Optimal Operation of A Micro Water-Energy Nexus

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Dedication

This MS Thesis is lovingly dedicated to my parents (Guochong and Junping), without whom my achievements so far could never be accomplished. They are the ones always nursing me with affections and love. Their support and encouragement have sustained me throughout my university life.

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Abstract

Optimal Operation of A Micro Water-Energy Nexus

Within the emerging concepts of smart cities and smart buildings, several critical services like electricity and water supply are supposed to be integrated by adopting and implementing the cutting-edge technologies in control, communication and management/optimization. In such a smart environment, several physical systems could be connected and operated jointly to achieve co-optimized decisions. Water as well as electricity are certainly two lifeline networks and essential resources in today's daily life. From the perspective of a power grid, water systems – including water distribution and treatment – consume a significant amount of electricity power; so water systems can be considered as a critical infrastructure, the operation of which is dependent on and influencing the power grid operation. Additionally, if judiciously integrated, some special loads in water systems, such as irrigation, are controllable and could provide extra flexibility for the power grid operation.

This thesis mainly focuses on the operation integration of both power and water systems. In the power system side, the alternation current (AC) power distribution systems integrated with renewable energy resources and battery storage systems is introduced. In the water system side, the pipe network with its hydraulic characteristics is applied. The two systems are connected and co-operated as one interdependent model, so called micro-nexus. Accordingly, a co-optimization framework is introduced and tested. Considering the individual and interdependent characteristics of both power and water systems, the proposed model is a mixed-integer non-linear programming formulation which runs in the GAMS optimization environment and is tested on the modified IEEE 13-bus test system. The results show the potential of co-operating the two systems for improving the flexibility and enhancing the security of both systems.

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Nomenclature

A. Sets and Indices

$i, j \in \mathbf{N_E}$	Set of buses of the electricity network.
$l \in \mathbf{L}$	Edge set of the electricity network.
$i, j \in \mathbf{N_E^G}$	Set of bus with controllable generations.
$i, j \in \mathbf{N_E^{PV}}$	Set of bus with PV panels.
$i, j \in \mathbf{N_E^{ES}}$	Set of bus with a BESS connected.
$m, n \in \mathbf{N_W}$	Node set of the water network.
$k \in \mathbf{J}$	Edge set of the water network.
$k \in \mathbf{E_W^P}$	Set of pipes with a pump installed.
$m, n \in \mathbf{N_W^{TK}}$	Set of nodes with connected to a tank.
$t \in \mathbf{T}$	Set of time periods.
$b \in \mathbf{B}$	Set of battery energy storage system.

B. Parameters

$r_i j$	Resistance of line ij.
$x_i j$	Reactance of line ij.
$P_{i,t}^{\mathrm{L}}$	Active power load of bus i at time t.
$Q_{i,t}^{\mathrm{L}}$	Reactive power load of bus i at time t.
$P_{i,t}^{\mathrm{PV}}$	Active power output of PV at bus i at time t.
$Q_{i,t}^{\mathrm{PV}}$	Reactive power output of PV at bus i at time t.
$\underline{P}_G$	Maximum active output of generator.
$\overline{P}_G$	Minimum active output of generator.
$\underline{Q}_G$	Maximum reactive output of generator.
$\overline{Q}_G$	Minimum reactive output of generator.
$\underline{V}_i$	The lower limit of square of voltage magnitude at node i.
$\overline{V}_i$	The upper limit of square of voltage magnitude at node i.
$SOC_{b,0}$	Initial state of charge of BESS b.

nES_b	Efficiency of BESS b.
C_t	Energy Price at time t.
$\overline{P}_b^{\mathrm{C}}, \overline{P}_b^{\mathrm{DC}}$	Maximum charging and discharging power of BESS b.
$\underline{SOC}$	Minimum state of charge of BESS b.
$\overline{SOC}$	Maximum state of charge of the BESS b.
$f_{m,t}^{\mathrm{L}}$	Water load of node m of the water system at time t.
h_m	Elevation at node m of the water system.
$dist_k$	Length of pipe k.
$diam_k$	Diameter of pipe k.
R_k	Friction coefficient of pipe k.
SW_{max}	Maximum water volume the source reservoir can provide.
$\overline{ftk}_{in}$	Maximum water inflow of the tank.
$\overline{ftk}_{out}$	Maximum water outflow of the tank.
$\underline{Vtk}$	Minimum volume of the tank.
$\overline{Vtk}$	Maximum volume of the tank.
f_{irr}	Fixed irrigation flow.
N	Total hours needed for irrigation system.

C. Variables

$P_{i,t}^{\mathrm{G}}$	Active output of generator of bus i at time t.
$Q_{i,t}^{\mathrm{G}}$	Reactive output of generator of bus i at time t.
$P_{l,t}$	Active branch power in line l at time t.
$Q_{l,t}$	Active branch power in line l at time t.
$I_{l,t}$	Square of current magnitude of line l at time t.
$V_{i,t}$	Square of voltage magnitude of bus i at time t.
$Pes_{i,t}^{\mathrm{C}}$	Charging power of BESS of bus i at time t.
$Pes_{i,t}^{\mathrm{DC}}$	Discharging power of BESS of bus i at time t.
$Qes_{i,t}$	Reactive power output of BESS of bus i at time t.

$y_{m,t}$ Water head of node m of the water system at time t.

$y_{m,t}^{\text{Pump}}$ Water head provided by pump in pipe m at time t.

$P_{i,t}^{\text{Pump}}$ Active consumption of the pump at bus i, time t.

Vtk_t Total water volume in the tank at time t.

Sw_t Water from the source at time t.

$f_{k,t}$ Water flow in pipe k of the water system at time t.

f_t^{tk} Water flow into/ out of the tank at time t.

$SOC_{i,t}$ State of Charging of BESS at line i, time t.

D. Binary Variables

$bes_{b,t}$ Charging of discharging status of BESS b at time t

(1 if the BESS is charging, 0 means the BESS is discharging).

irr_t Status of irrigation system at time t

(1 means on, 0 means off).

Chapter 1: Introduction

1.1 Background

Water and energy are thought to be two of the most critical lifeline networks and important resources for human life and production [1]. For any society, clean energy and water are essential for sustainable development and its social, economical and environmental needs [2]. To ensure the secure delivery of the two important resources, the water and energy networks were developed over years providing vital services to most communities. There is no doubt that the two networks cannot be completely independent [3]. On the contrary, they are intertwined. In fact, the water industry is an energy-intensive industry: this is because in the water value chain, many steps consume a lot of electricity [2, 4, 5], some of which are described in the following:

- ***Abstraction:*** Water abstraction means to take or extract water from various sources (e.g. pumping underground water) for irrigation, water treatments for drinking or some more uses [6]. Over-extraction of water may lead to damaged rivers or some underground water sources [7]. In order to protect the water sources, some restrictions might be placed on the amount of water to be extracted from the water sources.

- ***Purification:*** Water purification refers to the process of removing contaminants from raw water. After purification, water could meet people's drinking needs or industrial requirements. Eye observation cannot determine whether the water quality meets the requirements; so several methods like filtration, biologically active carbon or electromagnetic radiation are typically applied in practice [8].

- ***Distribution:*** Distribution aims to deliver water to consumers while ensuring that the delivered water must have proper water pressure and high quality [1].

- ***Utilization & Disposal:*** Include heat water for domestic use or some other industrial utilization, wastewater treatment and irrigation.

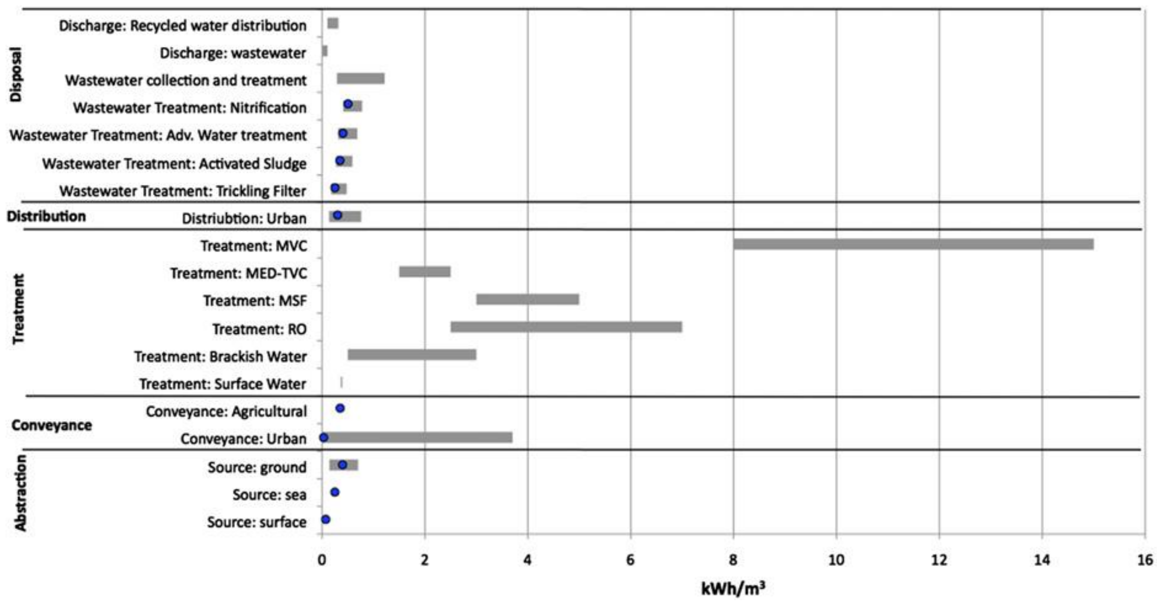

Figure 1.1: Energy consumption in different stages of the water system [6]

Due to many geographical, physical and technical factors, the actual energy consumption of each process may vary greatly. For example, in the abstraction process, if the depth of water varies, the electricity consumption of pumping the underground water would change. And during the distribution process, because the characteristics of water pipes are different, the energy consumption could also be affected. Figure 1.1 shows the range of energy consumption per unit volume (one square meter) for different processes involved in water systems or services. In Figure 1.1, MVC reflects the mechanical vapor compression, MED_TVC means multiple effect distillation with thermal vapor compression, MSF means multistage flash distillation, and RO means reserve osmosis [9]. In the case of conveyance in urban areas, the upper limit of the energy consumption range is for California's State Water Project (SWP) [10]. The original purpose of the SWP was to provide water to Southern California for the water shortage and SWP provides clean water to around 20 million people in the state. Meanwhile, the energy industry is also water-intensive. Water is widely used in the process of fuel production, power generation, energy conversion or transportation. Fuel production and power generation are the two main parts needing water the most. Figure 1.2

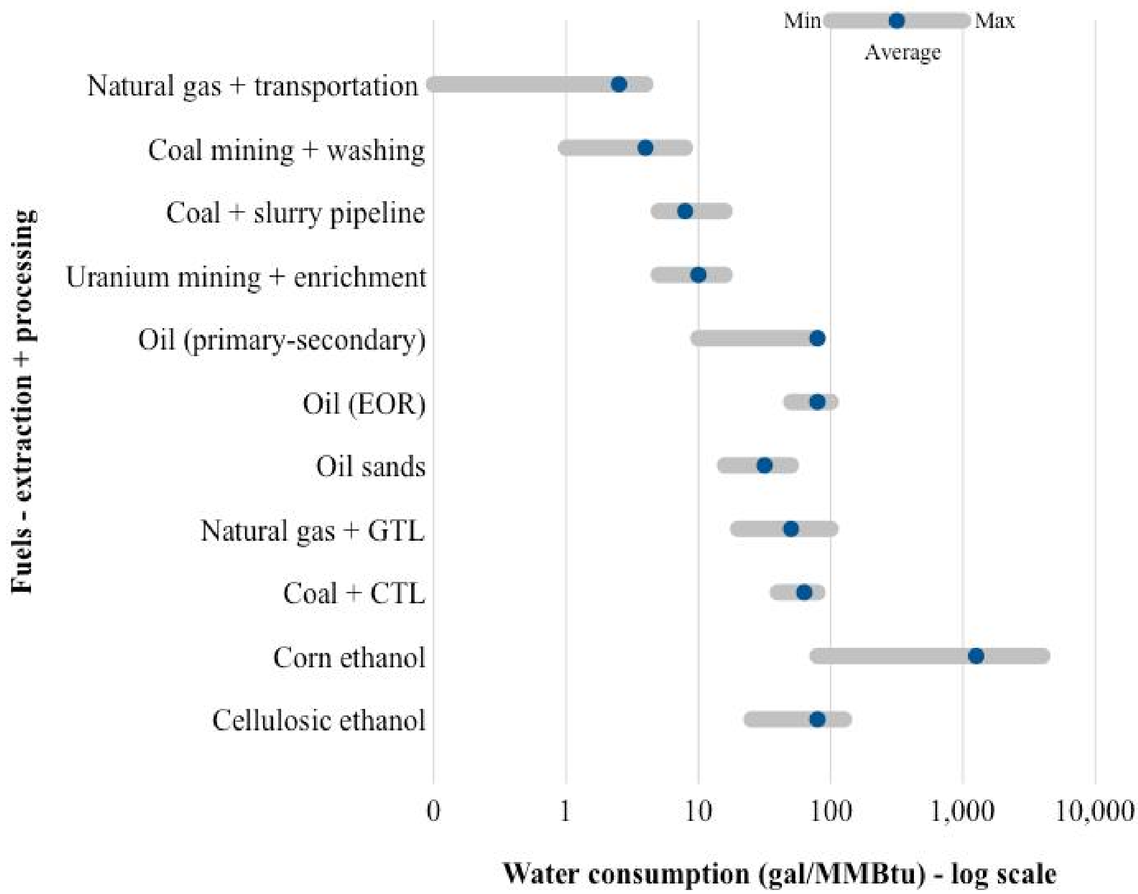

Figure 1.2: Water consumption and the extraction of fuels [11]

demonstrates the water consumption range and the average value of different fuel production processes [11]. As can be seen, corn ethanol, which belongs to biofuels, are the most water-intensive application because the growing corn requires a lot of water for irrigation. The average water consumption of the corn ethanol is 10 times larger than the consumption of the cellulosic ethanol, which is a more advanced biofuel source. It highlights the fact that a shift to focus on cellulosic ethanol might bring a much lower water usage for biofuels industry [12], while additional advancements are yet to be designed and deployed to fully achieve the aforementioned goal and target [13].

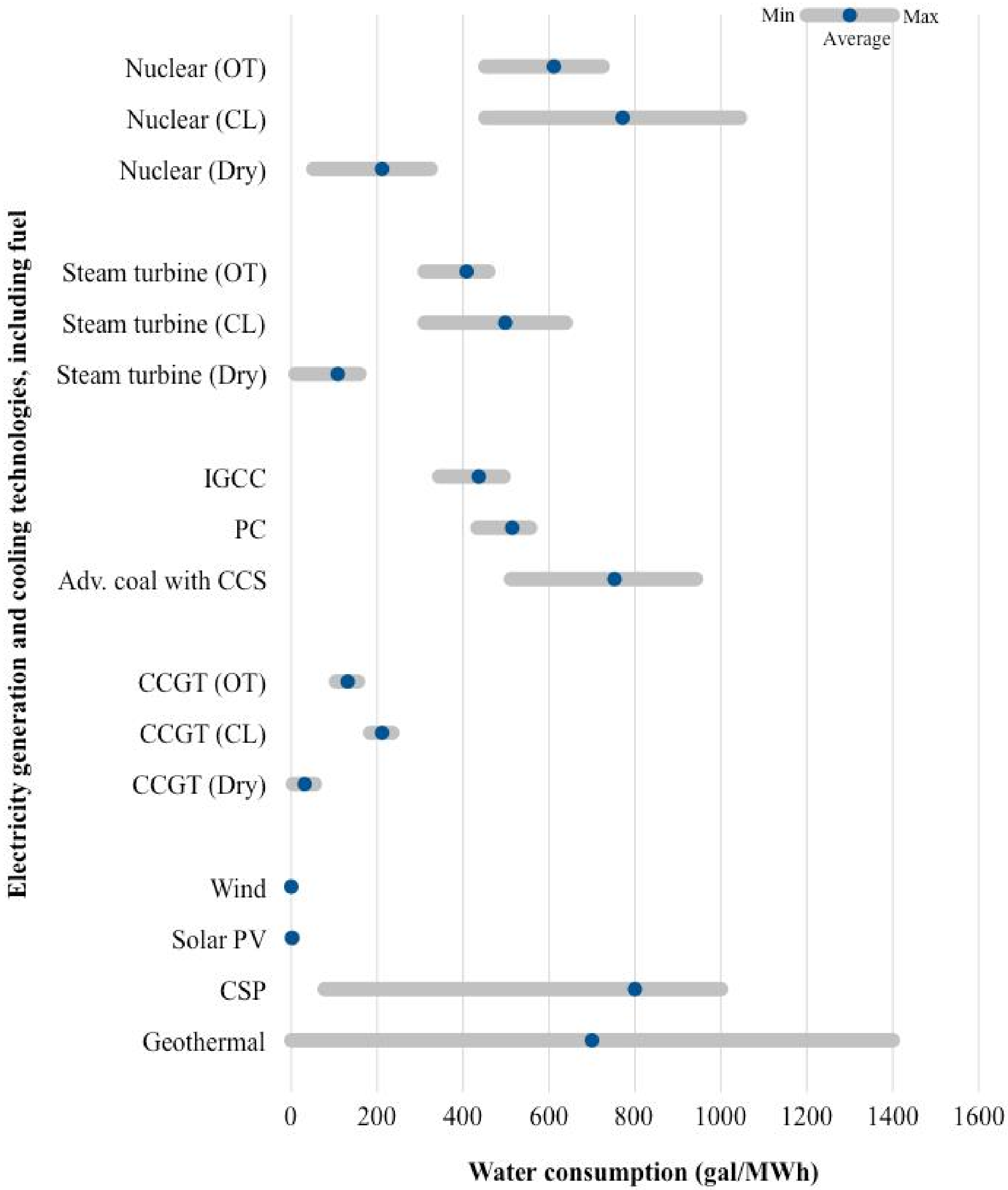

Figure 1.3: Water consumption in electricity generation [11]

In thermoelectric generation, steam is used to drive turbines and convert mechanical energy into electricity [14]. And then, water is used for cooling purposes. In the United States, cooling of thermal power plants can take up around 4% of the total water consumption in the country [11]. Open loop cooling, or once-through cooling (OT), closed loop cooling (CL) and dry cooling (or air cooling) are the three types of cooling methods used most widely [15]. Figure 1.3 presents the water consumption range for unit production during power generation process. Most new power plants are using CL cooling because the water intake can be lower, while the total water consumption is higher. Old power plants are now replacing their OT cooling to CL cooling, which may result in an even higher water consumption during power generation process in the future [11]. Besides, the penetration of nuclear power generation has grown significantly over the last decades. Compared with thermoelectric generation, the water consumption is much higher in such applications. It means that the water consumption for power generation would increase further in the coming years with the growing advancements in the nuclear power generation. At the same time, some of the renewable sources like wind and solar, have almost no water usage during the generation process. So, further development of these technologies may be helpful to reduce the overall water consumption in the electric industry. Conventionally, energy and water have been considered as two "independent" resources, where the power system and water system have been treated as two separate systems and operated by different departments. Recently, the link between the two essential resources began to attract people's attention. Future research should focus on the role of water networks in power grid operation and control, and to develop new mechanisms that can effectively capture the interdependence among these two lifeline services.

1.2 Research Motivation

Recently, the concept of smart cities/grids are investigated more and more frequently. In these smart communities, physical systems, especially power systems and water systems, must play an important role [16–19]. Many research efforts on the topic have indicated that there is a future trend for the cities to be smarter with embedded intelligence in the infrastructure, operation, and control paradigms [20–28].

- ***Smart City:*** In a smart city, new technologies and resources should be coordinated to provide a sustainable development and higher quality of life. Its physical infrastructure or systems should be combined or integrated for convenience and security. It is not simply to add every system together, but to build a whole network using cutting edge information and communication technology to meet further requirements. For example, the quality of several essential resources in the society such us water, air, electricity and food should be improved, the operation of the city affairs needs to be rapid and convenient, and the ability of recovery in/after some extreme events should be developed. Among all the physical infrastructure, water and energy can be regarded as the core enablers of a smart city.

- ***Smart Grid:*** The first official definition of Smart Grid was given in 2007 [29]:"*a reliable and secure electricity infrastructure that can meet future demand growth and to achieve each of the following, which together characterize a Smart Grid: (1) Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid. (2) Dynamic optimization of grid operations and resources, with full cyber-security. (3) Deployment and integration of distributed resources and generation, including renewable resources. (4) Development and incorporation of demand response, demand-side resources, and energy-efficiency resources. (5) Deployment of 'smart' technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation. (6) Integration of 'smart' appliances and consumer devices. (7) Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal storage air conditioning. (8)*

Provision to consumers of timely information and control options. (9) Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid. (10) Identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services.".

The link between water and energy systems has attracted the attention of many researchers. Recently, researchers begin to study the water-energy network from different perspectives. Their core focus includes the impact of climate or environment, the interaction with economic growth, the characteristics of the water energy network related to regional factors and some social effects of both physical systems individually and in an integrated manner [30–32]. With the power gird is becoming smarter with more intelligent sensors, operation and control [33–49], the penetration of renewable energy gets higher and the load becomes more complex. It brings extra uncertainty to the power system. Researchers are exploring various methods or management strategies to deal with the uncertainty and the negative effects it may cause. One of the possible consequences is the imbalance between power supply and demand. Then the demand side management can be critical to the stability and security of the entire system.

In this thesis, our target is to develop a mathematical model to co-operate and co-optimize a micro water-energy nexus, hereafter called micro-WEN, at a distribution layer. Figure 1.4 is the schematic diagram of the proposed nexus. With the physical components connected, and information and communication technology applied, the nexus of the two important physical systems can be a basis for a smart community. Integrated with PV systems and battery energy storage systems (BESS), the micro-WEN also needs additional flexibility. The potential in the water network side to provide demand response services to the power grid will also be tested.

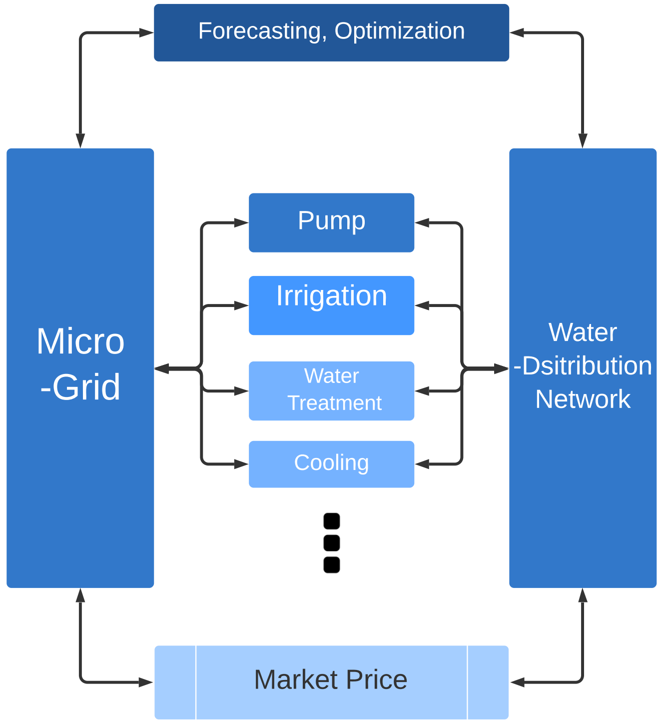

Figure 1.4: Schematic of a smart micro-WEN

1.3 Thesis Outline

Chapter 2 reviews some related work and literature on the power and water systems and smart communities. It also describes some efforts on the management of water and energy systems. Chapter 3 introduces the proposed models to formulate the WEN (water-energy nexus). The power network is an electrical distribution system while the water side is a water distribution system. Chapter 4 investigates the performance of the proposed WEN models in an smart environment, i.e., with integrated renewable generation and battery energy storage systems. The model is optimized and analyzed in GAMS programming environment. Chapter 5 tests the potential of the water network to provide flexibility to the power system. Chapter 6 finally concludes this thesis research.

Chapter 2: Literature Review

2.1 Introduction

Recently, the concept of "smart city", "smart community" and "smart village" are highlighted in different domains. In [16] and [50], the smart community is defined to be a set of cyber-physical systems integrated with cooperation. It means to connect many physical systems using some cutting-edge technologies like Internet of Things (IoT), information and communication. Reference [50] calls the smart community "an Internet of Things application". In a smart community, the energy system and water system can be regarded as the basis [17]. As an important physical system, the power system is also supposed to be smart. Using both electricity and information flow to operate, the smart grid is considered to be the next generation power grids [51]. The main goal in a smart grid is to enhance the efficiency and reliability with automated control, modern communication, disruptive technologies and electric vehicles [52–62], modern management techniques [20–28], sensing and metering technologies [44–49, 63]. Two important characteristics is the integration of distributed resources and generation including renewable resources [27, 30–32, 64–74]. Advanced electricity storage technologies [75, 76], power electronic interfaces at the edge [77–81], and peak-shaving technologies [82–86] should also be utilized.

As another important physical system in a smart community, the management of water system has also attracted the attention of many researchers. In [6], the current practice in the management of water system and energy system in Middle East and North Africa is analyzed. In this area, the coupling of both systems is relatively low in fresh water facilities. But in water abstraction facilities and production systems, the dependence of the water and energy is much stronger. In China, the situation is a little different. The high rates of economic growth in China leads to increasing demands in both water and energy. In the current setting, energy consumption in providing non-agricultural water is not very high, but with the growing developments in China, the fraction might increase greatly in the coming years. And the water "migration" from agriculture to non-agricultural demand may also have important impacts on the energy system [87].

2.2 Research and Application of Renewable Energy

The penetration of renewable energy in the power gird is becoming higher and higher. Compared with traditional fuel resources, the renewable energy sources are more environmental-friendly with lower greenhouse gas emissions; furthermore, some kinds of renewable energy like wind power and photovoltaics solar power have lower water consumption. However, renewable energy has its own drawbacks too. An important characteristic of the renewable energy resources is their uncertainty and intermittency. It means that renewable generation can not provide stable electric power to the grid. In order to reduce the impact of this uncertainty to the power grid, application of renewable energy requires more attention on developing advanced risk mitigation tools and uncertainty-aware solutions for the grid operation, protection, and control.

Reference [88] discusses the complexity of smart grids and envisions that renewable energy penetration might increase as the population and the demand for quality power increases. For better operation and management of the smart grid, more information is needed. Short-time forecasting and long-term assessments are both essential for the secure and reliable operation of the grid. For example, the long-term assessment of weather is required before choosing the suitable location for renewable generation. And short-term forecasting may also impact the management of the renewable energy. In [89], a new pricing strategy for smart community with integrated renewable energy sources is introduced. The community here is thought to be the set of smart homes. In a smart home, scheduling techniques allow customers to manage their electric power usage to fulfill their own target automatically. Because the price of renewable energy is relatively lower, customers may compete for the lower price energy, which enables the community to make full use of renewable energy and reduce the total energy cost at the same time. The test results show that the strategy can greatly reduce the total energy bill by about 30%. A new method to operate the grid with high penetration of variable renewable energy is introduced in [57, 90]. Battery swapping station (BSS) is traditionally the charging center of electric vehicles (EVs). The uncertainty of supply, demand and price are considered and the quality of power is also ensured. A real-time management scheme for BSS is designed to use renewable energy to charge for EVs. Residential loads can also be met. The introduced strategy can simplify the energy management and improve the cost efficiency. Application of renewable energy is also improved.

2.2.1 Research and Application of Solar Energy

Solar energy harnesses light heat from the sun. Some key techniques related to solar energy include solar heating and photovoltaics (PV). Solar PV has been growing rapidly because solar energy has high cost-efficiency and great potential compared with other renewable energy resources. With years of development, in 2017 solar generation accounted for around 2% of the total generated power globally. Considering its great potential and huge capacity, many researchers are focusing on the management and application of solar energy. To make full use of the solar energy, an important part is to deal with the uncertainty and variability because the output of PV generation can often be affected by climate parameters like sunshine time, overcast days and environmental evaporation levels. In [32, 91], some methods of solar forecasting are introduced. Artificial intelligence technologies are utilized to solve the discontinuous and variable problems of solar resources. The feasibility of applying these forecasting models to power system management is also investigated in detail. PV distributed generation systems also have the possibility to provide reactive power support to reduce the voltage variation [92]. The voltage violation can be caused by reverse power flow and uncertainty of the load and renewable energy. The scheme can greatly increase the system's reactive power compensation level and further develop the penetration level of PV into the system. In [93], the PV solar farm is utilized as the static synchronous compensator to improve the capacity of the transmission system instead of purchasing expensive additional equipment like capacitors or transmission system controllers. During night, because of the characteristics of PV energy, the total inverter capacity can be used for voltage control. During daytime, the surplus inverter capacity can be applied with voltage maintenance and control. The stable power transfer limits can thus be improved while a lot of active power are generated. [94] proposes a new energy management method for next-generation PV. PV here are integrated with power storage and other components. Connected by the communication networks, the new management works both in the grid side and the customer side. To ensure the power quality against the uncertainty of solar energy, a solution is to co-operate the PV-based generators and gas micro-turbines to fulfill the power demand for customers, and simultaneously, reduce the cost and greenhouse gas emissions. For the customer side, several energy storage techniques and Supercapacitors are also included to better coordinate with the power system energy management.

2.2.2 Research and Application of Hydropower

Hydropower is the power derived from the energy of falling or fast-running water. Since water is about 800 times denser than air, even slow water flow can provide considerable amounts of energy. There are three main forms of hydro-power. Traditionally, large dams and reservoirs are built for hydroelectricity. The traditional form is still popular in many developing countries [95]. Small hydro systems usually refers to systems that produce up to 50 MW of power, which are sometimes built on small rivers. They can have less impacts on the rivers. Another type is the run-of-the-river hydroelectricity. In a run-of-the-river hydroelectricity plant, there's no large reservoirs. Water falls through a penstock and then drives the turbine to produce electric power. Although hydropower has the longest history among all kinds of renewable energy, related technologies still have a lot of potential for updates and upgrades. And its impact to the environment has attracted a lot of researchers' attention. In [96], the water consumption by hydropower generation in the United States is studied. A better method is introduced to measure the evaporation. Then a better model is introduced to calculate the hydropower system water consumption during generating process. The water usage is around 1.7 m^3 per GJ electricity produced. Application of wind and hydro power in power grid resilience is studied in [58]. But the hydro may also have some negative impacts to the environment. The emergence of a liberalized electricity market and the hydropower programs in Turkey forces the hydroelectricity companies to build hydropower infrastructures to control the water flow instead of allowing the natural change to rivers to fulfill the market needs. But it may have some invisible impacts on the environment and the society. And because of the droughts in some areas, speedy development of hydropower is generally limited. From 2011 to 2015, the hydropower experienced a reduction of about 57,000 GWh, primarily due to the droughts. The reduced part was mostly replaced by natural gas, which cost more money and caused more greenhouse gas emissions [97].

2.3 Research and Application of Energy Storage Technologies

Energy storage means to capture energy produced for later use. For energy storage systems, energy input may have different forms like radiation, chemical and electricity. The development of energy storage devices depend largely on the new technologies related to new materials. Besides, the materials outbreak is closely related to the application and development of renewable energy [98]. In power grid, energy storage can play an important role by improving power quality and reliability [99]. For example, batteries are widely used in electrical vehicles [59–62]. And flywheel are sometimes used for uninterruptible power supply to provide electric power to loads with requirements for high stability. With the penetration of renewable energy becoming higher and higher, energy storage, especially battery systems have great potential to deal with the intermittence [100] and also for resilience services during emergencies [101–105].

Energy storage can also contribute to reducing the cost of peak demand management

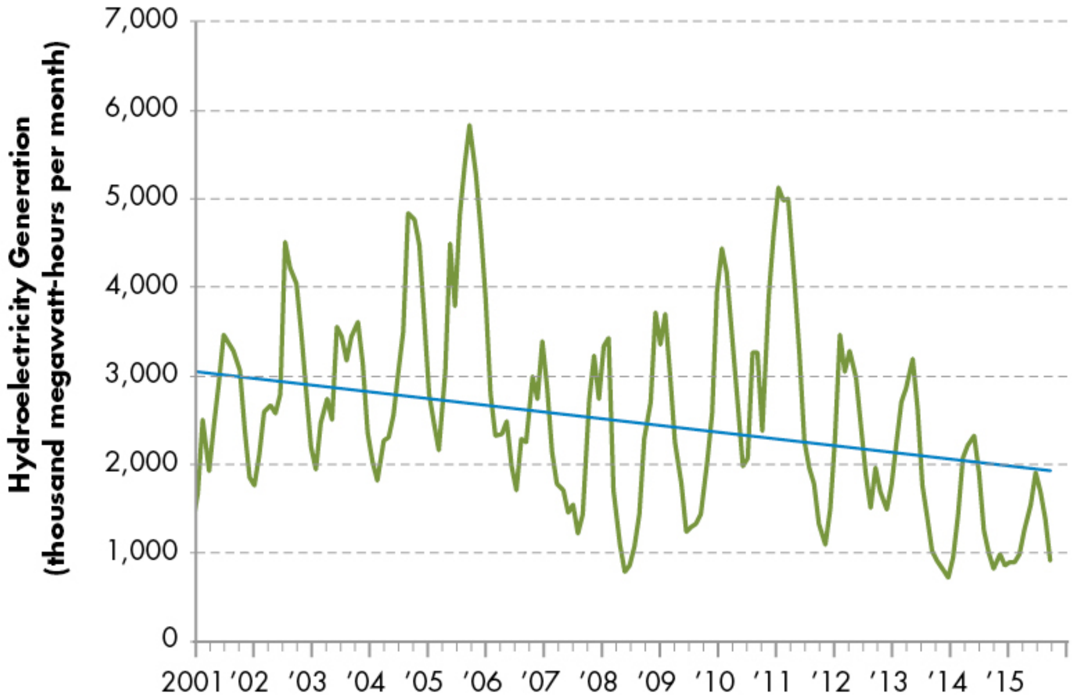

Figure 2.1: Total hydroelectricity generation per month in California [97]

and integration of different types of renewable energy. Previously, the main form of energy storage used to be pumped hydroelectric [106]. With the technology outbreaks, the cost of battery systems are becoming lower and lower while the performance are even better. As a short-term energy storage system that is commonly used, supercapacitors is suitable for integration with wind energy resources. They have high density of energy and longer service time compared with other battery systems. After implementing supercapacitors, the output curve can be smoothed. They can also help deal with unexpected disturbances [107]. In [108], several different types of electrical storage technologies are introduced and compared and the impact of short-term and long-term storage system to the grid is also evaluated.

2.4 Research on Connection Between Energy and Water Systems

Traditionally, the water system and power system were thought to be two separate physical systems and operated by different operators. Historically, people often presumed that the water and electricity would not be threat or constraint to each other [109, 110]. That might be the main reason why the link between water system and power system used to be ignored. But recent increase in the demand for electricity, climate change and industrial development force people to focus on the connection and interdependence between water and energy systems. The water-energy nexus (WEN) brings both challenges and opportunities. Resource scarcity and uncertainty are causing extra vulnerabilities in the water and energy systems. But now, some old infrastructures or devices are to be upgraded, which may provide opportunities for additional development [111]. If treated properly, the WEN can lead to a higher efficiency of energy production and water management while enhancing the reliability level of water and energy system alike. The future trends in population and resource consumption also calls for innovations in the water-energy nexus. New techniques are required in the following perspectives: lower water consumption generation, greenhouse gas sequestration and water pre-treatment [112]. Deriving energy from water or in return, water from energy, may also become the focus of new technologies. The paring of new technologies and public perception can be important for the sustainable development in the future. The impact of water management on power generation is discussed in [113, 114]. Water scarcity and warming are two limits on power generation because water is typically used widely in the process of energy conversion. River flow decreases or the temperature increases can have negative effects on power generation. A smart management system is introduced in [113] to minimize the power curtailments cased by hydrological changes. The water policy constraint's effect on power generation is discussed in [114]. It proposes that some flexibility in policy can ensure the generation capacity during some severe situations like droughts. But the type or amount of constraint relaxation is also flexible, depending on the actual situation. It is suggested to consider water-energy nexus when managing water distribution systems in [115]. But some knowledge gaps are also mentioned. Current optimization models are thought to be incomplete without spatial factors, environmental impacts and the increasing uncertainties related to renewable energy or water and power demand. Similar to [109], a long term model is required for analysis and management of WEN. The importance of water-energy nexus during city's metabolism is discussed in [116]. From the perspective of a smart city, the relationship between city development and water-energy nexus management can be critical because water and energy are necessities for development. Water-energy nexus should cooperate with other systems in the city for further and sustainable development. Some researchers focus on the water-energy nexus in some areas of the world [6, 87, 117–121]. In [117], structural decomposition analysis is used to analyze the driving factor of water-energy nexus in China during 1990 to 2014. The trend of annual consumption patters is obtained. Some industries like real state are closely related to water-energy nexus. The coupling of electric transmission systems and virtual water flows is discussed in [118]. The energy-water nexus can balance the trade-off between electricity supply and water resources inequity. A Global Change Assessment Model (GCAM) is modified and utilized to model the electricity and water systems in the U.S. [119]. Then the trade-off between decreasing withdrawals and increasing consumptive use is also discussed to indicate the importance of water-saving technologies. The water-energy nexus in New South Wales, Australia is discussed in [120]. A long-term prediction scenario is also included to explore the future implications of water-energy nexus. The contents are also suitable for other Australian states because they have the same policy. The electricity consumption for water abstraction and supply is calculated in [121].

New techniques in the water-energy nexus are also being studied. Several optimization models are analyzed and classified in [115]. A two-level decision model is developed in [122] to improve the decision-making process in water-energy nexus through provision of an integrated model. An interactive optimization method is introduced to satisfy two-level decision makers. The analysis can also help to adjust the tolerances for better management. Linkage analysis is applied in [123], where the main focus is to analyze the relationship of water energy consumption and economic sectors. Agriculture and food processing sectors are major virtual water suppliers while fuel production and electricity industry are major energy suppliers. A graph theory-based network is utilized to optimize the water-energy nexus in [124]. The topology of water-energy nexus is represented by a directed bipartite graph. Then a systematic method is applied to the graph to lower the water or energy consumption while all power and water demands can be met. A model to optimize the energy flexibility provided by water distribution systems is given in [125]. The increasing penetration of renewable resources attracts more attention on the coupling of renewable energy and water-energy nexus [126–128]. Water is considered to be the source of power to obtain energy from natural or waste water through membrane-based system in [126]. Waste heat and organic matter in waste water can also be re-used for water treatment or power production. Seawater desalination is another energy-intensive process. Solar energy is used in [127] for desalination, where an indirect collection system is introduced. One sub-system is for energy collecting and the other works for desalination. Ocean energy is also discussed in [128]. Ocean energy has great potential in desalination and even electricity generation which can improve sustainability of the future water-energy nexus.

Chapter 3: Problem Formulations of A Micro-WEN

3.1 Introduction

Figure 3.1 shows the physical structure of a typical Micro-WEN. On the left side, there is a power distribution system or a microgrid with generators, renewable energy sources and battery systems. On the right side is a water network, made of pipes, tanks, reservoirs, pumps, several water treatments and facilities. In this thesis, the focus is on the distribution layer, which means that only the components related to energy distribution and water distribution would be included. Other components like electric vehicles or waste water treatment plants might be included in future research.

As mentioned in Chapter 1, the structure of a micro-WEN could be regarded as the core or basis of the future smart communities. In a smart community, the physical systems should be interconnected through cutting edge information and communication technologies, for example the Internet of Things. It would be quite essential to design the mathematical model for the micro-WEN so that other techniques or operation methods could be utilized for optimization of the on the micro-WEN.

In this chapter, the basic model of a micro-WEN is built. First, an AC-microgrid or an electric distribution system is modeled. Then, a model for water distribution network with pipes, pump and tank is built to deliver water to customers. Finally, some constraints of power consumption of pumps can act as the connection points of the two systems so that the micro-WEN is integrated.

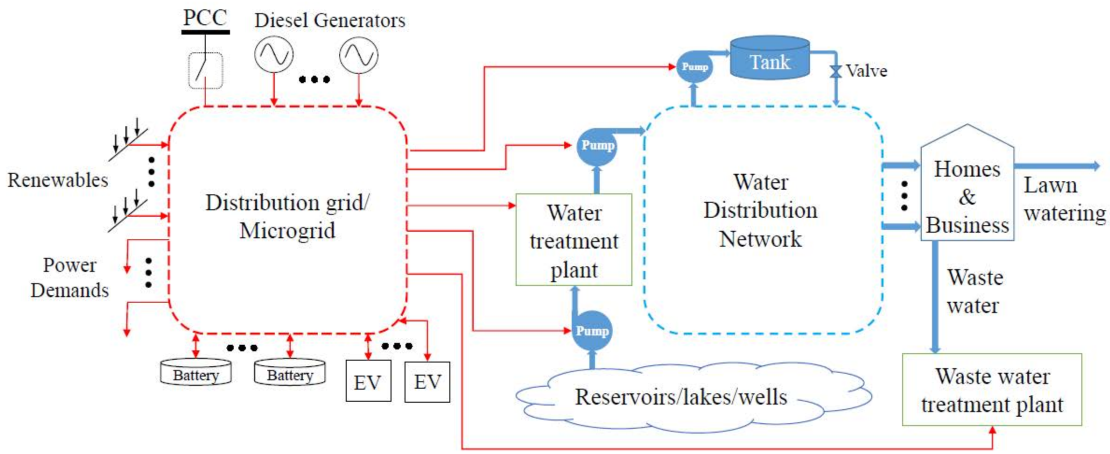

Figure 3.1: Physical structure of a typical micro-WEN [1]

3.2 Mathematical Models for Microgrids

In this Section, a basic model of an electric distribution system is introduced. The topology of an AC-microgrid or electric distribution system is often radial. Based on this topology, the *DistFlow* model [129, 130] is selected to model the energy side of the micro-WEN. Several system constraints are also considered in the model as follows.

- ***Power Balance Constraints:*** Constraint (3.1) describes the active power balance at each node. The left side reflects the total active power flow to node i, and the right side is the total active power flow from node i plus the active power demand at node i. Constraint (3.2) reflects the reactive power balance. The left/right side shows the reactive power flow to/from node i respectively.

$$P_{i,t}^{\mathrm{G}} + \sum_{(j,i)\in\mathbf{L}} (P_{ji,t} - r_{ij} I_{ji}) = P_{i,t}^{\mathrm{L}} + \sum_{(i,j)\in\mathbf{L}} P_{ij,t} \tag{3.1}$$

$$Q_{i,t}^{\mathrm{G}} + \sum_{(j,i)\in\mathbf{L}} (Q_{ji,t} - r_{ij} I_{ji}) = Q_{i,t}^{\mathrm{L}} + \sum_{(i,j)\in\mathbf{L}} Q_{ij,t} \tag{3.2}$$

- ***Power Flow Constraints:*** Constraints (3.3) and (3.4) demonstrate the relationship between the power flow in line ij and the node voltage and line current. Constraint

(3.5) reflects the power flow limits of the distribution lines. It reflects the maximum power flow allowed in line ij.

$$V_{i,t} - V_{j,t} + (r_{ij}^2 + x_{ij}^2) I_{ij,t} = 2(r_{ij} P_{ij,t} + x_{ij} Q_{ij,t}) \tag{3.3}$$

$$P_{ij,t}^2 + Q_{ij,t}^2 = V_{i,t} I_{ij,t} \tag{3.4}$$

$$P_{ij,t}^2 + Q_{ij,t}^2 \leq \overline{S}_{ij}^2 \tag{3.5}$$

- ***System Constraints:*** To ensure that every component of the electric distribution system can work safely and stably, some conditions must be met and some parameters must be limited within a reasonable range. Constraint (3.6) is the line current constraint, meaning that the current flowing through line ij can not violate the line's maximum current. Constraint (3.7) is the node voltage constraint. In an electric network, the voltage level can neither be too high nor too low. Because in both cases, electrical components may not work properly or even get damaged. Constraint (3.7) ensures that the system will work at a suitable voltage level. Constraints (3.8) and (3.9) are the constraints for generators. Also, generators must work at a proper status to keep a high efficiency and security.

$$0 \leq I_{ij,t} \leq \bar{I}_{ij} \tag{3.6}$$

$$\underline{\mathrm{V}}_i \leq V_{i,t} \leq \overline{V}_i \tag{3.7}$$

$$\underline{P}_i^G \leq P_{i,t}^G \leq \overline{P}_i^G \tag{3.8}$$

$$\underline{Q}_i^G \leq Q_{i,t}^G \leq \overline{Q}_i^G \tag{3.9}$$

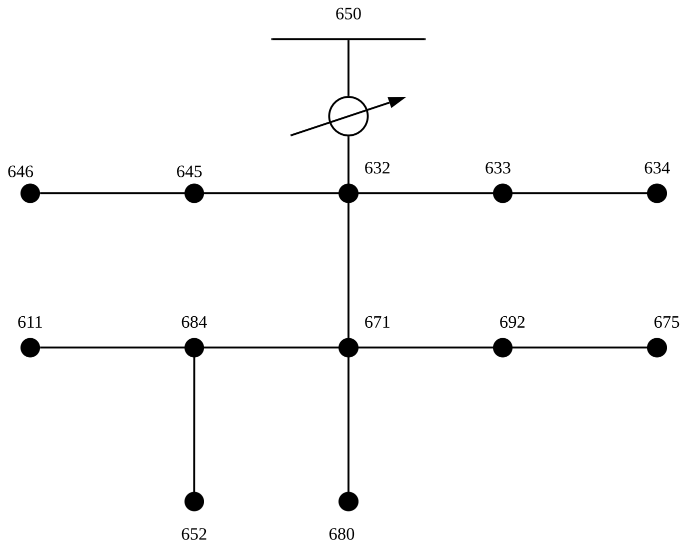

Figure 3.2: IEEE 13-bus test system

As is shown in Figure 3.2, we select the IEEE 13-bus test system as the test model for power distribution system. Based on the load data at 9 am provided by IEEE, the 24-hour load data can be obtained by applying the this data to a load curve for a 24-hour interval. Figure 3.3 shows the load curve for the system typical for a summer season [131].

3.3 Mathematical Model of the Water Distribution System

In this Section, the formulations to model a water distribution system are presented. Components of a basic water network, including water source or reservoirs, pipes, pumps, tanks and customer loads are modeled. Some hydraulic constraints related to the network components are considered. Some assumptions are made for convenience during the modeling process as follows. First, for the pipe, the network is considered to be a directed graph. For pumps, it is considered to be connected between two nodes and provide extra water pressure. And the power efficiency of the water pump is thought to be a constant, which means the ratio the pump converts electric power into mechanical power will not change.

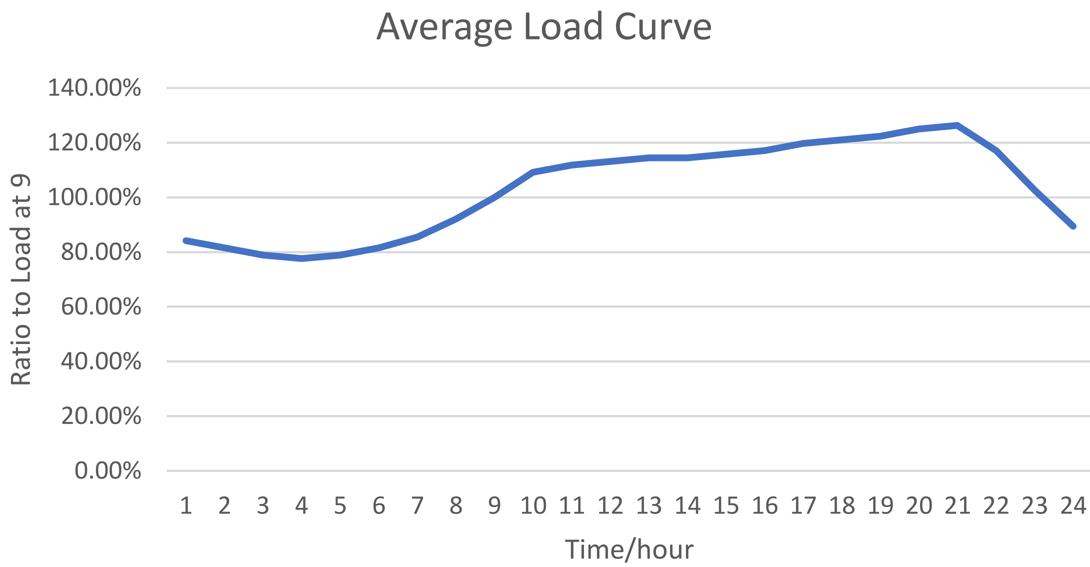

Figure 3.3: Average load of the system in a summer day

- ***Water Flow Balance Constraints:*** Constraint (3.10) reflects the water flow balance of the pipe network. On the left side is the water flow from the water source and other nodes to node m at time t. On the right side is the sum of the water load at node m, the water flow to other nodes from node m and the water flow to tank at time t. It's also worth mentioning that the value of the water flow to tank can be positive or negative. When it's positive, it means the tank is charging or the water flow is into the tank. Otherwise the tank would be discharging or providing water to the system.

$$Sw_{m,t} + \sum_{(n,m)\in \mathbf{J}} f_{nm,t} = f^{\mathrm{L}}_{m,t} + \sum_{(m,n)\in \mathbf{J}} f_{mn,t} + f^{tk}_{t} \tag{3.10}$$

- ***Water Head Loss Constraints:*** Based on the Darcy-Weishach equation [132], which describes the relationship between water head loss and the water flow inside the pump, constraint (3.11) is formulated. In (3.11), k is the pipe connecting node m and node n. Parameter R_k is decided by the length diameter and the surface roughness of the pipe k.

$$y_{m,t} - y_{n,t} = R_k f_{k,t}^2 \tag{3.11}$$

- ***Tank Volume Constraints:*** Constraint (3.12) reflects the range of water volume of the tank. Vtk_0, which is the initial state of water volume of the tank is set to be zero.

$$\underline{Vtk} \leq Vtk_0 + \sum_{t=0}^{t} ftk_t \leq \overline{Vtk} \tag{3.12}$$

- ***Water Network Constraints:*** Just like for the electric network, in the water network, there are some principal constraints for the components to ensure that the network can work properly. Constraint (3.13) limits the water flow of each pipe k at time t to a reasonable range. Constraint (3.14) is for the water head at node m. Constraint (3.15) is the maximum water flow that the water sources can provide. Constraint (3.16) shows the maximum water inflow/outflow of the tank that is allowed.

$$\underline{f_k} \leq f_{k,t} \leq \overline{f_k} \tag{3.13}$$

$$\underline{y_m} \leq y_{m,t} \leq \overline{y_m} \tag{3.14}$$

$$\underline{Sw} \leq Sw_t \leq \overline{Sw} \tag{3.15}$$

$$\underline{ftk} \leq ftk_t \leq \overline{ftk} \tag{3.16}$$

Based on the above constraints, we select an 8-node water distribution network from the EPANET manual [133] and modify its topology as the test case in this thesis. As shown in (Figure 3.4), the water source/reservoir is located at node 1, while the water pump is connected between node 1 and 2. The water tank is connected to node 3. The load file of each node at time period 8-12 in the water distribution system is given from the manual as shown in Table 3.1. The hourly water demand can be calculated by multiplying the coefficient for each time period as shown in Table 3.2.

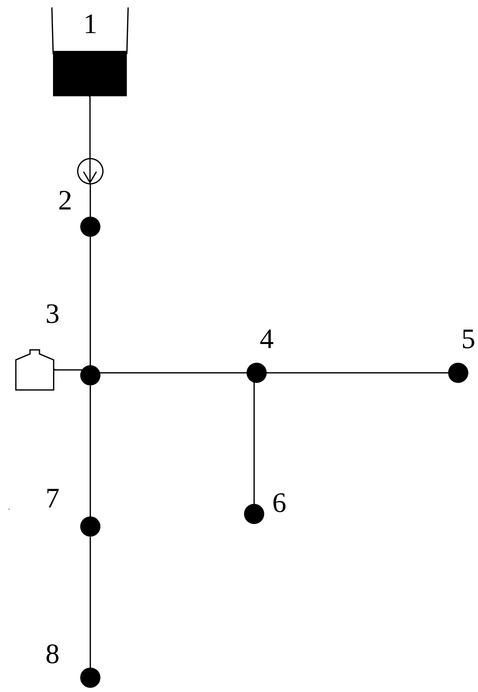

Figure 3.4: Topology of the Water Distribution System

Table 3.1: Nodal Load of the Water Distribution Network

Node	1	2	3	4	5	6	7	8
Demand(gpm)	0	0	150	150	200	150	0	150

3.4 Integration of Water and Power Systems

Now that both water distribution system (the water side) and the microgrid (the electric power side) are modeled, we try to integrate both system for co-optimization of both networks in a given WEN. Then with the pump power equation (3.17), the constraints (3.1) and (3.2) should be re-written, by adding the active/reactive power consumption of the water pump.

Table 3.2: Time Pattern of the Load

Time Period	1-4	5-8	9-12	13-16	17-20	21-24
Multiplier	0.5	0.8	1.0	1.2	0.9	0.7

$$\eta P_{i,t}^{Pump} = f_{m,t} y_{m,t}^{Pump} \tag{3.17}$$

$$P_{i,t}^{\mathrm{G}} + \sum_{(j,i)\in\mathbf{L}} (P_{ji,t} - r_{ij} I_{ji}) = P_{i,t}^{\mathrm{L}} + \sum_{(i,j)\in\mathbf{L}} P_{ij,t} + P_{i,t}^{Pump} \tag{3.18}$$

$$Q_{i,t}^{\mathrm{G}} + \sum_{(j,i)\in\mathbf{L}} (Q_{ji,t} - r_{ij} I_{ji}) = Q_{i,t}^{\mathrm{L}} + \sum_{(i,j)\in\mathbf{L}} Q_{ij,t} + Q_{i,t}^{Pump} \tag{3.19}$$

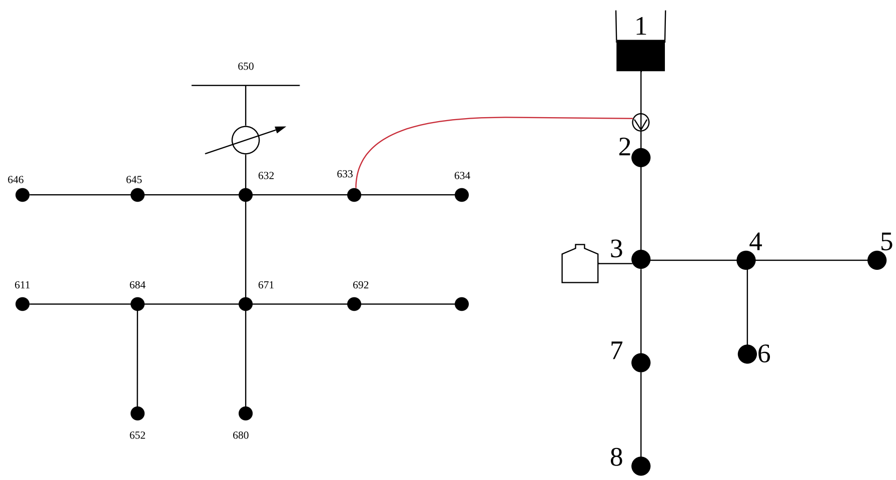

Figure 3.5: Basic Topology of the Studied WEN

3.5 Case Studies

Based on the basic model developed, there are two possible ways one can optimize the operation of the WEN. The first one is a two-stage process. In the first stage, the water distribution system operator is supposed to minimize the power consumption of water pumps by optimizing the pump schedules. Then the schedule would be reported to the power system operator. An optimized power distribution schedule is then created to meet all the power demands while minimizing the energy cost. Another approach is to co-optimize the micro-WEN as a an integrated physical system. In this section, the two models are used for the basic micro-WEN respectively and the results are compared.

3.5.1 Micro-WEN's Hierarchical Optimization Approach

The first step is to minimize the total power consumption of the water pumps as shown in the objective function (3.20). In the test system, we have only one pump connected to the network.

$$min\ OF = \sum_{t=1}^{t} P_t^{Pump} \cdot C_t \tag{3.20}$$

So the optimization model is achieved as follows:

1. Objective Function: Equation (3.20)

2. Constraints: Equations (3.10)–(3.17)

The optimized power consumption of the water pump should be then considered as parameters and added to the power balance constraint in the power distribution system; the second step is formulated to minimize the total cost on the energy consumption:

$$min\ OF = \sum_{t=1}^{t} P_t^{G} \cdot C_t \tag{3.21}$$

In summary, the formulation for the second step of the micro-WEN optimization model is achieved as follows:

1. Objective Function: Equation (3.21)

2. Constraints: Equation (3.3)–(3.9), Equations (3.18) and (3.19)

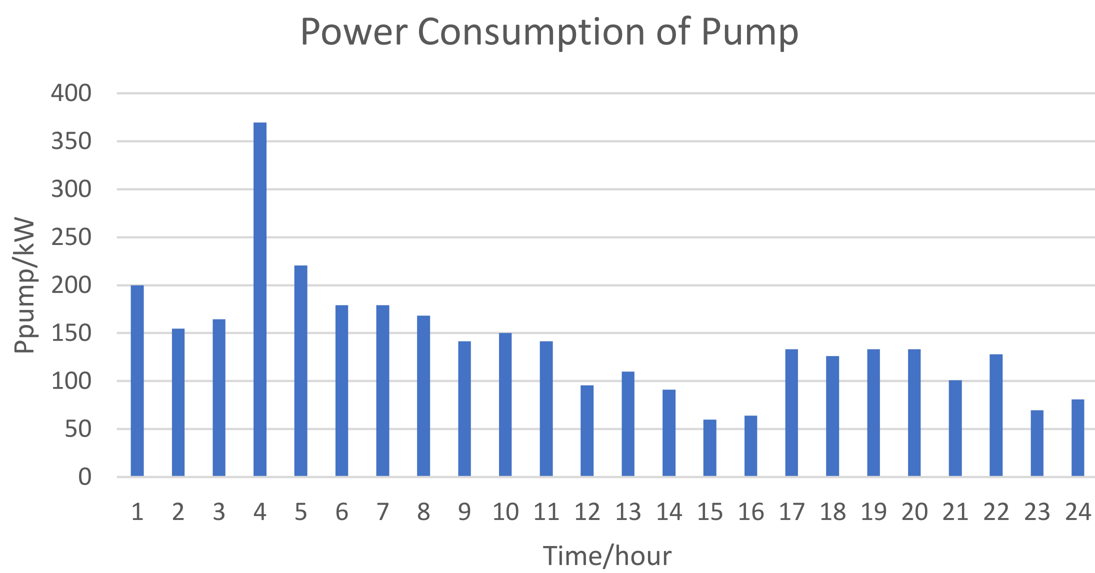

Figure 3.6: Hourly Power Consumption of Water Pump

Applying the first stage of the optimization model to the introduced water distribution network, several results are obtained. Figure 3.6 shows the optimized schedule of the pump. To maintain a low power consumption cost, the pump delivers more water when the electricity price is lower and stores water in the tank. And when the water demand decreases to an extreme low level during night, the power consumption decreases as well. From Figure 3.7, we can see that the water volume of the tank increases during hours 0 to 8 o'clock and decreases then after.

Figure 3.8 represents the 24-hour electricity power price for the AC-microgrid. Taking the price into consideration, and using the results obtained from step 1, the step 2 which optimizes the total operation cost of the whole system, is implemented. Figure 3.9 shows the optimized results for the hourly active power consumption of the whole micro-WEN after the two-step optimization process is implemented. And the optimized total cost of the energy consumption is found $2173.28.

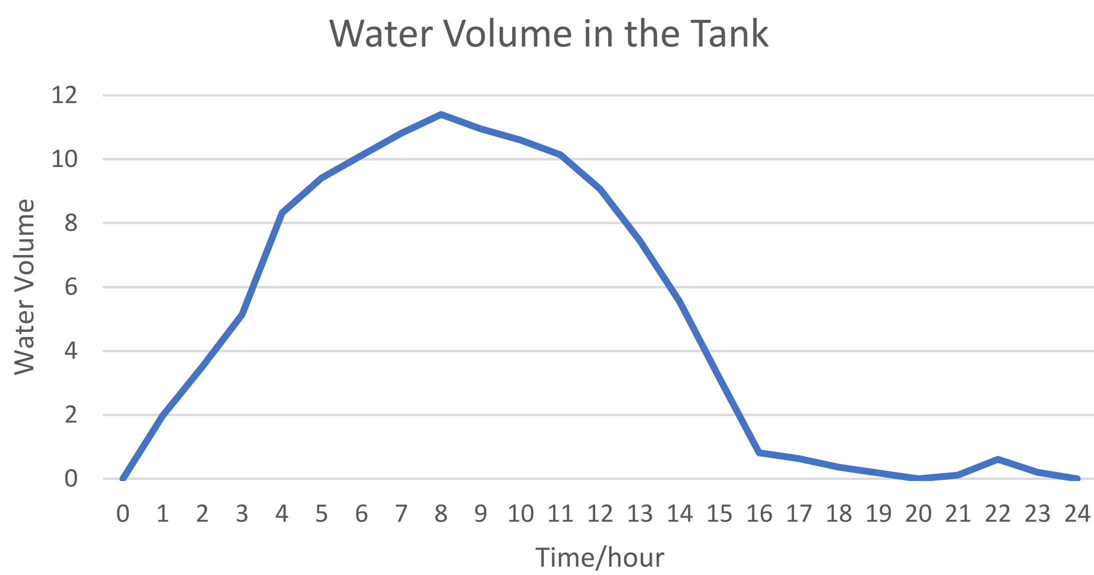

Figure 3.7: Hourly Water Volume in the Tank

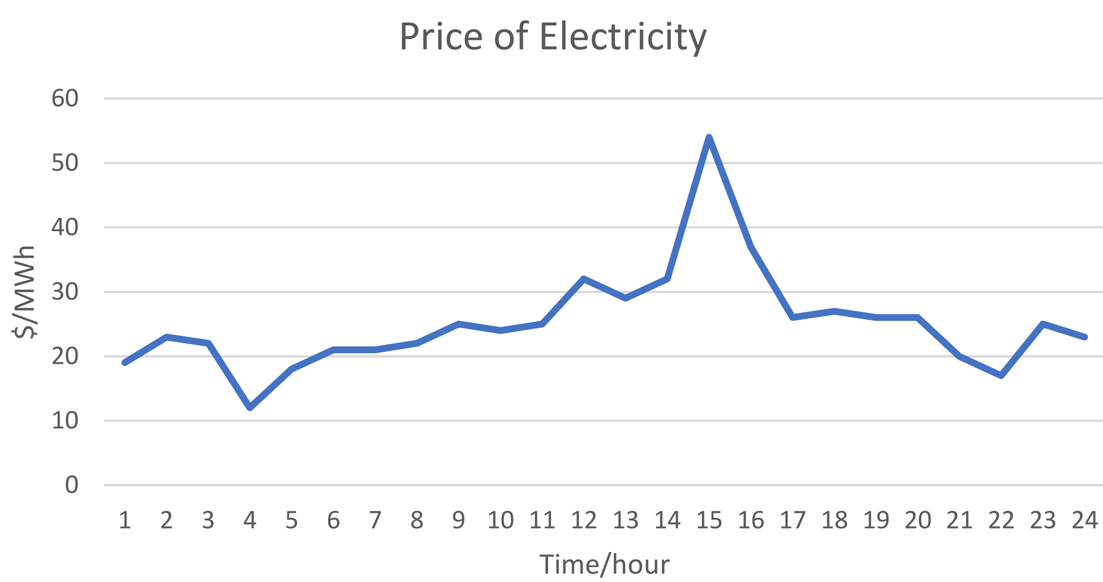

Figure 3.8: The 24-hour energy price

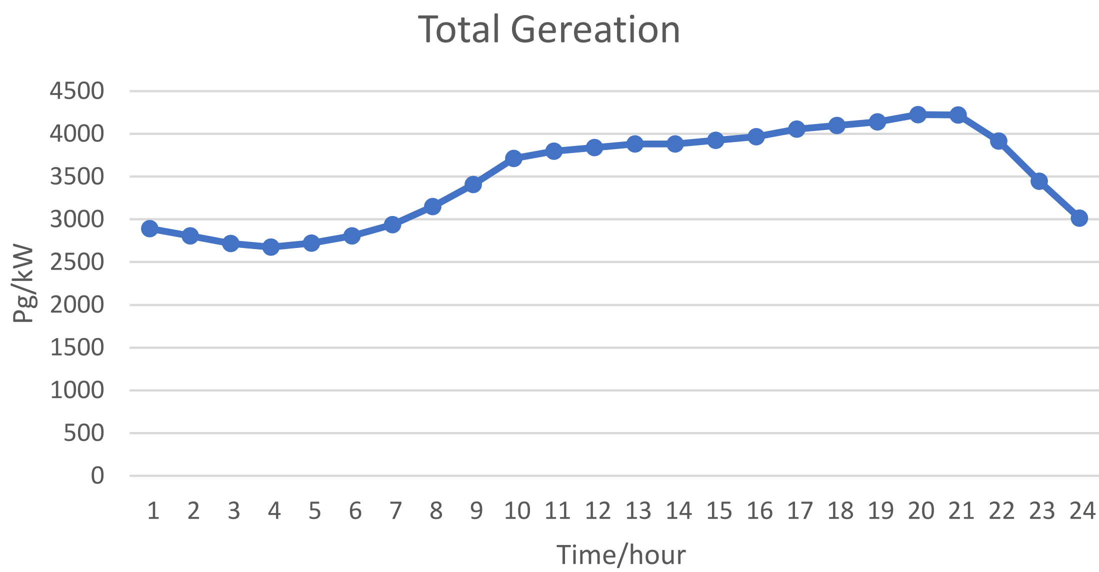

Figure 3.9: Hourly output of the system generator

3.5.2 Micro-WEN's Co-Optimization Approach

Based on the previous content, a co-optimization model for the micro-WEN can be expressed as follows:

1. Objective Function: Equation (3.21)

2. Constraints: Equations (3.3)–(3.19)

With the introduced co-optimization model applied, the optimal micro-WEN schedules is obtained with the optimized total energy consumption being \$2172.91. Figure 3.10 shows the hourly output of the system generator once the co-optimization method is applied to the whole micro-WEN. Figure 3.11 shows the corresponding power consumption of the pump. As can be seen, the pump power consumption is extremely high at hour 4, during which the energy price is the lowest of the entire day and gets lower when the price is higher. This means that the water pump delivers more water and stores the extra water in the tank. When the energy price is high, the water in the tank can be used for the system so that the total cost could decrease. Figure 3.12 shows the hourly water volume in the tank after applying

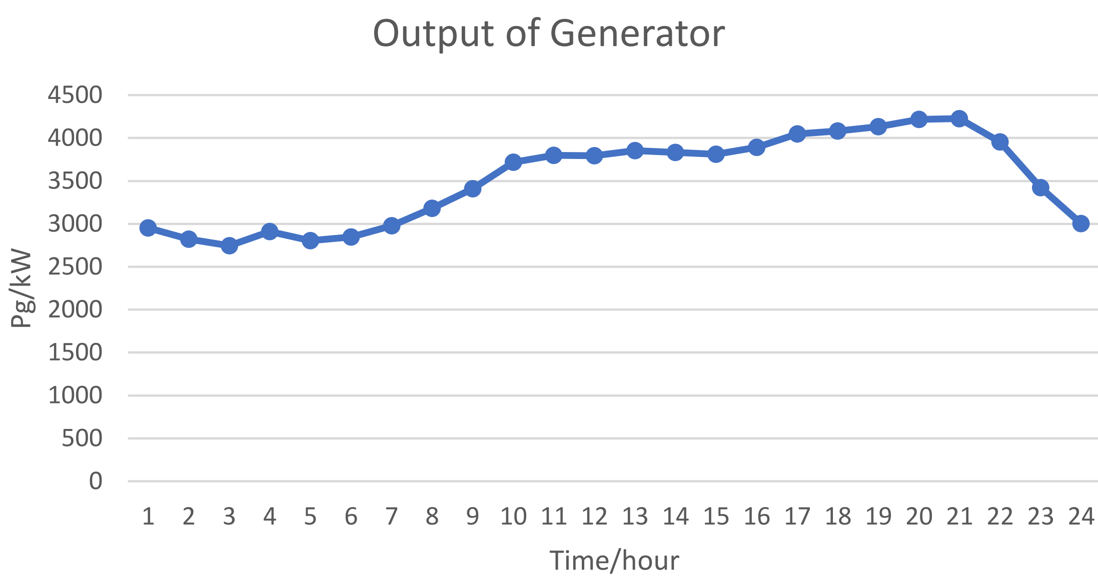

Figure 3.10: Hourly output of the system generator

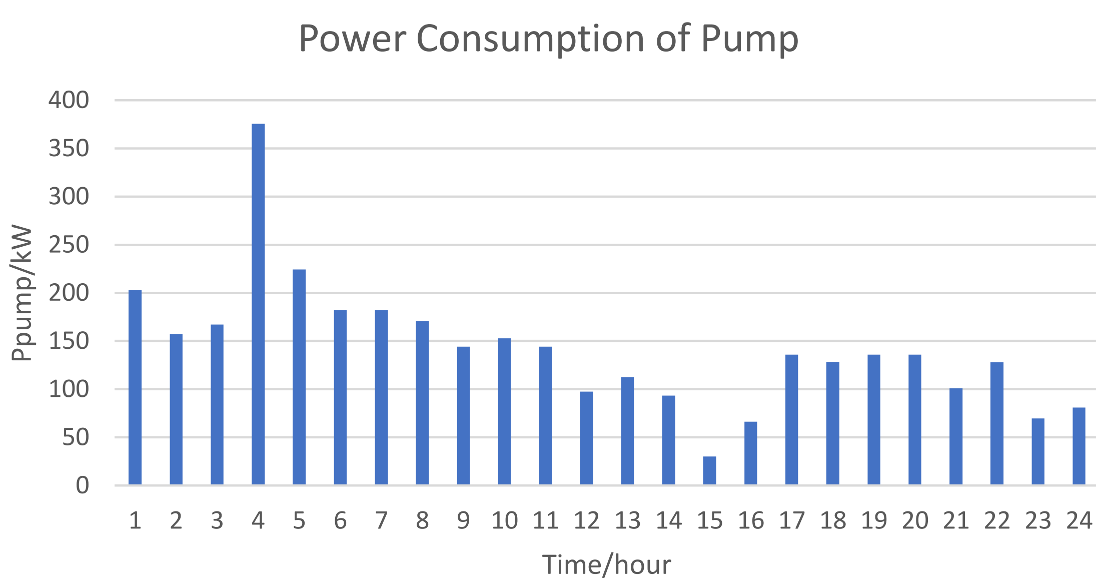

Figure 3.11: Hourly Power Consumption of the Water Pump

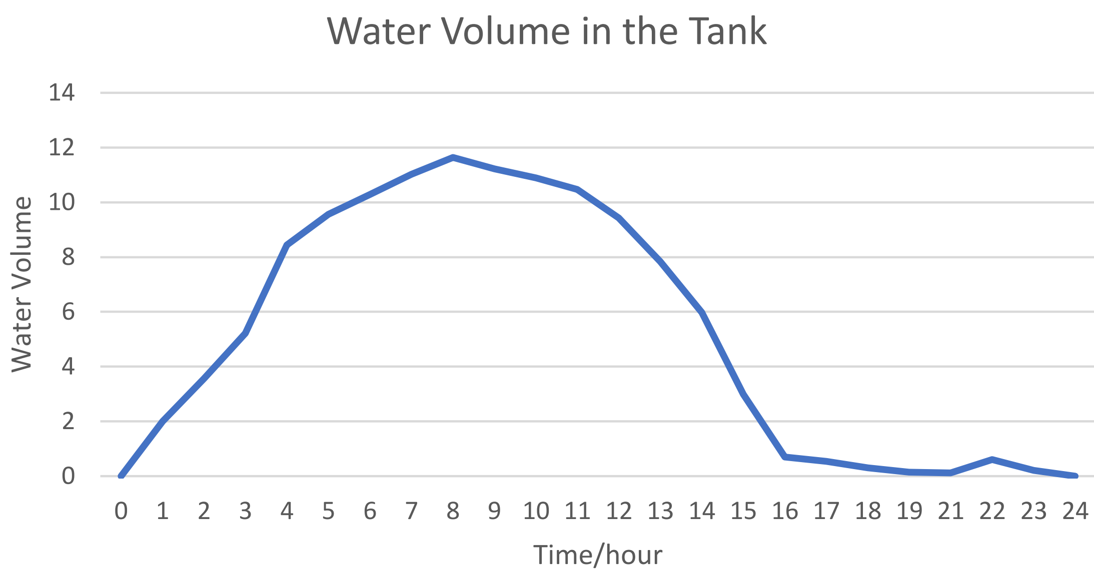

Figure 3.12: Hourly Water Volume in the Tank

the co-optimization strategy. Compared with Figure 3.7, the curve looks smoother.

Table 3.3: Comparison of The Two Approaches for Micro-WEN Optimization

Operation Scheme	Optimal Solution ($)
Hierarchical Optimization	2173.28
Co-optimization	2172.91

3.6 Conclusion

In this chapter, the formulations of the micro-WEN model are introduced. As shown in 3.3, compared with the two-step hierarchical optimization scheme for a micro-WEN, the co-optimization of the micro-WEN provides better results in minimizing the energy cost of the whole system. While showing a negligible difference in the studied small-scale network, the proposed co-optimization approach has the potential for significant cost saving in large-scale applications. In the rest of the thesis, the micro-WEN will be optimized using the co-optimization method under a variety of operating conditions and the availability of other distributed resources.

Chapter 4: Micro-WEN with Integrated PVs BESSs

4.1 Introduction

In a smart grid, the source of electric energy is varied. Especially in microgrids, the energy contributions of the renewable generation accounts for a large part of the total electricity consumption. Compared with other power generation methods, the solar photovoltaics (PV) has very low water consumption during the generation process. Another important component of the smart grid is the energy storage systems. As the important basis for the future smart communities, the micro-WEN should also be equipped with battery energy storage systems (BESSs) and components. In this chapter, the PV system as well as battery energy storage system are formulated and applied to the basic micro-WEN model.

4.2 Integration of PV

4.2.1 Formulation of A Micro-WEN with PVs

Table 4.1: PV System Parameters

PV location (bus#)	PV capacity
611	0.2 MW
633	0.5 MW
680	0.5 MW

Figure 4.1 shows a typical average output curve of PV systems. Table 4.1 shows the location and capacity of PV systems connected to the test micro-WEN system. Based on those parameters and the curve, the new topology of the test system is illustrated in Figure 4.2. The hourly output of each PV system can be obtained and the power balance

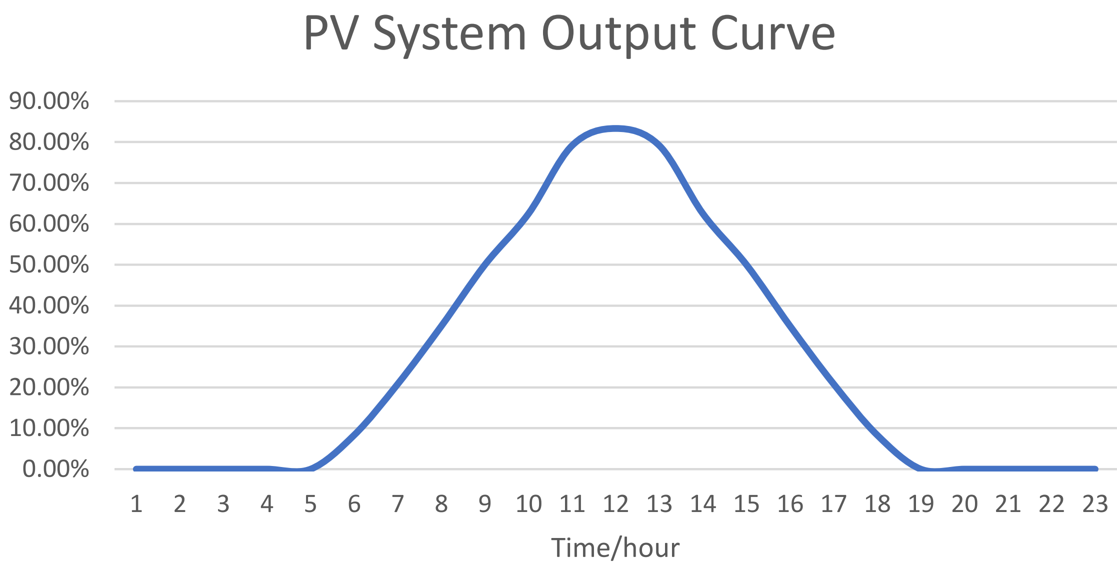

Figure 4.1: Curve of PV output

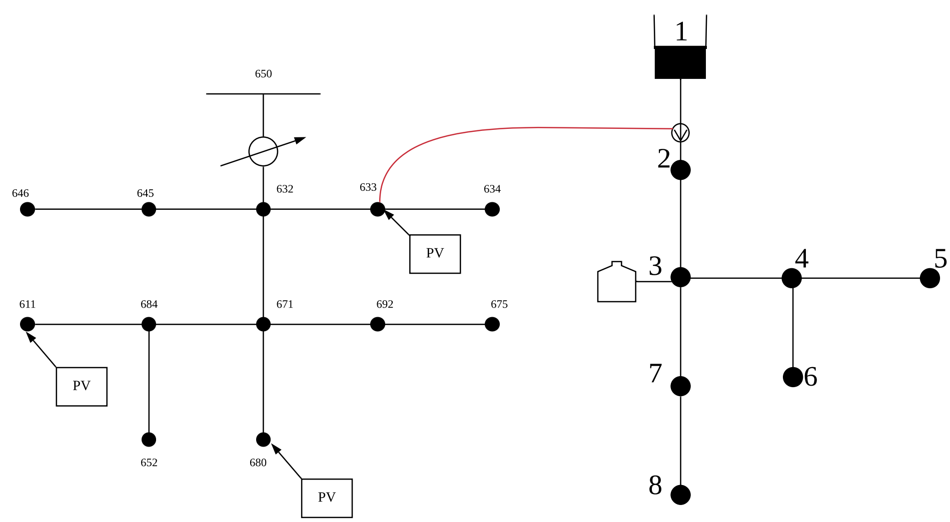

Figure 4.2: Topology of the Micro-WEN with PV

constraints of the test system need to be re-written as follows:

$$P_{i,t}^{\mathrm{G}} + P_{i,t}^{\mathrm{PV}} + \sum_{(j,i)\in\mathbf{L}} (P_{ji,t} - r_{ij}I_{ji}) = P_{i,t}^{\mathrm{L}} + \sum_{(i,j)\in\mathbf{L}} P_{ij,t} + P_{i,t}^{Pump} \tag{4.1}$$

$$Q_{i,t}^{\mathrm{G}} + Q_{i,t}^{\mathrm{PV}} + \sum_{(j,i)\in\mathbf{L}} (Q_{ji,t} - r_{ij}I_{ji}) = Q_{i,t}^{\mathrm{L}} + \sum_{(i,j)\in\mathbf{L}} Q_{ij,t} + Q_{i,t}^{Pump} \tag{4.2}$$

The co-optimization model of the micro-WEN integrated with PV systems is also modified:

1. Objective Function: Equation (3.21)

2. Constraints: Equation (3.3)–(3.17), Equations (4.1) and equation (4.2)

4.2.2 Case Study

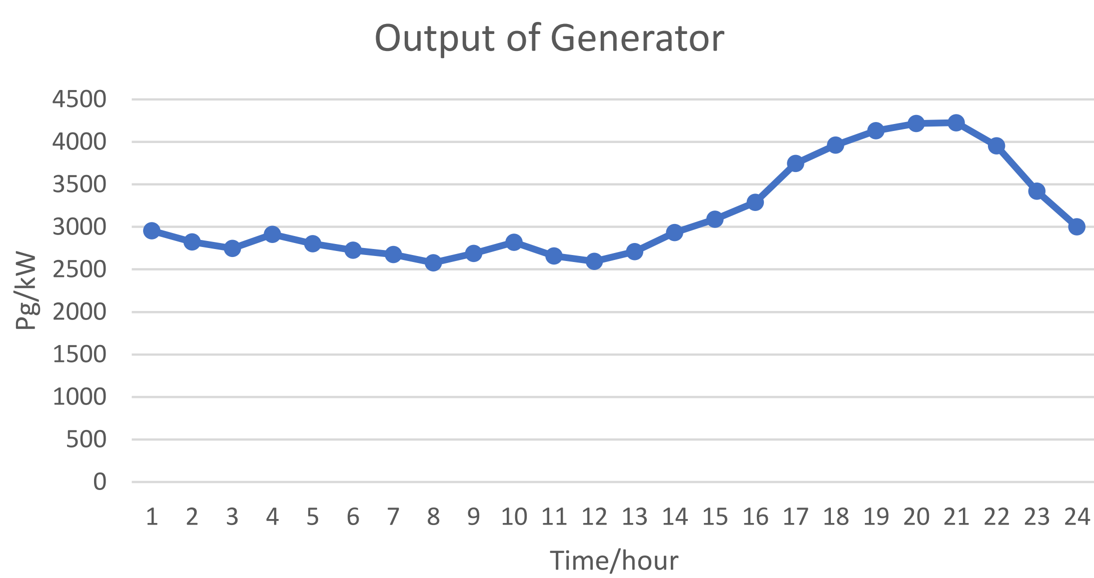

Figure 4.3: Hourly Output of the System Generator with Integrated PV

Figure 4.3, Figure 4.4 and Figure 4.5 illustrate the optimized generator output, power consumption of water pump and the state of the water tank, respectively. To compare the difference in the generator output before/after adding the PV systems in the studied micro-WEN, Figure 4.6 is presented. Apparently, there is an output difference between 6

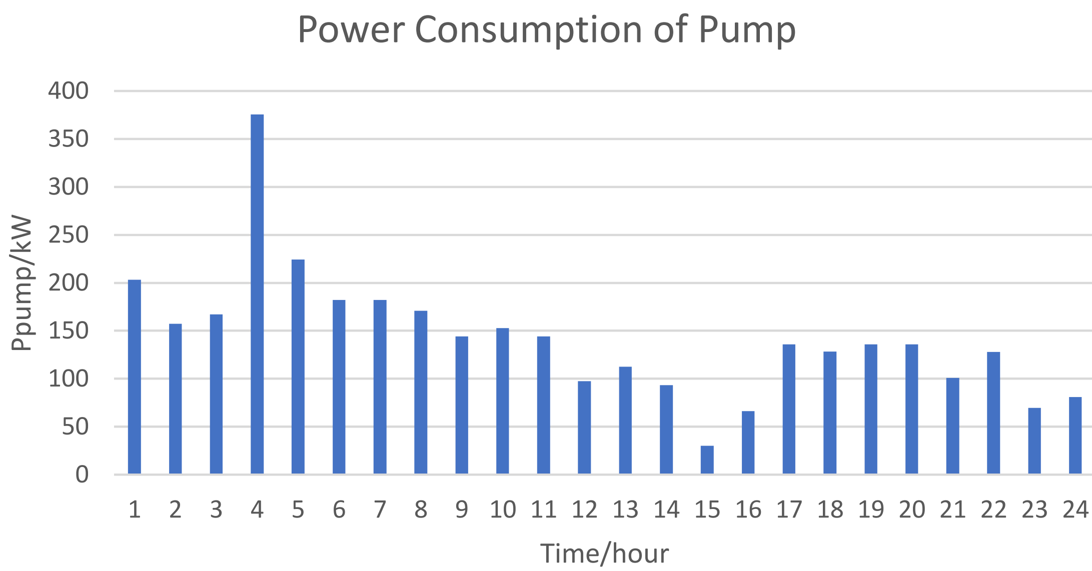

Figure 4.4: Hourly Pump Power Consumption with Integrated PV

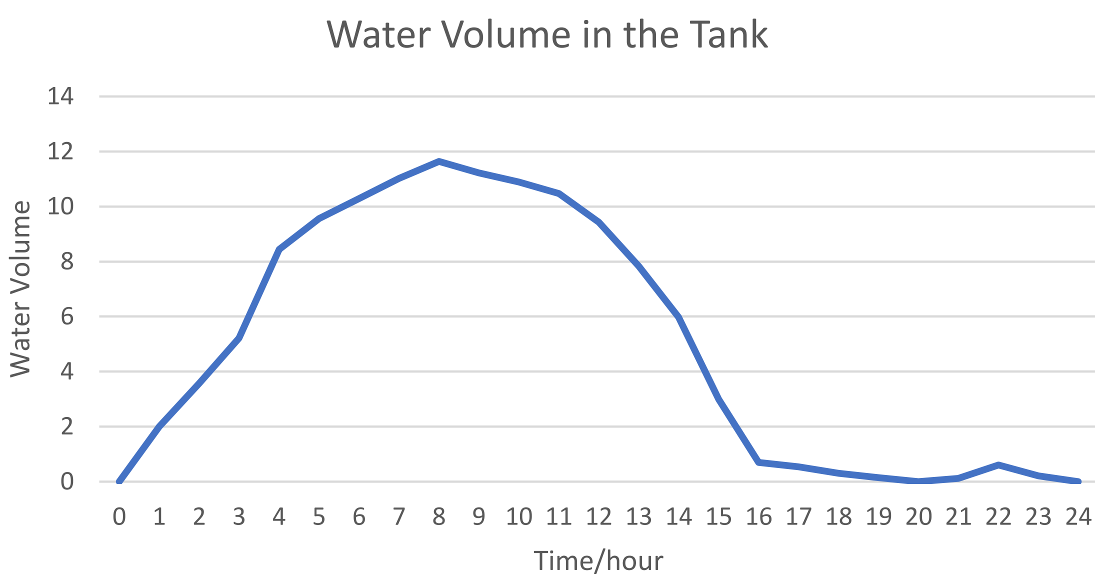

Figure 4.5: Hourly Pump Power Consumption with Integrated PV

o'clock to 18 o'clock, during which the PV systems work and provide power to the system. Because of the PV systems, the generator power output decreases. Thus, the total energy cost is found \$1910.36, lower than that in the basic case condition without PV systems.

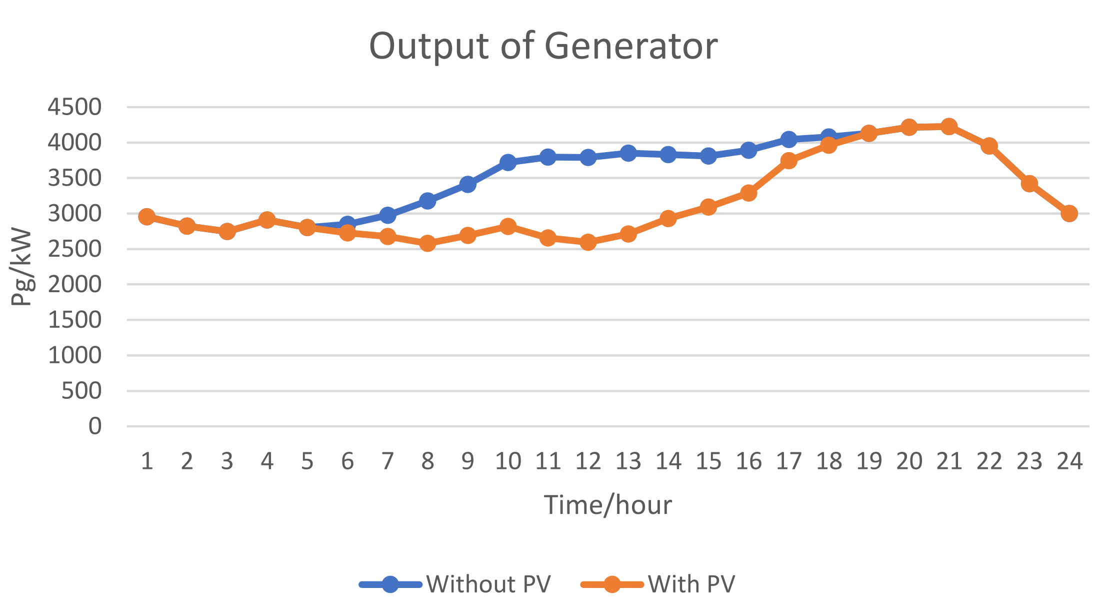

Figure 4.6: Comparison of the Hourly Output of Generator with and without the PV integration

4.3 Integration of BESS

4.3.1 Formulations of A Micro-WEN with Integrated BESS

Energy storage system is another important part of a smart grid. It can store surplus electricity and release it when the load rises. The model of a BESS is formulated as follows:

$$SOC_{i,t} = SOC_{i,t-1} + \frac{nES_b Pes_{i,t}^C}{Eb} - \frac{Pes_{i,t}^D C}{nES_b Eb} \quad (4.3)$$

$$\underline{SOC} \leq SOC_{i,t} \leq \overline{SOC} \quad (4.4)$$

$$0 \leq Pes_{i,t}^C \leq bes_{b,t} \overline{Pes^C} \quad (4.5)$$

$$0 \leq Pes_{i,t}^{DC} \leq (1 - bes_{b,t}) nES_b \overline{Pes^{DC}} \tag{4.6}$$

$$SOC_{i,end} \geq SOC_{thres} \tag{4.7}$$

Constraint (4.3) represents the state of charge of BESS at bus i at time t. nES is the charging/discharging efficiency of the BESS and Eb is the capacity of the BESS. Constraint (4.4) denotes the maximum/minimum state of charge for the BESS. $bes_{b,t}$ is a binary variable to reflect the charging or discharging status of the BESS. When $bes_{b,t}$ is 1, it means the battery works at charging mode, and is consuming electric energy. When $bes_{b,t}$ is 0, the battery works at discharging status and delivers energy to the system. Constraints (4.5) and (4.6) denote the range of charging/discharging power, respectively. Constraint (4.7) states that at the end of the day, the SOC of the BESS must be above a certain level. In this thesis, we set the level to be 30%. Because of the integration of BESS to the test system, the power balance constraints need to be rewritten by adding the power capacity of the BESS:

$$P_{i,t}^{\mathrm{G}} + P_{i,t}^{\mathrm{PV}} + Pes_{i,t}^{DC} + \sum_{(j,i)\in\mathbf{L}} (P_{ji,t} - r_{ij} I_{ji}) = P_{i,t}^{\mathrm{L}} + \sum_{(i,j)\in\mathbf{L}} P_{ij,t} + P_{i,t}^{Pump} + Pes_{i,t}^{C} \tag{4.8}$$

$$Q_{i,t}^{\mathrm{G}} + Q_{i,t}^{\mathrm{PV}} + Qes_{i,t}^{DC} + \sum_{(j,i)\in\mathbf{L}} (Q_{ji,t} - r_{ij} I_{ji}) = Q_{i,t}^{\mathrm{L}} + \sum_{(i,j)\in\mathbf{L}} Q_{ij,t} + Q_{i,t}^{Pump} + Qes_{i,t}^{C} \tag{4.9}$$

With the location of BESS provided in Table 4.2, the topology of the studied micro-WEN integrated with PV and BESS services is updated as shown in Figure 4.7. The co-optimization model is updated accordingly as follows:

1. Objective Function: Equation (3.21)

2. Constraints: Equations (3.3)–(3.17), and Equation (4.3)–Equation (4.9)

Table 4.2: BESS Parameters and Specifications

BESS location (bus#)	BESS capacity
684	1.15 MVA, 2.5 MWh
692	1.41 MVA, 3.2 MWh

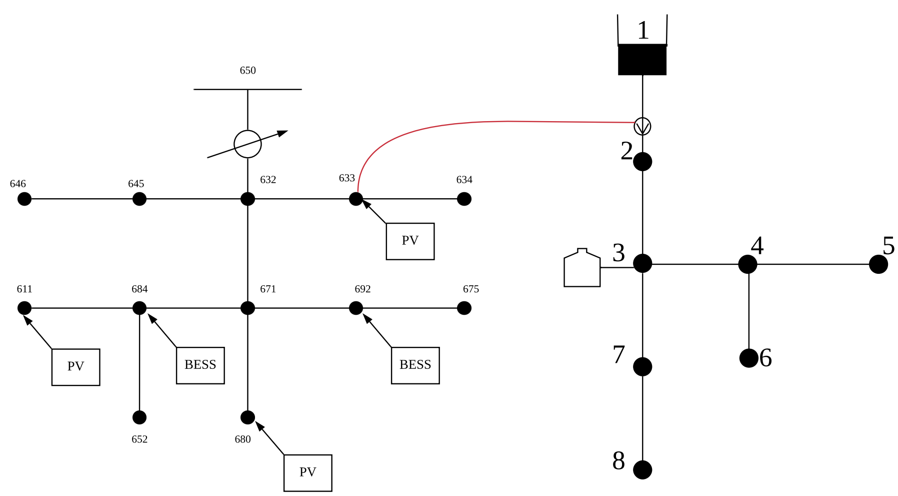

Figure 4.7: Topology of the Studied Micro-WEN with Integrated PV and BESS

4.3.2 Case Study

With 2 BESS integrated into the test system, the model becomes a MINLP optimization problem due to a binary variable which is introduced to represent the charging/discharging status of the BESS. With the BESS integrated, the total energy cost of the micro-WEN decreases to \$1797.94. Compared with the previous cost without BESS, the total cost is reduced by 6%.

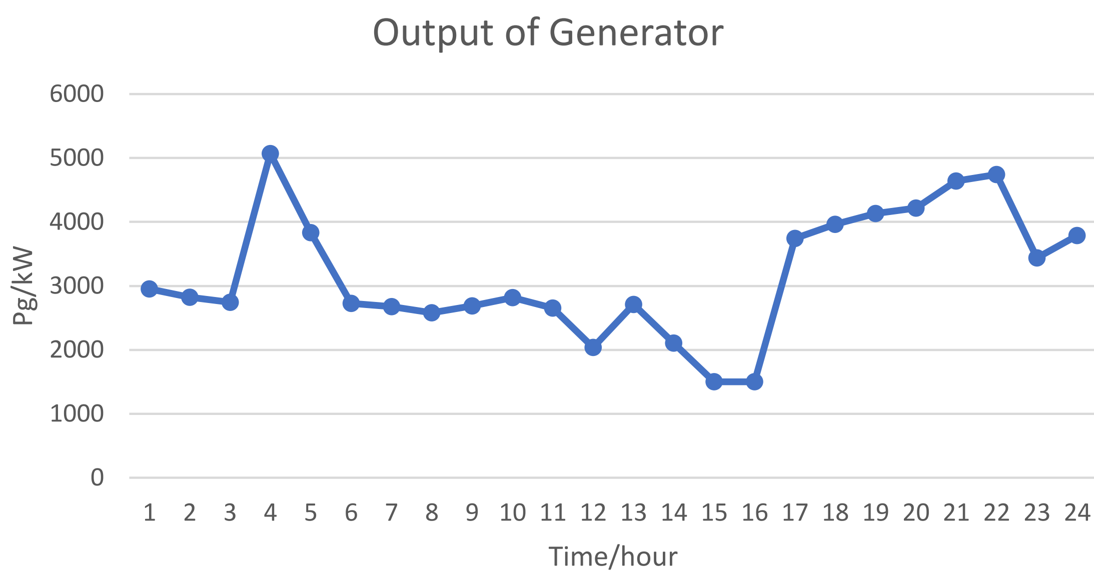

Figure 4.8: Hourly Output of the System Generator with Integrated PV and BESS

Figure 4.8 presents the hourly output of the generator in the studied micro-WEN with integrated PV and BESS. The output is high at 4 o'clock and low around 15 o'clock, during which the price of energy is quite low/high respectively. To compare the generator output with/without the BESS, Figure 4.9 is presented. From 3 to 6 o'clock and 20 to 24 o'clock, the test system with BESSs has higher energy consumption because the BESSs are in charging mode of operation. And during 11 to 17 o'clock, the system with BESSs consumes less power consumption. That's the 'time shifting' of BESSs, which means to buy and store power when it is least expensive and use the stored power during peak demand or when prices are highest.

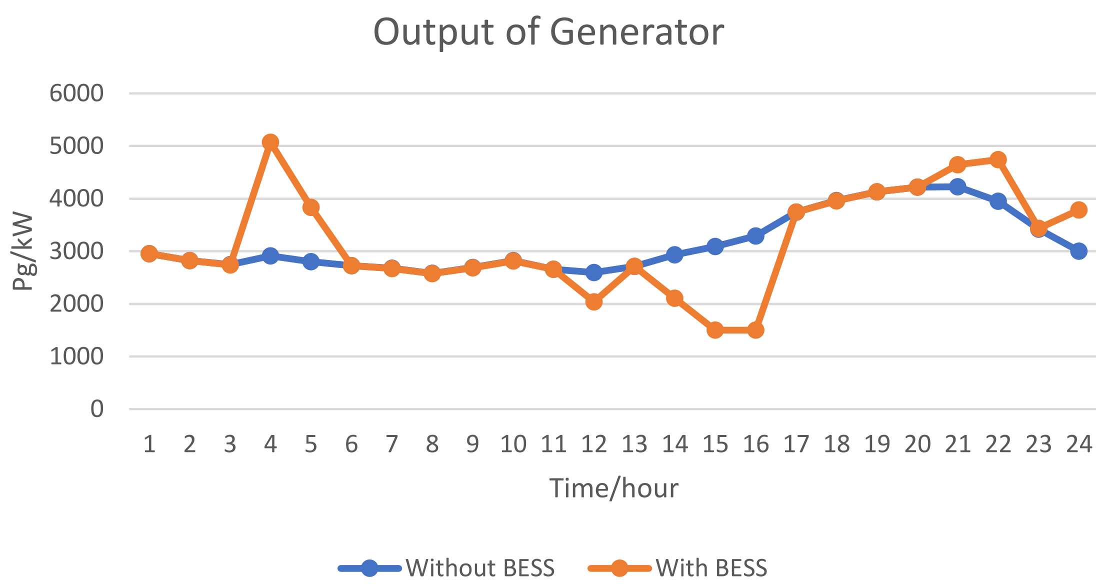

Figure 4.9: Comparison of the Hourly Output of the System Generator with and without Integrated BESS

Figure 4.10 and Figure 4.11 present the state of charging of the two BESS during the day. The initial state of charge for both BESSs is set at 50%. Corresponding to Figure 4.9, the state of charge for both BESS increases from 3 o'clock to 6 o'clock, which means BESS are storing energy. Then at 11 o'clock to 16 o'clock, the BESS is delivering energy to the system. The energy stored in the BESS can help avoid consuming too much energy when the price is high. Finally, beginning at 20 o'clock, the BESSs are charging again to 30%, which is the minimal final state of charging we set so that the BESS is ready to provide energy to the grid in the next day, if needed.

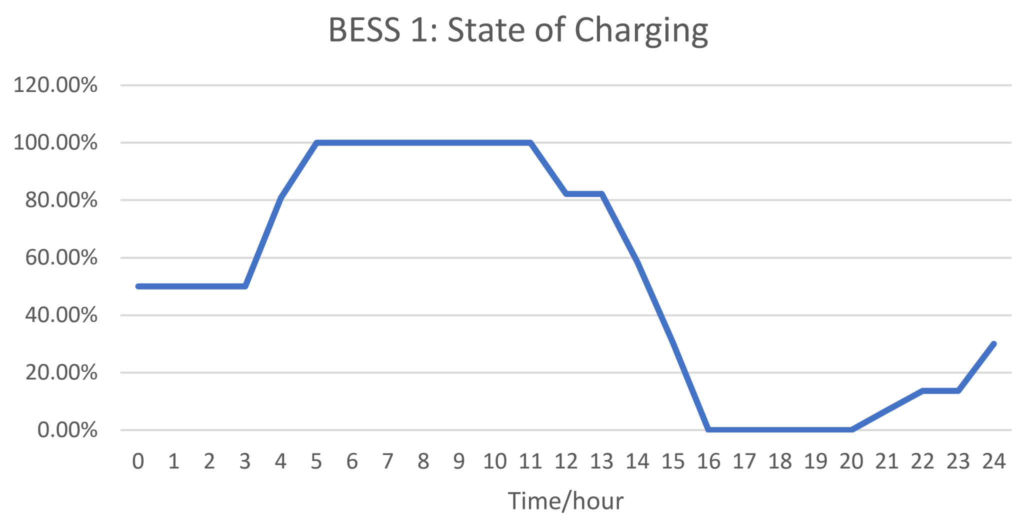

Figure 4.10: State of Charge of BESS 1

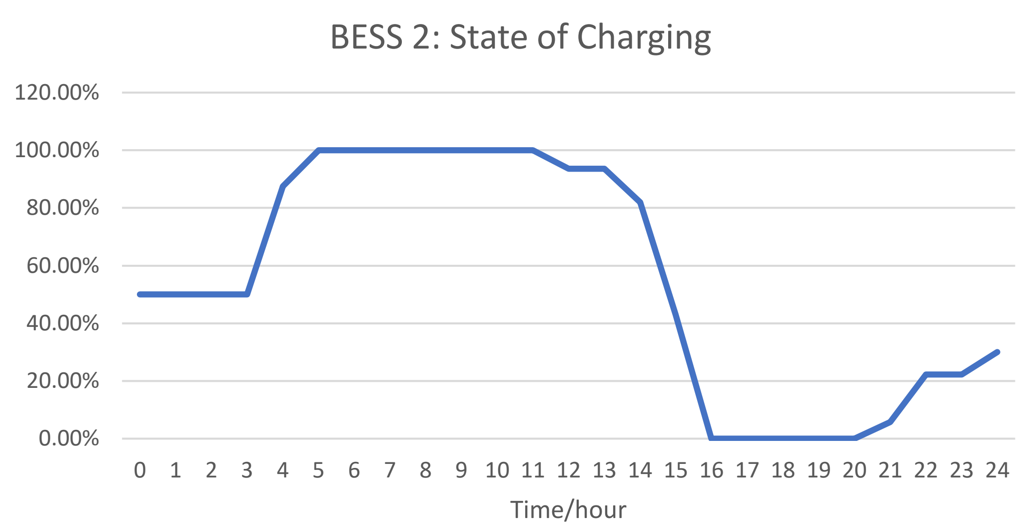

Figure 4.11: State of Charge of BESS 2

Figure 4.12 shows the state of water tank. The curve looks similar to that in previous test scenarios and the maximum volume in the tank is around 10, which means the water storage capacity of the tank is also fully utilized. Figure 4.13 reflects the power consumption of the test micro-WEN when integrated with PV and BESS. Compared with the previous case, the curves looks smoother.

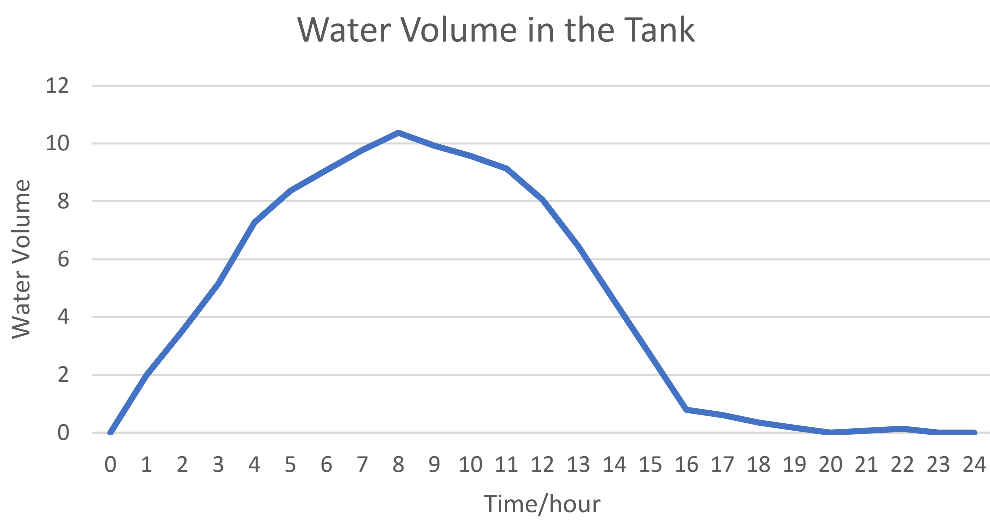

Figure 4.12: Water Volume in the Tank in the Micro-WEN Integrated with PV and BESS

4.4 Conclusion

Table 4.3: Comparison of the Optimization Results

Model	Optimal Solution
Basic Model	2172.91
With PV only	1910.36
With PV and BESS	1797.94

Previous chapter introduced a nonlinear mathematical model for the micro-WEN, which focused on the power and water distribution level. To further meet the requirements of a smart community, renewable energy sources and energy storage systems should be considered. In this chapter, photovoltaics (PV) systems and battery energy storage system (BESS) were introduced and integrated to the micro-WEN. As shown in Table 5.3, with the integration of PV and BESS, the cost efficiency of the micro-WEN is significantly improved. And with

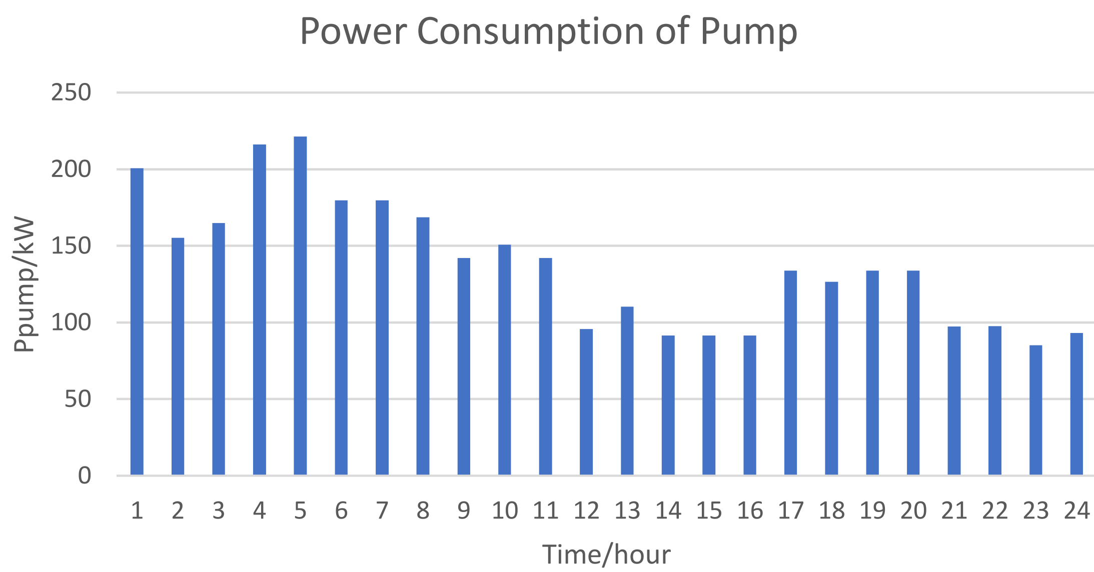

Figure 4.13: Pump Power Consumption after PV and BESS integrated

multiple energy sources and storage components, the system could reveal a better flexibility and security performance.

Chapter 5: Operation of the Micro-WEN with A Flexible Irrigation Strategy

5.1 Introduction

To improve the flexibility of the grid, researchers focus on the controllability of electrical loads so that when power imbalance or some contingencies occur, the power system can respond timely and accurately to potential disruptions. Due to the growing penetration of renewable generation, the system uncertainty has and is being significantly increased. When the water system and energy system are integrated and operated jointly, we may tackle the uncertainty from a new angel. Rather than operating the electric loads, the potential of loads from water side can also be taken into consideration. In some areas, water facilities like pumping, desalination and other water treatment services can consume up to 12% of the total electric power consumption. On the one hand, the water facilities are important loads which can not be ignored for the power grid. On the other hand, the water facilities can have great potential to provide demand response services for the power grid.

Sometimes, water loads are not particularly sensitive to time and water can be stored in the tank. It means if there's superfluous energy generated, it can be used to pump and store water in the tank for future use. If considering the characteristics of some certain kinds of water loadsextra potential for demand response services may exist. A good example is the irrigation services.

Table 5.1: Top States with Considerable Irrigation Water Usage

State	Cumulative Percentage of the Total Usage
California	16%
Idaho	29%
Arkansas	39%
Montana	47%
Colorado	54%

Table 5.1 shows the irrigation water usage in some states in the U.S. where the cumulative

percentage value can be over 50%. Since the irrigation service is not very sensitive to time, in this chapter, a flexible strategy of irrigation is introduced, and a mathematical model for such irrigation system is formulated. The model is then incorporated within the micro-WEN and optimized to minimize the total energy cost.

5.2 Formulation

To formulate the flexible irrigation strategy, we make some assumptions as follows:

- ***Irrigation Water Usage:*** Based on the load profile mentioned in previous chapters, we assume that 30% of the total water load is used for irrigation. It means for every load node in the water distribution network, the water load becomes 70% of the previous load and the irrigation water usage is supplied by the tank.
- ***Crops and Plants Needing Irrigation:*** We assume that the crops or plants are not very sensitive to the irrigation time of a day. It means the crops have no special water requirements in the morning, evening or some certain time periods of a day.
- ***Irrigation System:*** To formulate the irrigation water flow, we assume that the value of irrigation water flow is fixed. Then the irrigation water volume can be expressed by the irrigation flow and irrigation time. And the daily irrigation demand can be met by turning on the irrigation system for N hours per day.

Applying the flexible irrigation scheme to the micro-WEN, the constraints for water tank needs to be modified as follows:

$$\underline{Vtk} \leq Vtk_0 + \sum_{t=0}^{t} (ftk_t - f_{irr} \cdot irr_t) \leq \overline{Vtk} \tag{5.1}$$

$$\sum_{t} irr_t = N \tag{5.2}$$

In Equation (5.1), f_irr is the fixed value of irrigation water flow and irr_t is a binary variable to reflect the on/off state of the irrigation system at time t. When irr_t is 1 or 0, the irrigation system is turned on or off, respectively. N is is the total number of hours needed for the irrigation system to work so that the irrigation water demand can be met. Then the flexible irrigation scheme is applied to the studied micro-WEN and the optimization problem evolves as follows:

1. Objective Function: Equation (3.21)

2. Constraints: Equations (3.3)–(3.11), Equations (3.13)–Equation (3.17), and Equation (4.3)–Equation (5.2)

5.3 Case Study

Table 5.2: Time Periods at Which the Irrigation System is Turned On

Time	1	4	19	22	23	24
Working Status	On	On	On	On	On	On

Table 5.2 shows the optimized schedule of the irrigation system. The irrigation system is turned on at 6 hours per day to meet the irrigation demand. And the total energy consumption cost is found \$1795.14. Compared with the cost before applying the flexible irrigation strategy, the cost is achieve lower since the flexibility in water demand is effectively harnessed.

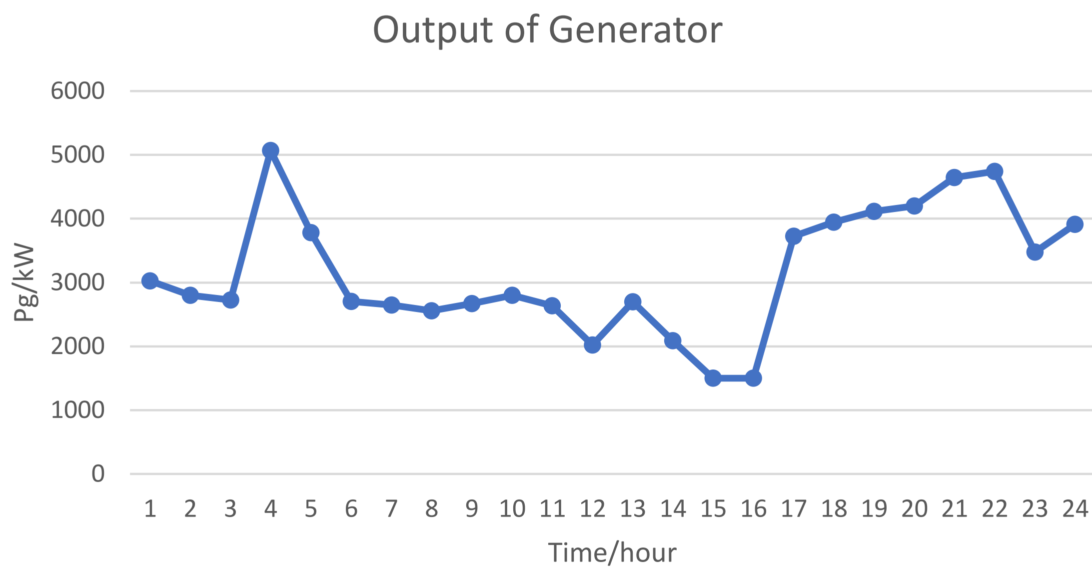

Figure 5.1: Hourly Output of the System Generator with Flexible Irrigation Strategy

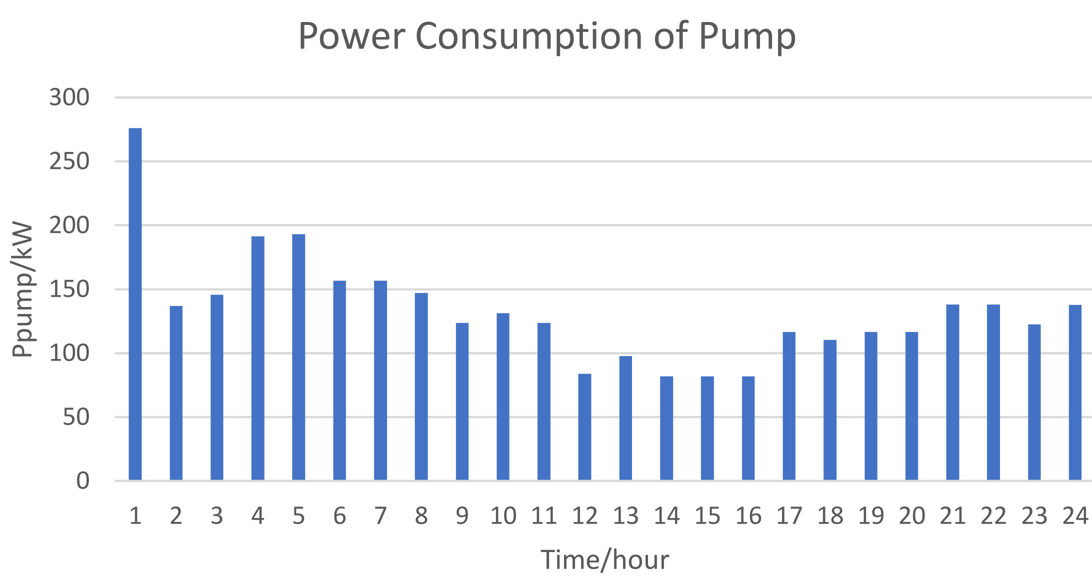

Figure 5.2: Hourly Pump Power Consumption with Flexible Irrigation Strategy

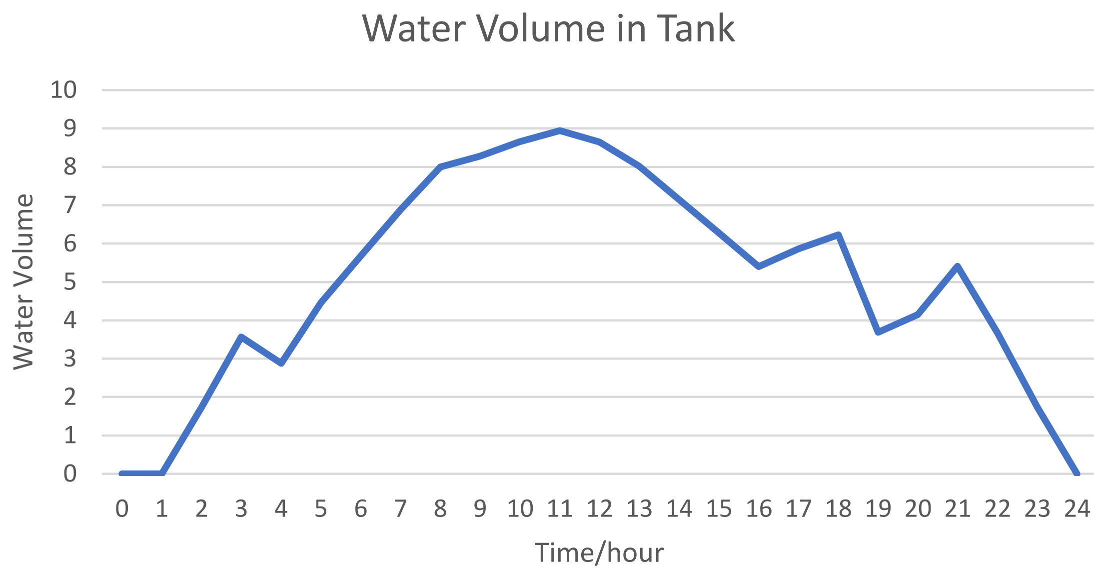

Figure 5.3: Optimized Hourly Tank Volume

The curve for hourly pump power consumption (Figure 5.2) and the water volume (Figure 5.3) are a little different from the corresponding ones in the previous case studies. According to the optimized working status of the irrigation system, the irrigation is on at time 1. So the pump consumes more water at time 1 to provide the flow needed for irrigation. The water tank keeps storing water from the system to make sure that there's enough water for the irrigation system. The irrigation system is on from time periods 22 to 24, so the water volume in the tank decreases fast during this time period and falls to 0 at the end. Figure 5.4 and Figure 5.5 present the state of charge of BESS1 and BESS2 in this test case, respectively.

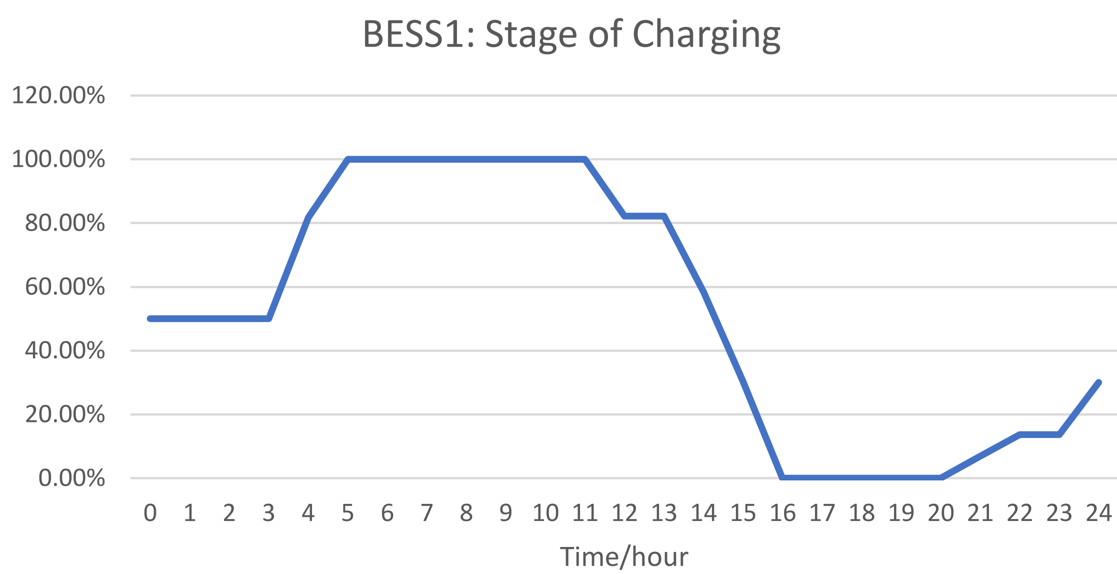

Figure 5.4: Optimized SOC of BESS1

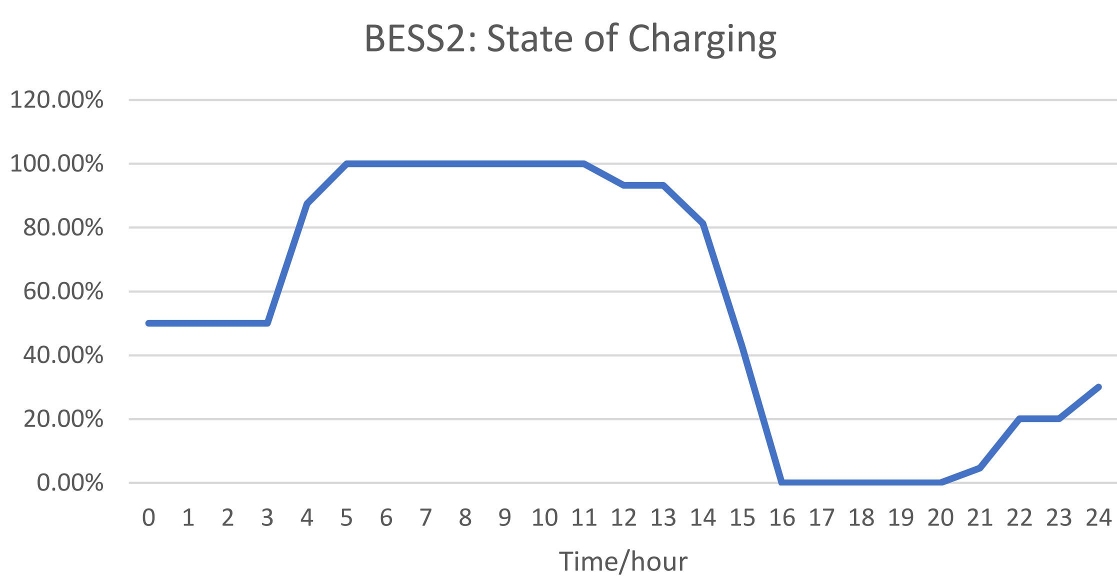

Figure 5.5: Optimized SOC of BESS2

Table 5.3: Comparison of Optimization Results

Model	Optimal Solution
Basic Model	2172.91
With PV only	1910.36
With PV and BESS	1797.94
Irrigation Strategy Applied	1795.14

5.4 Conclusion

In this section, we explored the potential of water loads to provide demand response (DR) services to the micro-WEN. In so doing, a flexible irrigation strategy was formulated and applied to the tested micro-WEN. Utilizing the flexibility of the irrigation loads in the water system, the total energy consumption for micro-WEN can be reduced. If considering the characteristics of other kind of loads in the water system, the effect may be even more attractive. If the strategy is used to larger-scale water-energy systems, the more significant economic benefits and cost savings can be achieved.

Chapter 6: Conclusion

6.1 Conclusion

As two of the most important physical systems in a smart community, energy system and water system are connected and intertwined together. Different from the traditional independent operation strategies, a distribution level co-operation model is introduced in this thesis. The water system and energy system are connected through the management or scheduling of pumps. A mixed-integer non-linear programming optimization model is established for co-optimization of the micro-WEN. The objective function is to minimize the total energy consumption cost for the micro-WEN considering the impacts of both water and energy networks. Constraints for both power distribution system and water distribution system are set in order to make sure that the micro-WEN can work properly.

In Chapter 3, the basic model of a micro-WEN is introduced. The energy side of the test system is selected to be the IEEE 13-bus distribution system and the water side is an 8-node water distribution system. The model is optimized by (i) a two-stage hierarchical optimization method and (ii) a co-optimization method. The co-optimization method, integrating both networks and running the optimization across both networks at once, revealed a higher cost efficiency.

In Chapter 4, the PV and BESS are introduced and integrated into the test micro-WEN system. As two important components of the smart grid, the integration of PV and BESS greatly decreases the total energy consumption cost for the micro-WEN.

In Chapter 5, a flexible irrigation strategy is introduced. Using the flexibility of irrigation load in the water system, an optimized schedule for the irrigation system can be obtained. Applying the flexible strategy of irrigation, the total energy consumption cost of the micro-WEN further decreases. Considering the scale of the test system, the economic benefits and cost savings could be more significant if applied to larger-scale WEN.

6.2 Future Research

This thesis only focused on the optimization of a limited number of water facilities like pumping, distribution and irrigation. In the future smart communities, more and more facilities should be connected through communication technologies , making it a cyber-physical WEN, that should be co-optimized so as to achieve an economically attractive and reliable operation. In line with the research focuses at GW Smart Grid Laboratory on resilience assessments and modeling, future research may focus on the co-optimization of cyber-physical WEN, and to investigate the reliability and resilience services a WEN can provide during emergency operating conditions and extreme events, respectively [28, 58, 101–103, 105, 134–145]. Future research should also focus on power systems with grid-support heterogeneous resources including different energy storage technologies and electric vehicles.

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