bubble diffusers. The contact area between air and wastewater decides the efficiency of aeration. In other words, the size of air bubbles plays an important role in determining the efficiency of aeration[12]. Generally, a WWTP with a certain size is equipped with more than one blower. All the blowers are running simultaneously during on-peak hours while one or more blowers run during normal hours depending on the amount of wastewater that needs to be treated. DO in each basin is measured by DO sensors for a period of time such as 15 minutes. The data from the DO sensors is delivered to modulating valves by which the amount of air that blowers blow into the aeration basin is controlled. A DO setpoint is programmed into the DO sensors and once the DO levels rise above or drop below the setpoint, the amount of air injecting into the basin is adjusted by the modulating valves to make the level of DO stay at a constant value[13].

1.2.2 WASTEWATER PUMPING

The second largest part is wastewater pumping (16.8%). Together with aeration, the energy use of these two parts is about two-thirds of overall energy use. The pumping system mainly consists of influent pumping and effluent pumping. There is also other pumping used within the facility. Influent pumping is used to pump the filtered wastewater from the junction chamber to the aerated grit chamber[14]. Different elevation of wastewater treatment facility sites and the influent sewers leads to different amounts of energy needed to pump influent[15]. Effluent pumping is to pump the treated wastewater which is going to be released into the river. During normal facility operation, not all the pumps runs at the same time. Instead, there will be some remaining pumps serving as emergency backup. The backup pumps are rotated among all the pumps[13].

Three types of pump are often used at wastewater treatment plants and they are centrifugal, progressive cavity, and positive displacement. Centrifugal is commonly used in raw wastewater pumping, primary and secondary sludge pumping and effluent wastewater pumping. Positive displacement is to pump primary sludge, thickened sludge, digested sludge, slurries and chemical feed. Progressive gravity is able to deal with all types of sludge and slurries[16].

Usually, the motors of aerators and pumps can only be turned on and off. Therefore, even if the load is less, the motors are still running at full speed, which can cause great energy waste. Installing variable speed drives (VSDs) on those motors allows them to operate at different speeds by changing input frequency and voltage instead of turning on and off. Then the speed of motors can better match to the changing loads. Installing VSDs on motors can help WWTPs reduce energy waste and increase the life span of motors.

1.2.3 SLUDGE DEWATERING

Since the sewage sludge after primary treatment and secondary treatment contains a large amount of water, it is common to see some sludge dewatering equipment in wastewater treatment facilities. The energy use of solids dewatering typically accounts for 7% of the total energy of a WWTP. The equipment used in this process has varying energy-intensities such as centrifuges, belt-filter presses, drying bed and lagoons[17]. It is also important to choose the most efficient dewatering method in order to reduce the energy consumption[1].

1.2.4 ANAEROBIC DIGESTION

Anaerobic digesters break down organic material existing in sludge in the absence of oxygen During this process, anaerobic bacteria consume the organic matter and convert them into water and a biogas consisting of methane and carbon dioxide. This biogas can be used directly by power gas engines to produce electricity, which makes anaerobic digestion a widely used source of renewable energy to generate electricity and heat. Anaerobic digestion now has received increasing attention due to its ability of reusing waste and producing electric power [18]. Nevertheless, electric utility usually will restrict the generation equipment using carbon based fuels such as diesel, natural gas or biogas within a certain annual working hours. If the WWTP is capable of storing the biogas, then it is possible to use the electricity generated by power gas engines with biogas as power source b during the on-peak hours or DR event. It can be an effective way to shift loads from on-peak hours to off-peak hours[11].

1.3 ELECTRIC UTILITY RATE STRUCTURE

Two main components, the quantity of electricity used and the demand for electricity, constitute the cost of the electricity used in WWTP. The quantity of electricity is measured in KWh while the demand charge is based on the customer's maximum demand for electricity measured in KW. For each billing cycle, the energy consumption charge based on the number of KWh can be further divided into on-peak and off-peak consumption. The electricity price during on-peak hours is higher than the one during off-peak hours. In the electric utility rate structure, demand charge sometimes can account for nearly half of the total cost of electricity, but electric utility usually will reward the customers who can demonstrate a flattened load curve. Having a ful understanding of electric utility's policies and rate structure is essential to energy management planning[2].

1.4 DEMAND RESPONSE

The description that DOE gives about demand response is "Demand response provides an opportunity for consumers to play a significant role in the operation of the electric grid by reducing or shifting their electricity usage during peak periods in response to time-based rates or other forms of financial incentives[19]." In demand response programs, increasing electricity rate, or incentives are often used by electric utilities to control demand when electricity demand is heavy enough to threaten the reliability of electricity supply. A demand response event means in situations when a utility anticipates extreme temperatures or power line damage etc., customers are asked, in advance, to adjust their energy consumption[20].

A demand response program usually includes rewards or penalties. PJM gives their description about demand response "Demand Response is a voluntary PJM program that compensates end-use (retail) customers for reducing their electricity use (load), when requested by PJM, during periods of high power prices or when the reliability of the grid is threatened. These customers receive payments from PJM members called Curtailment Service Providers[21]." Energy efficiency and demand response play an important role in reducing energy consumption and ensuring system reliability. Electricity use during on-peak hours can be decreased by many strategies and they can be divided into two types: load shifting and load shedding.

1.4.1 LOAD SHIFTING

The main purpose of load shifting is to reduce large energy load during a period of time by shifting some loads ahead or behind the DR event so that the electric power utility can have additional loads coming in. Load shifting is a widely known concept and has helped plenty of industrial and large-size commercial facilities reduce electric on-peak demand and energy cost[22]. The load shifting opportunities in WWTP may include over-oxygenation, using storage capacity to store untreated wastewater, and shifting some nonurgent load such as dewatering and anaerobic digestion in the sludge process to off-peak hours.

over-oxygenation means over-aerating the wastewater before the demand response event. The plant can, therefore, reduce the power output of aerators during the peak demand period. However, over-oxygenation may have some potential problems. Recent research conducted in a California food processing wastewater treatment facility shows that a 0.2mg/L DO decline can be achieved by a 10% peak load reduction when the wastewater is over-oxygenated. Also, if DO concentration in wastewater reaches the maximum value, a waste of energy use can happen when aerators continue inputting air into the wastewater. The oxygen levels and other parameters in the effluent should be carefully monitored by facilities to make sure the regulation requirements can be met[1].

If the WWTP is equipped with a storage system, then it will have the ability to store the untreated wastewater during on-peak hours and process it during off-peak hours. The size of the storage system may determine the amount of load being able to shift and the degree of energy can be reduced. A large size of storage system can lead to great load shifting and financial savings. Some problems such as the maximum retention time of wastewater in a storage tank and extra pumping cost to pump the wastewater from the storage tank to the facility need to be considered.

Some nonurgent facility processes like dewatering and anaerobic digestion can be rescheduled to off-peak hours while some unnecessary equipment can be turned off during on-peak operation hours.

1.4.2 LOAD SHEDDING

Load shedding is another mechanism to reduce the peak demand by helping manage the way electricity is used. To be more specific, the purpose of load shedding is to reduce the total amount of electricity usage during a DR event. In wastewater treatment facilities, load shedding includes installing VSDs motors so that they can operate at a lower capacity, turning off unnecessary equipment such as lighting etc., and utilizing standby generators such as a microgrid, gas power generators etc.[1].

Installing equipment with VSDs can help WWTP achieve load shedding during a demand response event. Utilizing VSDs on pumps and aerator blowers can effectively cut down electricity use during on-peak hours. Since pumps and aeration blowers are the most energy consuming equipment in WWTP, installing VSDs on their motors can have a great impact on reducing facility demand and energy cost.

During on-peak hours, shutting down some aeration blowers, some pumps, HVAC, and other unnecessary equipment also can be a good method to shed electricity consumption. However, applying this strategy may put the quality of effluent into a risk, so careful monitoring is necessary for ensuring the reliability of WWTP[1].

Usually medium or large WWTPs are equipped with some standby on-site generators, which can provide extra power during on-peak hours or some emergency situations such as electric outage of the main grid. These redundant power sources not only provide potential options for load shifting and shedding, but also increase the reliability of the wastewater treatment plants. A microgrid can operate as a backup generator when it disconnects with the main grid. A microgrid can provide a great quantity of green and clean energy when it integrates with renewable energy sources such as solar panels or wind turbines. Backup generators are an important source of energy because some loads which cannot be shifted need to operate at all times.

CHPTER 2 LOAD SHIFTING MODEL

2.1 INTRODUCTION

In this paper, we are focused on developing a load shifting model to help improve energy management and savings. The difficulty of this modeling is to make sure the quality and the reliability of wastewater is not compromised when shifting load from on-peak hours to off-peak hours. This chapter will first introduce the subjective function and then some constraints are going to be discussed. A case study is used to demonstrate the effect of this model. Finally, a software tool is developed to help with the decision making in planning and running WWTPs.

2.2 PROBLEM FORMULATION

The main problem of this model needs to solve is how to gain financial benefits or reduce energy cost while the reliability and quality of effluent is guaranteed. The main total cost function is formulated as:

$$\text{Min } \sum_{t=1}^{24}\left(\left(P_{pump}^{t}+P_{blower}^{t}\right)\times M_{elec}^{t}\right)+\sum_{t=1}^{24}\left(P_{expump}^{t}\times M_{elec}^{t}\right) \qquad (2\text{-}1)$$

P_{pump}^{t}: Energy used for pumps (KW)

P_{blower}^{t}: Energy used for aeration blowers (KW)

M_{elec}^{t}: electricity price ($)

P_{expump}^{t}: extra pumping energy (KW)

The total cost function is composed of two parts. One is the pumping and aeration cost, another is the extra pumping cost. Since the energy use of pumping and aeration blowers accounts for nearly half of the total energy consumption, they are the two pieces of equipment that we pay more attention to. In this model, it is assumed that the wastewater treatment plant is equipped with a certain size of storage system because owning a storage system is the key to shifting pump and blower loads. The storage system sometimes can lie below the WWTP, for example, in a deep tunnel, this situation may require an extra cost to pump the wastewater from the storage system to the WWTP.

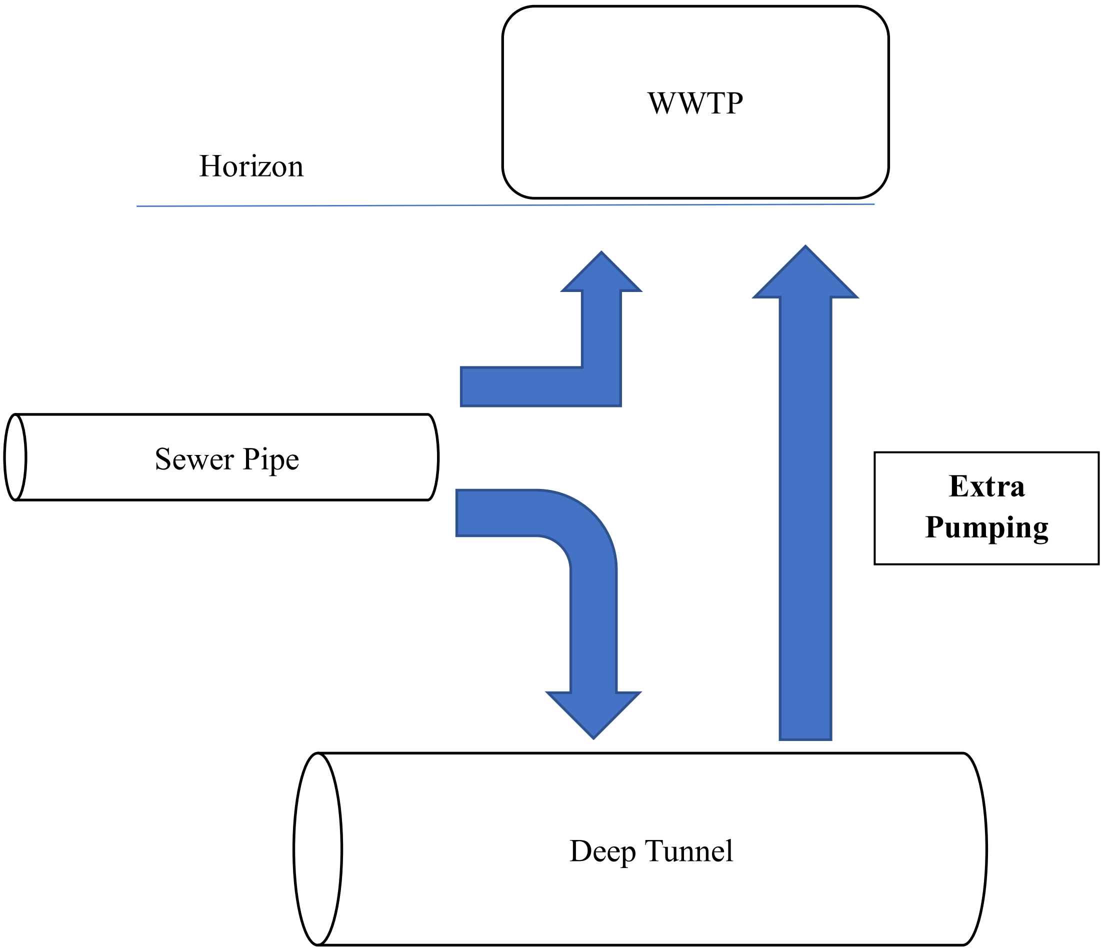

Figure 2-1 Extra pumping from deep tunnel to WWTP

2.3 PARAMETERS AND REALISTIC CONSTRAINTS

Some realistic constraints need to be considered when formulating the problem. The constraints include the treatment capacity of the WWTP, available capacity, and maximum holding time of wastewater.

2.3.1 TREATMENT CAPACITY

The treatment capacity is the maximum wastewater that the WWTP can process in one hour, and the hourly wastewater being treated should be less than the treatment capacity. It is formulated as

$$0 \leq W_p^t \leq T_{cap}^t \qquad (2\text{-}2)$$

W_p^t: the amount of wastewater need to be processed (MG)

T_{cap}^t: the treatment capacity (MG)

2.3.2 AVALIABLE CAPACITY

The storage system is used to store untreated wastewater temporarily during on-peak hours and release it during off-peak hours. For convenience, a new variable, available capacity of storage system, is introduced. It is the measurement of the amount of available capacity in the storage system at the beginning of each hour and it is formulated as

$$C_a^t = C_s^t - W_r^{t-1} - I^t \qquad (2\text{-}3)$$

C_a^t: available capacity at time t. (MG)

C_s^t: storage capacity at time t. (MG)

W_r^{t-1}: the remaining wastewater at time t-1. (MG)

I^t: the amount of influent at time t. (MG)

The constraint is

$$0 \leq C_a^t \leq C_s^t \qquad (2\text{-}4)$$

2.3.3 REMAINING WASTEWATER

The remaining wastewater is the amount of untreated wastewater which remains in the storage system at the end of time t. It is formulated as

$$W_r^t = W_r^{t-1} + I^t - W_p^t \quad (2\text{-}5)$$

The constraint is

$$0 \leq W_r^t \leq C_s^t \quad (2\text{-}6)$$

2.3.4 UNPROCESSED WASTEWATER

Unprocessed wastewater is the amount of wastewater which WWTP have no ability to process at time t when the amount of influent is much larger than the treatment capacity and storage capacity. This situation can occur during extreme weather conditions such as heavy rain. It is formulated as

$$W_n^t = W_r^t - C_a^t \quad (2\text{-}7)$$

The constraint is

$$W_n^t \geq 0 \quad (2\text{-}8)$$

This parameter indicates the reliability of WWTP. In a normal situation, it should be zero, which means all the incoming influent is processed by WWTP. If it is larger than zero, it means there is some wastewater that cannot be treated at this time, and it has to be poured into the river without any treatment. It may pollute the surroundings and damage the public health. WWTPs can be less reliable if this parameter becomes larger.

2.3.5 MAXIMUM HOLDING TIME

Maximum holding time is the maximum length of time that the wastewater can stay in the storage system. If the time that the wastewater stays in the storage tank is too long, the quality of the effluent can be affected. Other factors such as temperature need to be considered when determining the value of maximum holding time. The holding time can be shorter during summer and longer during winter. An operator with rich experience is recommended to get involved in the determination of the maximum holding time based on different conditions.

2.4 FORMULATION PROCESS

This problem is in a unit of one hour and it is used to calculate the total cost in WWTP for one day/24 hours. The process is described step by step as follows.

Step 1: input the one day/24 hours influent data and real time electricity prices. Determine the maximum holding time of wastewater and acceptable electricity price.

Step 2: if the current price is lower than acceptable price, the incoming influent will be processed as much as possible at this time. Otherwise, the influent will be stored first. When influent needs to be stored, one of two scenarios will occur.

Scenario 1: if the storage system is full, then the influent has to be processed at this time.

Scenario 2: if the storage system is not full and is able to store all the incoming influent, then all the wastewater is stored.

Step 3: based on current information, some parameters are calculated such as remaining wastewater in the storage system, processed wastewater and the wastewater being poured into the river.

Step 4: measure the wastewater holding time and compare it with maximum holding time. If it is larger than maximum holding time, then no matter how much money it can cost, this certain amount of wastewater will be processed. Otherwise, it will continue staying in the storage tank.

Step 5: the value of remaining wastewater in the storage system, processed wastewater and the wastewater being poured into the river are updated.

Step 6: if the time index reaches 24, then the whole process stops and relative parameters such as remaining wastewater in the storage system, processed wastewater and the wastewater being poured into the river is outputted. Otherwise, it will go back to step 2.

2.5 CASE STUDY ANALYSIS

In this case study, it is assumed that the WWTP is equipped with a storage tank which can be used to store as much as 20 MG wastewater and the treatment ability is 8 MG per hour. At the beginning of time t, we assume there is 0.3 MG wastewater remaining in the storage tank. The input data of electricity price and influent is shown in figures 2-2 and 2-4.

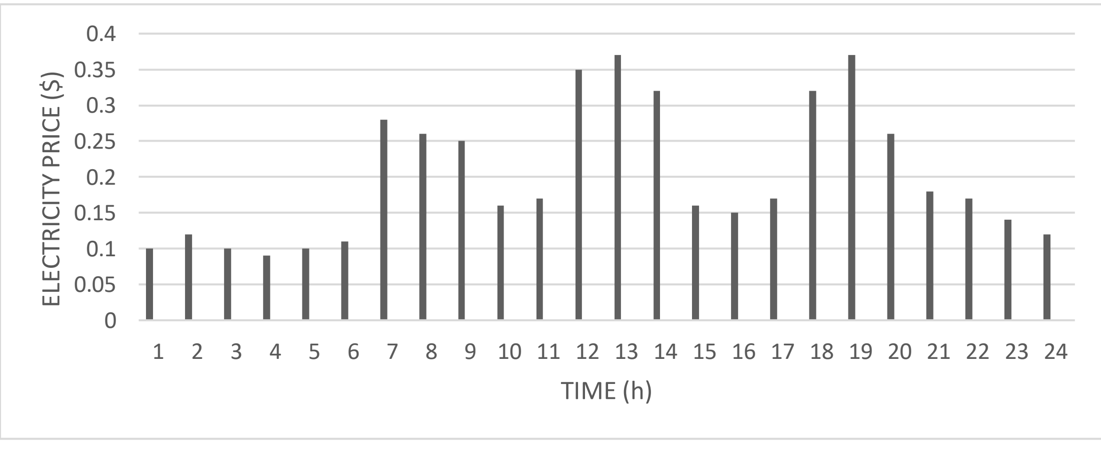

Figure 2-2 Real-time electricity price

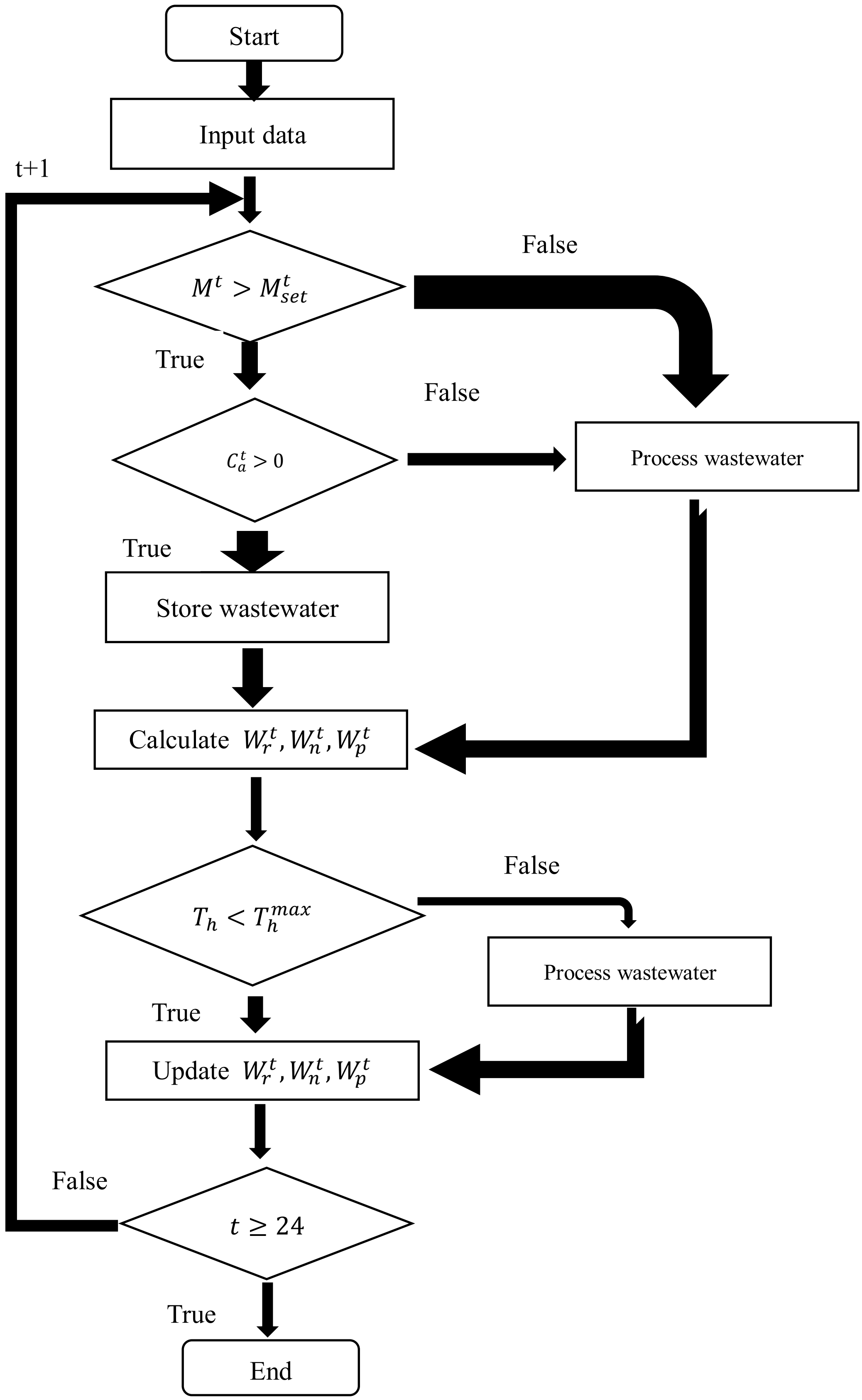

Figure 2-3 Flow chart of load shifting formulation

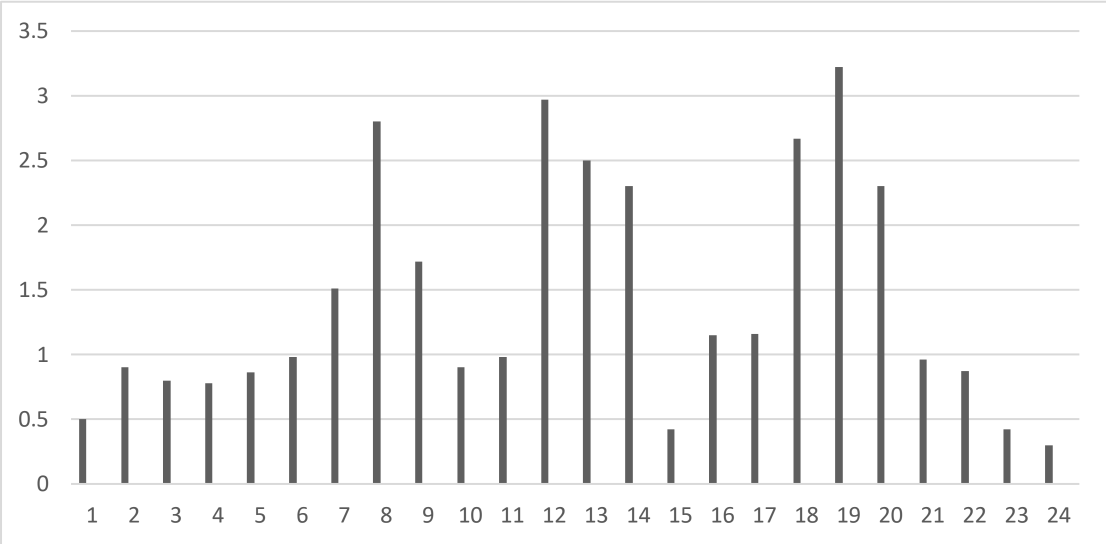

Figure 2-4 Incoming influent at different time

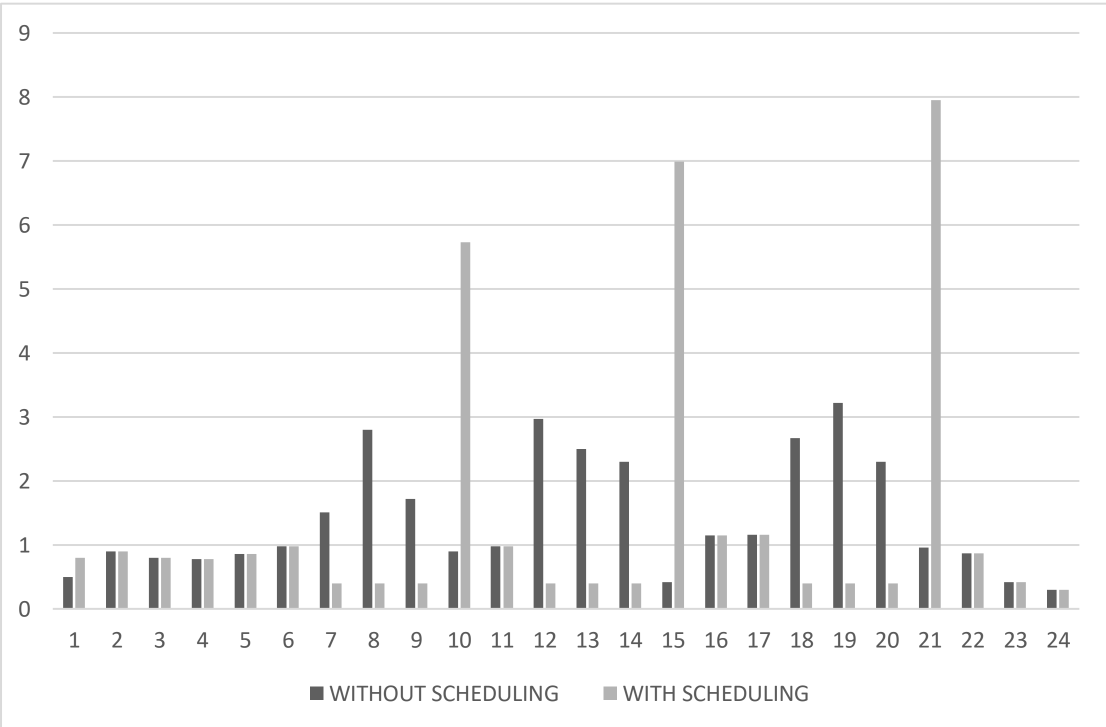

Figure 2-5 The comparison between treatment with load shifting and without load shifting

The result is depicted in figure 2-5. The black bar represents the processed wastewater without any scheduling. The WWTP treats no matter how much wastewater comes in. The grey bar is the processed wastewater with load shifting. It moves some loads from on-peak hours to off-peak hours.

2.6 CONCLUSION

In this case, the entire operation cost of the WWTP without any scheduling is $2,577 per day and it is reduced to $2,000 per day when applying the load shifting model. It saves $577 per day and the total annual cost reduction is $210,605. Compared to the annual cost without scheduling which is $940,605, nearly 22% of utility cost can be condensed.

2.7 SOFTWARE TOOL

A software tool has been well developed. The users can get an estimation of daily and annual cost savings by inputting some parameters of their WWTP such as electricity price, influent, storage capacity and maximum holding time. The graphic user interface is shown in figure 2-6.

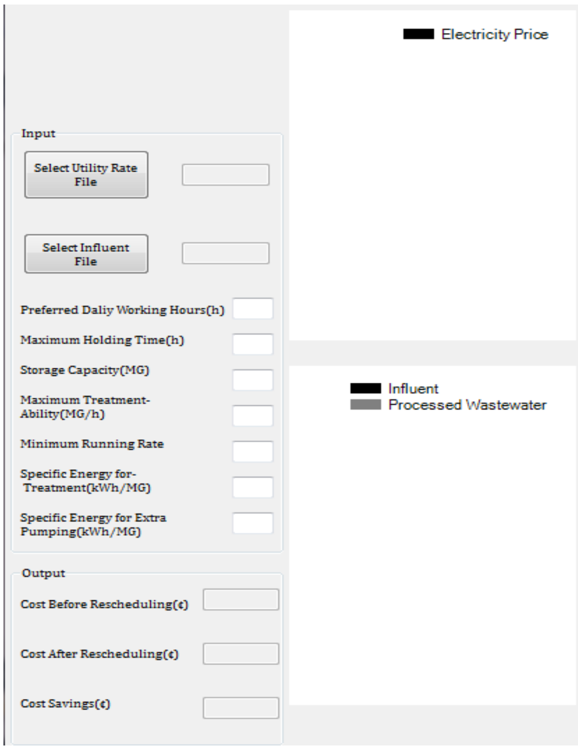

Figure 2-6 Graphical user interface of load shifting software tool

The software tool is made up of three parts: Input part, output part and graphic part. The user first needs to load the utility rate file and influent file. Then, several parameters such as maximum holding time, storage capacity need to be typed in. finally, by clicking the simulation button, the result will be shown up in output and in the two graphs. The first graph just shows the electricity price while the second one compares the influent and the wastewater that is recommended to process.

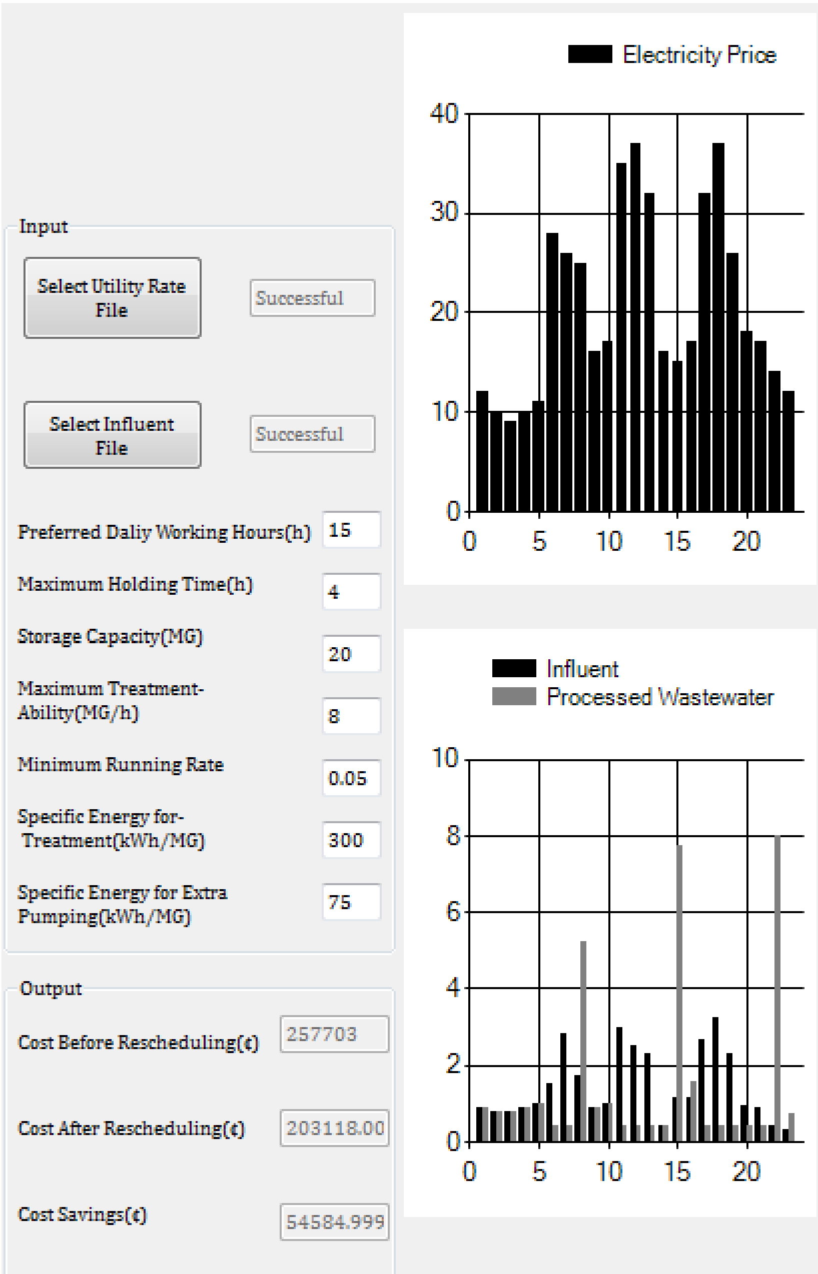

Figure 2-7 An example showed in the software

CHPTER 3 DISTRIBUTED ENERGY SOURCES

3.1 INTRODUCTION

The modern power system in the world is mainly a centralized and single electricity supply which is featured with large units, large grid and high voltage. Most of the loads are getting power from this single and centralized large grid. Nowadays the whole world wants the energy sources and electricity supply to be more reliable and secure. The large and centralized grid is obviously not able to meet this requirement any longer. Any kind of malfunction and disturbance in any part of the large gird can cause a huge impact to all of the users who are connected to the grid. If a serious power blackout occurs, it leaves millions in dark. Some important institutions like hospitals or government buildings need to rely on the continuous supply of electricity. A power blackout can threaten the life of patients and public order. What is more, the large grid is easy to become a target of terrorists or enemies during a war. The large and single grid can be a great threat to the national security and economy. The best solution is combining the large grid system and distributed power generation system. It can save the investment, reduce energy consumption, and increase the system security and flexibility[23].

Distributed power generation usually refers to small size generators which are on-site or close to the users. These small size generators can contain fuel cells, gas turbines, microturbines, renewable energy sources such as PV power generators or wind turbines, and reciprocating engines[24]. Since distributed power generation is close to users, it can increase the reliability of power serves and quality of electricity. With the development of technologies, the expansion of the electric market, distributed power generation now becomes an important choice when selecting energy source.

The advantages of distributed power generation include:

1. By combining the distributed power generation and the centralized power system, large-scale blackouts can be avoided so that the security and reliability of electric power supply is increased. The distributed generators being used usually are medium, small or micro size generators which have advanced performance. It is easy to turn the distribution generators on and off, and it is also convenient for users to utilize all of their functionalities. The power stations in distributed power generation are independent from each other so users can control them respectively[23].
2. Distributed power generation can cover the shortage of the large grid such as the lack of stability and reliability. The investment for distributed power generation is less and the time to construct a whole facility is short. It can help supply electric power when unexpected disasters happen. Because of the small size of distributed power generators, they will not take too much space. Now it becomes an indispensable backup power for hospitals, militaries or any other institutions or communities.
3. Distributed power generation can do real time monitoring for the quality and performance of local electricity. Compared with traditional power sources such as thermal power or hydropower which can be harmful to the environment, Distributed power generation mostly use clean energy sources like PV panels or wind turbines. Greenhouse gas emissions, especially carbon dioxide, can be reduced. Some companies, for example, Focus On Energy,

now are providing incentives for each renewable energy source installed so they can encourage more electricity users to pick Distributed power generation[25].

4. The transmission and distribution losses of distributed power generation are low and can be negligible. To transmit the electric power over long distance, the centralized large grid needs to increase the voltage and reactive power and some of the electric energy is lost during the transmission. With distributed power generation installing near to the users who use electricity, the waste can be significantly reduced. Besides, there is no need to build a power station for it so the additional cost for power transmission and distribution can be reduced or avoided. Also, the cost for building and installation is low. For a traditional centralized power grid, a breakdown in any point of the grid can shut the power down for every user in the area. When utilizing the new distributed power generation system, each user will only suffer the power outage due to his/her own power system failure[26].
5. According to a report written by the U.S. department of energy, approximately 12 million distributed power generators with a total capacity of 200 GW have been installed in the United States. Not only being used as an emergency backup power for customers, the distributed power generators can also help reduce the peak load since users with distributed power generation systems would rather use their own power instead of purchasing electricity at a high price. Demand response program now is popular in some areas. By receiving signals ahead of time from utility companies, electricity users can get financial incentives by reducing power consumptions during on-peak hours. In the same way, users can also be punished by the electric utilities if they break the rules. Besides, the distributed power generators can help provide ancillary services like voltage support and improve the

quality of electric power. If the power generated by the distributed power generators can meet the requirement of local loads, the reliability of the total electric power system can be enhanced[27].

3.2 WIND TURBINES

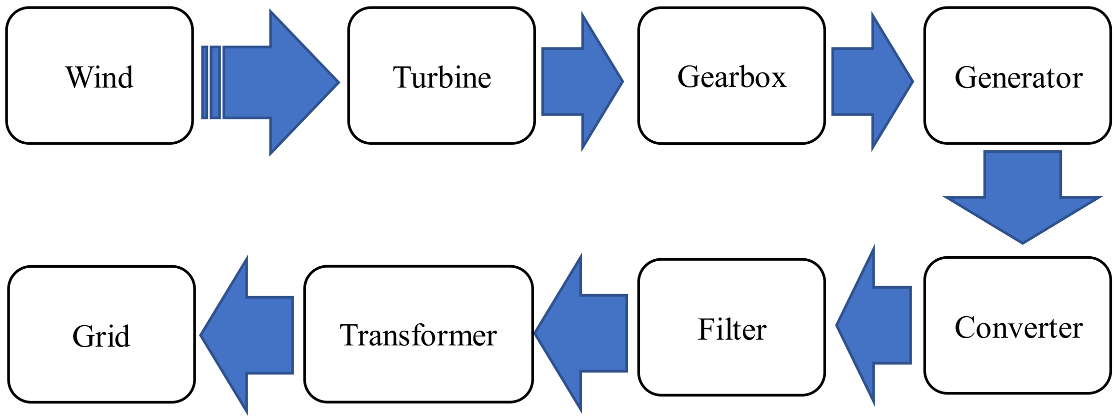

Figure 3-1 Wind turbine system[28]

A flowchart of how a wind turbine generates electricity power is shown in figure 3-1. The input power source wind drives the blades of the turbine. The turbine converts the wind into mechanical energy. The adoption of a gearbox which is inside the turbine makes the conversion from mechanical power to electrical power with a high speed and low torque. Then the size and weight of the electrical generator can be condensed. Now the mechanical energy becomes electrical energy. The job of the converter is to convert the DC power to AC power which shares the same phase with the power in the grid. Then some signals which are not needed will be moved out by a filter. The transformer is used to change the voltage of the generated electricity so that the power can better match with the grid[28].

3.2.1 TYPES OF WIND TURBINES

Typically, there are two main types of wind turbines, horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). Horizontal axis wind turbines are the most commonly used types in the world. The design of HAWT is quite similar to a windmill. The blades of a HAWT rotate on an axis which is horizontal to the ground while the blades of a VAWT rotate on an axis which is vertical to the ground.

3.2.1.1 HORIZONTAL AXIS WIND TURBINES

As for HAWTs, the main rotor shafts, gearboxes and the generators that produce electricity are all located in the top of its tower. They have to face the wind to generate electric power effectively. Most large wind turbines are equipped with a wind sensor to help turn the turbine into the wind and a gearbox used to increase the rotation speed of the rotor which is more helpful for electric generators to produce electricity. Some wind turbines are designed to be the upwind mode with turbine pointing upwind of the tower and other wind turbines are designed to be the downwind mode with turbine pointing downwind of the tower so that the wind goes through the tower without striking the blades. Some small upwind turbines usually utilize a tail vane to keep the blades in the right direction which is facing the wind. The down wind turbines usually chose not to have a tail vane on them to make the machine rotor tracking the wind naturally. Most HAWTs are designed to be the upwind mode because downwind mode has the problem of turbulence which can lead to fatigue failure[29].

The advantages of HAWT include:

1. The design of many kinds of pith of the blades in horizontal wind turbines can help a large amount of wind energy be collected by the wind turbines. The blades are

vertical to the direction of incoming wind, which makes more power received for rotation and it increases the efficiency of horizontal wind turbines[30].

2. The tall tower base structure of HAWT can protect itself from even the strong wind. When handling high speed wind, it can produce more electric power. It also has high efficiency and good functionalities because of the movement of blades. When the blades move, they do not need backtracking[31].
3. The design of HAWTs is unchanging so that the installation and maintenance can be relatively easy.
4. The design of blades makes the turbine more stable.
5. The taller the tower is, the more wind the turbine can access. The tall tower base can help the turbine receive more wind energy.
6. Mutable blade pitch allows the blades of the turbines to adjust themselves to the optimal angle of attack. Controlling the attack angle of the blades remotely can be much easier, and the wind energy collected by the wind turbine can constantly reach near maximum over the whole year or season[32].

3.2.1.2 VERTICAL AXIS WIND TURBINES

The vertical axis wind turbines, also known as VAWTs, have vertical main rotor shafts. Unlike HAWTs which have tall towers, VAWTs have all their components near the ground so that a tall tower is unnecessary. Their maintenance can be easier than HAWTs, but the wind energy they can catch is less. Another problem VAWTs can have is turbulence. Since the main components of VAWTs are located near the ground, the air flow near the ground can cause vibration of the facility which may decrease its life span and increase the times of maintenance[29]. However, VAWTs also have some advantages:

1. Too much wind is not required to set up the system, and primary components including shaft and generators, can be installed at ground level. Laborers can maintain the whole facility easily instead of climbing a tall tower.
2. Even low wind speed can make the VAWTs generate power.
3. VAWTs can be installed on the rooftops or hilltops where the locations are near to the ground.
4. VAWTs do not need to be pointed into the wind to generate electric power, which makes them more durable. In strong wind situations, VAWTs are more likely to avoid damage than HAWTs[33].

The large size HAWTs in wind farms are often used to generate electricity for centralized large power grids because of their high efficiency and ability to produce large amounts of electric power. However, a small, low noise level and low risk vertical axis wind turbine is appropriate to urban areas, and most importantly it makes more sense to have a small vertical axis wind turbine installed as a distributed generation source. They require a smaller investment and are easy to install. They are also safer because they have a lower rotation speed. As a distributed energy source, VAWTs can receive wind from any direction which can make the power supply more reliable[34].

3.3 PV POWER GENERATION

Begin from 1839, the PV effect was first found by Becquerel[35]. In the late 1950s, the first traditional PV cell was produced, and during the next ten years, it was mainly used for satellites. In the 1970s, the technology of the PV cells had been updated. The quality and performance of the model were greatly improved. The cost to build and install the PV cells was reduced and the efficiency to produce electric power was increased. In the 1980s, PV cells became popular sources for calculators, water heaters, watches and other applications[36]. Nowadays, solar power has become widely used, for it has the ability to produce electric energy without polluting the environment.

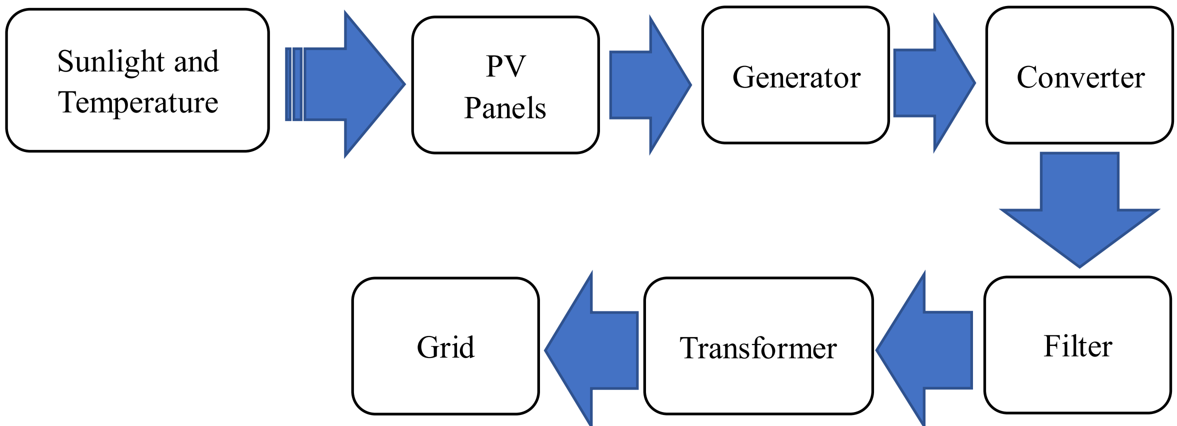

Figure 3-2 Flowchart of PV power generation[28]

PV technology is able to convert sunlight into electric power. One single piece of PV is known as a cell. When one or more PV cells are put together to produce more electric power, the group is called a PV panel or module. If one or more PV panels or modules are combined to supply electricity for users, they are usually called a PV system. A PV system can be large or small, it depends on the requirement for electricity. It can be large enough to support a WWTP or it can be small enough to supply energy for a watch.

First, the sunlight and temperature will be received by each cell of PV panels, where the solar energy is transformed into electric energy. Unlike wind turbines that use mechanical conversion to get electric power, there is no mechanical conversion in the PV power generation. Instead, the photovoltaic effect is utilized to complete the conversion. The following steps are similar to wind power generation. Generators are used to produce electricity and the electricity generated is converted from DC to AC by converters. Unwanted signals are removed by a filter. Transformers are used to increase the voltage so that the power generated by PV panels can be transmitted through the grid.

3.3.1 TYPES OF PV CELLS

The most commonly used PV cell that can be found on the market is the silicon solar cell. It is estimated that near 90% of the PV cells are silicon solar cells and around 95% of silicon solar cells are crystalline solar cells. Purity of the cells is the factor which can determine the efficiency of the transmission rate from sunlight to electricity. If the purity of the silicon solar cells is high, then more electricity can be converted from the same amount of sunlight compared to a lower level of purity[37]. In crystalline solar cells, the crystal lattice, which is formed by the connection of silicon atoms, provides an organized structure. The structure in some sense is called purity[38].

There are two types of solar cells in crystalline solar cells. The monocrystalline and polycrystalline. The monocrystalline solar panels have good performance and high efficiency. They also can be used for a long time. However, they are expensive. The polycrystalline solar panels also have a nice efficiency, and the most attractive factor is they are cheap. The disadvantage is they are sensitive to high temperatures and have a low life span[39].

Unlike crystalline silicon, the thin film silicon has a lower efficiency as well as cost. Thin film solar cells were first invented in the 1970s by scientists in the University of Delaware in the U.S. They were put into use in the 1980s. They were made into small strips and installed into watches or calculators. By now, technology has been further improved. Thin film solar cells are more flexible than ever, which means they can be installed in curved surfaces such as the surfaces of buildings or cars[40].

CHPTER 4 MICROGRID IN WASTEWATER TREATMENT PLANTS

4.1 INTRODUCTION

The definition of a microgrid can be found in U.S Department of Energy Microgrid Exchange Group:

"A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode[41]."

As a localized group of electric energy sources and loads, a microgrid runs connected to and synchronous with the traditional main grid in normal situations, while it can also disconnect with the main grid and operate independently. Many microgrids are often integrated with renewable energy sources such as PV panels or wind turbines. Microgrids can be divided into four types, customer microgrids, utility or community microgrids, virtual microgrids, and remote power systems[42].

Customer microgrids are the most famous and commonly used type of microgrid. They can perfectly be matched into existing technology and the structure[42].

A remote power system is the one which operates in an island mode and never connects to the main grid due to financial problems and geographic limitation[43]. Generally, a remote off-grid microgrid is built in the area which is far away from the transmission and distribution infrastructure. It is not able to receive the electricity provided by the main grid[44].

As the world now is paying more attention to renewable energy generations and plans to use it as the solution to climate change, microgrids can provide plenty of benefits both locally and nationally regarding environmental protection, cost savings, and efficiency improvement. Microgrids usually have distributed generator sources, most of which are renewable energy sources such as solar panels and wind turbines. The installment of microgrids can offer several advantages: Improve local energy delivery, minimize the impact for environment due to the usage of renewable energy source, enhance the reliability of electric power supply, reduce cost, increase the resilience of the grid etc.[45].

By providing a source of backup power, microgrids can minimize the losses of WWTPs when the main grid goes down. The smart energy devices, such as smart switches and sensors and the software in the energy management system, will help microgrids operate without connecting to the national grid when power outage occurs. Also, microgrids can help reduce the need to import energy from abroad where the politics and society are instable. This can make energy become more secure[45].

Microgrids can help reduce the cost and provide revenue for the users. The smart energy management system can decrease energy waste by increasing the efficiency of energy consumption. It can also help increase the reliability of the power system so that even though power outages happen, microgrids can still disconnect with the main grid and produce electricity independently. Currently, more than 150 billion dollars are paid due to power outages per year in the United States[45]. Microgrids can also generate revenue for WWTPs by providing energy services. When microgrids generate excess electricity power, WWTPs can sell it back to the main grid to get paid. One other way is to generate and store the power during off-peak hours and use or sell the power back to the main grid during on-peak hours.

Microgrids can create new job opportunities. They can also help stimulate the research into renewable energy technologies which are more effective and environmentally friendly[45].

Since local, distributed sources of generation are used in microgrids, they can make WWTP more resilient to unforeseen circumstances such as a big storm or an interruption of power supply of the main grid. Reliability is an ability to keep power on continuously, while the resilience is the ability to recover quickly from power outages[46]. The microgrid facilities which are near the users can make sure the power is supplied more quickly and efficiently than the one generated by a large centralized power station[45].

4.2 PROBLEM FORMULATION

In chapter 2, a load shifting model is introduced and an improved scheduling for the wastewater treatment is calculated. Based on the load shifting model, a model with a microgrid involving in a WWTP is formulated. The object is the same with load shifting model, which is reducing energy cost while making sure the quality and reliability of effluent is not compromised. In fact, far from compromising the reliability of effluent, microgrid can help build up the reliability and quality of the WWTP.

The objective function is[47]

$$\sum_{n=1}^{N}\sum_{t=1}^{24} (\lambda_{O\&M}^{n} * P_{out}^{n,t}) + \sum_{t=1}^{24}(M_{elec}^{t} * (P_{load}^{t} - (P_{out}^{t} - P_{mc}^{t}) + P_{gc}^{t} - P_{D}^{t}) \quad (4\text{-}1)$$

$\lambda_{O\&M}^{n}$: operation and maintenance coefficient.

$P_{out}^{n,t}$: power generated by microgrid (KW).

M_{elec}^{t} : the electricity price ($).

P_{load}^{t}: load power (KW).

P_{mc}^{t}: charged power from microgrid (KW).

P_{gc}^{t}: charged power from main grid (KW).

P_{D}^{t}: discharged power (KW).

P_{b}^{t} : battery storage at time t (KW).

The objective function consists of two parts. One is the daily operation and maintenance cost. It is assumed the operation and maintenance cost has a positive correlation with the power generated by the microgrid, so an operation and maintenance coefficient is used in this part. Another part is the cost used to purchase or sell electricity from or to the main grid. Therefore, the value of this part can be positive or negative. Positive indicates WWTP is selling electricity back to the main grid at this moment of time while negative means WWTP is purchasing electricity from the main grid.

It is also assumed a battery bank is used to store energy mainly during off-peak hours or whenever there is excess electric power. The power will be released during on-peak hours to avoid purchasing high electricity price or during a power outage when the main grid cannot supply enough electricity. The power used to charge the battery can either come from the main grid or the microgrid. The power stored in the battery can not only be used in WWTP but can also be sold back to the main grid.

4.3 REALISTIC CONSTRAINTS

Some realistic constraints must be considered while simulating the problem. the constraint for power generated by the microgrid is formulated as:

$$P_{out}^{n,min} \leq P_{out}^{n,t} \leq P_{out}^{n,max} \quad (4\text{-}2)$$

The constraint for battery system is

$$P_b^{t,min} \leq P_b^t \leq P_b^{t,max} \quad (4\text{-}3)$$

$$P_b^t = P_b^{t-1} + \eta_c P_C^t - P_D^t/\eta_D \quad (4\text{-}4)$$

$$P_C^t = P_{gc}^t + P_{mc}^t \quad (4\text{-}5)$$

η_c is the charge efficiency while η_D is the discharge efficiency. The charge and the discharge cannot happen simultaneously. P_C^t is the charged power which can be purchased from the main grid (P_{gc}^t) when the price is low or can come from the microgrid (P_{mc}^t) when the price is high. P_D^t is the discharge power.

Based on equation (3-2) and (3-3), the constraint for charged power can be formulated as

$$0 \leq P_c^t \leq (P_b^{t,max} - P_b^{t-1}) \div \eta_c \quad (4\text{-}6)$$

The constraint for discharge power is

$$0 \leq P_d^t \leq (P_b^{t-1} - P_b^{t,min}) \times \eta_d \quad (4\text{-}7)$$

4.4 PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) is used to solve this problem. PSO is a computational method created by J. Kennedy and R. C. Eberhart in 1995 and it has been successfully applied in function optimization, artificial neural network training, and other areas[48].

The inspiration of this method comes from the social behaviors of bird flocking or fish schooling. In PSO, the system is set up with a population of random solutions called particles. Particles have no mass, no volume, but have velocity and acceleration. By updating the generations, an optimal solution can be found during the iterations.

4.5 PSO ALGORITHM

The algorithm of PSO is similar with the behaviors of bird flocking or fish schooling. Supposing a group of birds are looking for food in an area and each bird is searching randomly. It is also assumed that there is only one food in this area and none of the birds knows the exact position of it. Once a bird finds the food, it makes some noise to let other birds know where the food is. When hearing the sound, other birds fly towards the bird, and finally most of birds will find the food[49].

In the bird example, each single bird represents a solution in PSO and it is also called a particle. Those particles have fitness values and velocities. To optimize the fitness values, fitness function is used to do the evaluation. The evaluation, in this problem, is the subjective function which calculates the total energy cost. The velocities of particles are mainly used to show the flying direction. To achieve the best solution, all particles will follow the current optimum particles[49].

The PSO algorithm is explained step by step as follows.

Step 1: Some parameters are initialized with certain values. These parameters include operation and maintenance coefficient, number of variables, and constraints such as boundaries of variables and battery, charge and discharge efficiency, maximum number of iterations, population size or swarm size, inertia weight and its damping ratio, personal and global learning coefficient, and velocity limits.

Step 2: PSO is initialized with a group of random particles. Each particle has its own position, velocity, and best position called personal best position. Each particle will be updated by its own personal best position and global best position. Personal best position is the best position the particle itself has ever reached and global best position is the best one obtained by any particle in the whole group.

Step 3: After initialization, several iterations will be performed. During each iteration, the velocity and position of the particles are updated by the following two functions[49].

Velocity = w * Velocity+ c1 * rand() * (pbest- pPosistion) + c2 * rand() * (gbest- pPosition) (4-8)

$$\text{pPosition} = \text{pPosition} + \text{Velocity} \qquad (4\text{-}9)$$

Velocity is the particle velocity. w is the inertia weight. c1 is the personal learning coefficient and c2 is the global learning coefficient. pPosition is the current particle position. pbest and gbest are personal best position and global best position respectively. Rand() is a random number between 0 and 1.

Step 4: After each small iteration, the position and velocity of each particle are updated. A global best position is calculated. If the number of particles reaches their population size n, then the small iteration for one swarm is completed. If the number of big iteration "it" is smaller than the setpoint "it_{max}", then the algorithm goes back to execute the next big iteration. While a certain number of big iterations have been performed, a final global best position is shown up and it is the best solution within these iterations.

4.6 CASE STUDY ANALYSIS

The case study is performed based on the case in chapter 2. The same system is used in this analysis. The processed wastewater which is calculated in the previous chapter is also used in this case study. It is assumed a microgrid with battery bank is generating electricity power in WWTP. Some parameters used in the simulation are given below.

Item	Value
Microgrid	300 KW
Microgrid Operation and Maintenance Coefficient	0.2
Battery Bank	100 KWh

Battery Charge Efficiency	90%
Battery Discharge Efficiency	95%

Table 4-1 Model items and values

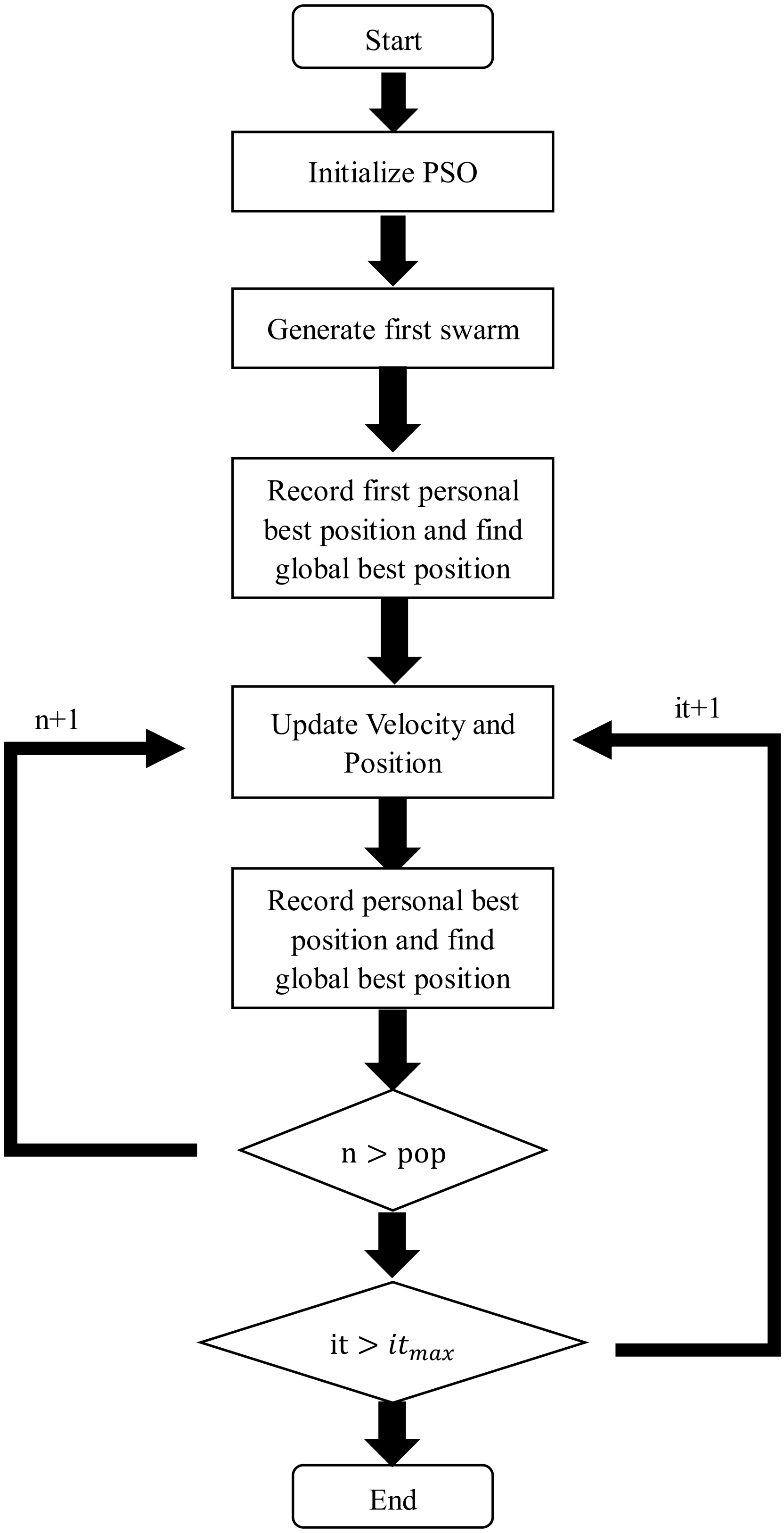

Figure 4-1 PSO algorithm flowchart

Parameter	Value
Number of Variables	24
Maximum Number of Iteration	1000
Population Size	100
Inertia Weight	1
Inertia Weight Damping Ratio	0.99
Personal Learning Coefficient	1.5
Global Learning Coefficient	2

Table 4-2 PSO parameters and values

Three particles are involved in the PSO iteration. They are the power generated by microgrid, charged power of the battery bank, and discharged power of the battery bank. After 1000 iterations, the best solution of these three particles is simulated.

4.7 SIMULATION RESULTS

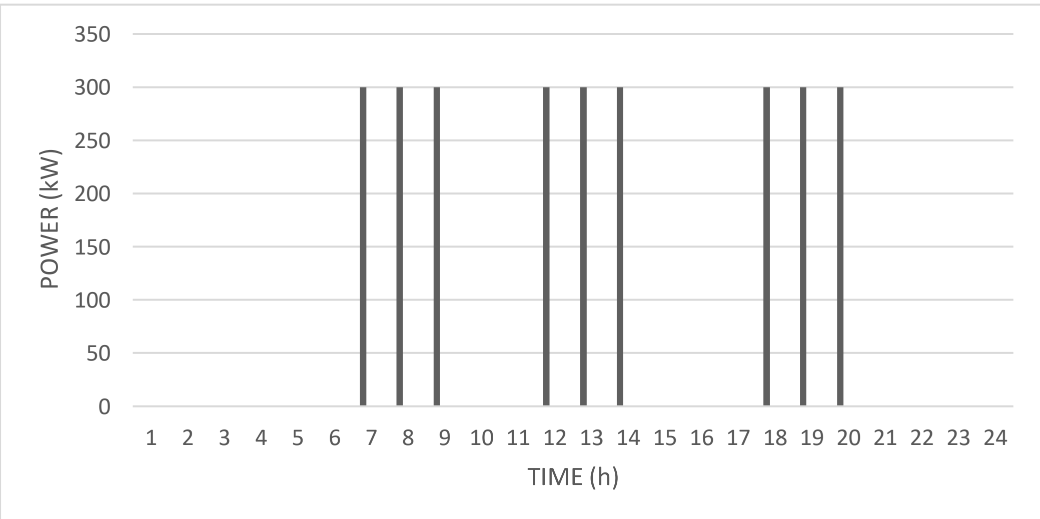

Figure 4-2 Power generated by microgrid at different hour in one day

It is obvious that microgrid begins to generate power at 7 because by looking at figure 4-3, the electricity price is relatively low before 7. It can also be found microgrid mainly generates power during time periods from 7 to 9, 12 to 14, and 18 to 20. These three time periods are the on-peak hours during the day. The algorithm helps microgrid choose the best time to generate electric power. In off-peak hours, WWTP can use the power from the main grid due to lower electricity price and the microgrid can be turned off. In on-peak hours, it can be expensive to use power generated by the main grid. Especially when WWTP is in a demand response program, electric utility companies can charge WWTP an additional fee for punishments. Therefore, the microgrid should be turned on to generate as much electricity power as possible to keep the whole WWTP running. Extra electricity may have to be purchased from the main grid if the power generated by microgrid cannot cover the whole usage of electricity.

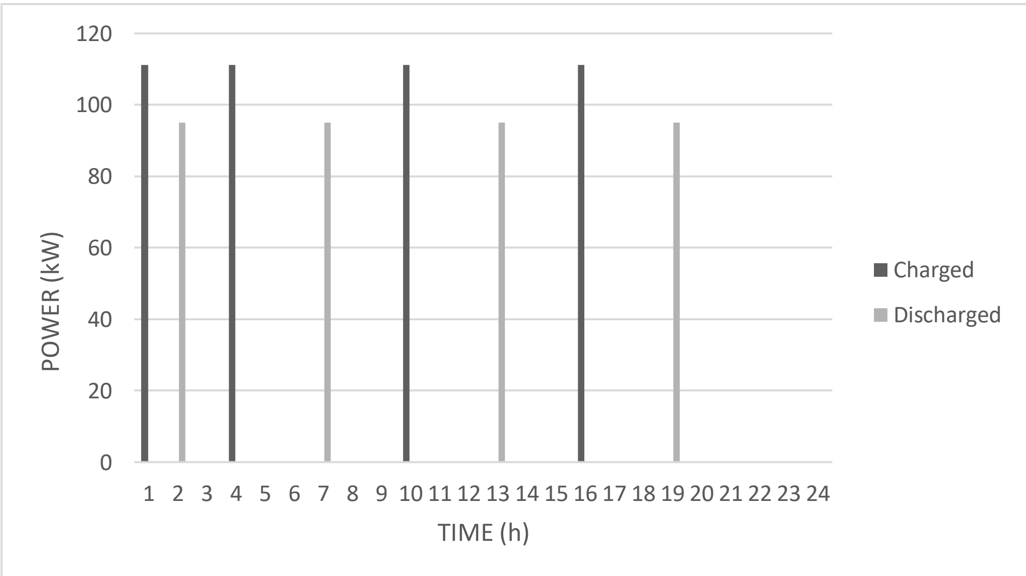

Figure 4-4 Charged and discharged power at different hour in one day

Figure 4-5 demonstrates the charged and discharged electric power in the battery bank at different times. The time to charge battery bank is selected at 1, 4, 10, and 16 where electricity prices are relatively low than the prices followed. The discharge time is chosen at 2, 7, 13, and 19 where electricity prices are the highest before the next charge time. The battery bank is charged at the lowest electricity price and discharged at the highest electricity price, which allows WWTP to gain financial benefits and helps increase the stability of the main electricity grid.

4.8 CONCLUSION

Microgrids can increase the cost savings further in WWTP based on the load shifting model. The daily operating cost by applying the load shifting model in chapter 2 is $2,000 with $577 savings per day. In the same WWTP system which has the same electricity price, influent, and any other factors, the daily operating cost with the microgrid but without the battery bank installed is $1,472. It further decreases the expense in operating the plant by $528. If the battery bank is added to the microgrid system, then the daily running expense is $1,420. It reduces the daily operating cost by $580 compared to the system with the load shifting model only and by $52 compared to the system with load shifting model and microgrid only. The annual operation cost of the system with microgrid only is $537,280. It reduces the annual operation cost compared to the system with load shifting model only by $192,720, and about 26.4% electric utility cost has been saved. The annual operation cost of system with microgrid and battery bank is $518,300. It reduces the annual operation cost compared to the system with load shifting model only by $211,700 and about 29% electric utility cost reduction has been achieved. All in all, the combination of load shifting model and microgrid model can reduce the energy cost by $1,157 per day and $422,305 per year. Nearly 50% of utility cost reduction is accomplished.

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