



Optimal sizing of renewable-storage based electricity supply systems for households in remote areas: A comparative study of battery and fuel cell

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ABSTRACT

This report focuses on the study of the optimal capacity of systems that rely on solar photovoltaic (SPV) and small wind turbine (SWT) as the primary sources of electricity supply. Standalone households in remote areas of South Australia (SA) that have difficulty accessing power networks due to distance problems will be focused. Two storage systems are investigated: fuel cell storage (FCS) and battery energy storage (BES) alongside the renewable energy systems. There are two basic configurations: SPV-SWT-FCS and SPV-SWT-BES. In addition, four other auxiliary systems, including SPV-FCS, SWT-FCS, SPV-BES and SWT-BES will be simulated for comparative analysis. The optimal capacity of the components in each system configuration will be calculated based on the net present cost (NPC) of the power system as the objective function. It is assumed that uninterrupted supply of power demand will be guaranteed in all configurations. The power supply process is mainly divided into three situations: the generation equals the demand; the generation exceeds the demand and the generation is less than the demand. This study analyses the optimal configuration of the system according to different supply and demand relations using particle swarm optimization (PSO) algorithm. In addition, the configurations with BES will be compared with that of FCS to explore the advantages and disadvantages of each system. In the last section, the use of mixed energy storage system SPV-SWT-BES-FCS to investigate the minimum NPC of the system will be discussed. The mixed energy storage configuration has the same modeling method as the previous configurations, adopting the mentioned three supply relationships. Next, the SPV-BES-FCS and SWT-BES-FCS configurations are simulated as well. Additionally, the comparison of the mixed energy storage system and the single energy storage system is included in the thesis. At the end, there is sensitivity analysis of the mixed energy storage system based on the costs of BES and FCS.

In the simulation, MATLAB software is used to model the data for ten households. The Visual Studio is also used to model the SPV-SWT-FCS system and SPV-SWT-BES system for one household. Mock objects include SPV-SWT-FCS, SPV-FCS, SWT-FCS, SPV-SWT-BES, SPV-BES, SWT-BES, SPV-SWT-BES-FCS, SPV-BES-FCS and SWT-BES-FCS configurations. In simulation results, the optimized component number, the output power, the minimized system net present costs and the levelized cost of energy (LCOE) are the outputs. Power input and output

diagrams of key components are also displayed to determine the role of each device in the overall operation of the systems.

Index Terms— capacity optimization, standalone households, remote area, uninterrupted supply, fuel cell, battery, particle swarm optimization, mixed energy storage.

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Chapter 1

I. Introduction

1.1 Background

Removed due to copyright restriction (Foran, Fleming and Spandonide 2014). Therefore, the study of the power situation in remote areas is particularly important. Removed due to copyright restriction (ARENA, 2019).

Renewable resources, such as solar, wind, tidal and geothermal energy, are clean sources of energy from nature that do not emit greenhouse gases such as carbon dioxide and therefore do not increase the risk of greenhouse effect. Compared with other forms of power generation, such as fuel generators, solar and wind power generation in remote and rural areas has obvious economic advantage, less investment and safer, cleaner, in India, Egypt, China, and Australia, standalone solar photovoltaic system provides the convenient cheap electricity for the local resident's life. With the iteration and update of technology, solar and wind energy, characterized by low energy consumption and low cost, has become a trend of renewable energy generation, which will help the residents in more regions without electricity and power shortage to realize the dream of "continuous electricity". Renewable energy generation has become the development trend of world energy supply. With the spread of green resources such as solar and wind power, the use of renewable energy for power generation is becoming more and more widespread, such as the combination of renewable energy power generation and fuel cells would greatly reduce greenhouse gas emissions, which is one of the biggest advantages of replacing fossil fuels.

Removed due to copyright restriction (Lehner, n.d.). Removed due to copyright restriction (Energy, 2019). Removed due to copyright restriction (Jager, 2017). Removed due to copyright restriction (Elnaggar, Edwan and Ritter, 2017).

Removed due to copyright restriction (Stapleton and Milne, 2013). The seasonal and daily variations in wind and solar resources can be fully used by the combined power system. However, the use of renewable energy depends to a large extent on natural conditions, such as in the rainy days, the solar energy production is greatly reduced, resulting in insufficient power to support the load. On the other hand, long periods of sunshine and strong winds can also lead to overproduction.

The excess electricity is dumped because it cannot be stored, resulting in a waste of resources. As a result, most hybrid systems operate independently off the grid via FCS or BES to achieve uninterrupted power supply. The storage system can be used to conserve the remaining power and output it to the load when the supply is low.

1.2 Problem Definition

Removed due to copyright restriction (Government of South Australia, n.d.). Most remote areas rely on diesel or natural gas to generate electricity, and the cost of electricity increases because of transport and storage costs. Although the South Australia government has properly subsidized the RAES scheme, the drawbacks of providing electricity in remote areas are clear. Firstly, the construction of infrastructure such as power transmission towers and long-distance power lines will consume a lot of manpower and resources. Secondly, a large amount of energy will be lost during the long-distance transmission of electricity. What's more, once the energy leakage occurs in transit, it will lead to serious environmental pollution. Therefore, to solve the problem of electricity use in remote areas is to seek a balance between power quality, power supply level and cost. However, with the continuous progress of off-grid system in the future, the difference may be gradually narrowed. The global demand for energy has been increasing, and it is mainly dependent on fossil fuels. Fossil fuels generate energy by burning non-renewable resources such as oil and natural gas. Rising fossil fuel prices in recent years have also heralded an energy crisis. In addition, the burning of fossil fuels produces large amounts of greenhouse gases, which have irreversible and harmful effects on the natural environment. At the same time, the extraction and transportation of fossil fuels also cause environmental problems.

If fuel cells are used in a system, the safety of flammable gases needs to be considered. Flammable gases such as hydrogen and methane are common in fuel cells. How to store combustible gas and prevent gas leakage to keep the system safe is one of the important factors.

1.3 Objectives

In order to reduce the long-distance transportation of electric energy and reduce the harm to the natural environment, environmentally friendly renewable resources are getting more and more attention. Hydrogen fuel cells convert the chemical energy of hydrogen and oxygen directly into electric energy, and the generation process is free of environmental pollution and noise. Removed due to copyright restriction (Siddiqui and Dincer, 2017).

Fuel cells have developed rapidly in recent years. Removed due to copyright restriction (Energy, n.d.) Each fuel cell has its own advantages and disadvantages. In this study, polymer electrolyte membrane fuel cell, which is also named proton exchange membrane fuel cell, is selected, as it is small and requires only hydrogen as fuel. Battery is another kind of energy storage method. Photovoltaic or wind energy is converted into electricity and stored in batteries for energy efficiency. Removed due to copyright restriction (Hoda et al. 2019, pp.144-168) At present, lithium ion batteries and lead-acid batteries are common in the new energy market.

The main contribution of this thesis is to investigate the optimal sizing and the costs of the SPV-SWT-FCS hybrid electricity system in the remote areas of south Australia. In addition, other five configurations, including SPV-FCS, SWT-FCS, SPV-SWT-BES, SPV-BES and SWT-BES systems, will be studied and compared in detail. The advantages and disadvantages of these configurations will be analyzed. The electricity consumption data used in this thesis are real and practical. Finally, the use of mixed energy storage system to investigate the NPC of the system will be discussed in this thesis.

Chapter 2

II. Literature Review

This chapter summarizes the literatures on renewable storage-based energy systems. In addition, this section also investigates literatures on the battery and fuel cell's lifetime and reducing the net present cost of the system by extending the battery and fuel cell's lifecycle.

With the progress of science and technology and the development of electronics, electric power and other industries, electricity generation from renewable resources such as photovoltaic and wind power is gradually popularized.

2.1 Research status

At present, many studies have achieved excellent results in the field of hybrid renewable energy and energy storage devices by designing the equipment model, obtaining the minimum net present value of the system through the algorithm, improving the stability of power supply and proposing various methods and management strategies for capacity optimization. Removed due to copyright restriction.

2.2 Existing defects

However, in some literatures, the analysis is not comprehensive enough. For example, the actual situation of different regions is not distinguished, accurate data application is not available or incomplete conclusions are drawn. These articles will be explained in the next section.

A. Actual situation

There have been many studies in the previous literature on optimizing system component capacity of the hybrid renewable system, but some actual situations, such as load requirements, weather and geographical location, have not been considered. Removed due to copyright restriction.

B. Data accuracy

In other literatures, although there is a reasonable hybrid generation configuration, there is no accurate system data analysis. Removed due to copyright restriction.

C. Comprehensive analysis

Some literatures have done detailed research on modelling and data collection, but the analysis is not comprehensive. Removed due to copyright restriction.

D. Data contrast

A lot of research is going into using batteries in hybrid renewable energy systems, and a few have used fuel cells. Therefore, in these papers, whether modelling or conclusion, only batteries or fuel cells are generally used, instead of comparing these two energy storage methods. Removed due to copyright restriction.

E. Resource utilization

The hydrogen used in fuel cells is usually obtained by decomposing hydrogen in water, but it can also be produced by disposing of wastes such as garbage. Although this method has low yield, hydrogen generated by waste decomposition is not only cheap, but also can be utilized to a large extent to reduce waste retention. In addition, households in remote areas of South Australia are dominated by animal husbandry, which produces large quantities of combustible waste every day. In the actual situation, this part of resources can be fully utilized to obtain hydrogen, which will play an important role in reducing the system cost. Most of the literature does not focus on using this method to obtain hydrogen. Removed due to copyright restriction.

F. Energy storage

The cost of energy storage accounts for a large proportion of the total system, so how to optimize the fuel cell and battery configuration plays a crucial role in reducing the overall cost. In previous literature, most of the articles focus on the research of attaching a control system to the energy storage system to increase the lifetime of fuel cells by adjusting external conditions instead of using mixed energy storage system. Removed due to copyright restriction.

2.3 Summary

In summary, the research on hybrid renewable energy system has reached a high level at present, but there are still some incomplete or inaccurate. Therefore, the research that can make up for these deficiencies becomes more important. The issues listed above will be discussed in the later section in the report.

However, the market price of such environmentally friendly renewable energy generation systems remains high. Without a reasonable choice of component capacity, it will be difficult to obtain the maximum technical and economic benefits.

Chapter 3

III. SPV-SWT-FCS System Modelling

3.1 SPV-SWT-FCS Hybrid System Configuration

In the SPV-SWT-FCS configuration, the system mainly consists of solar photovoltaic, small wind turbine, fuel cell, electrolyser, hydrogen tank and inverter (INV). The power generated by SPV and SWT is supplied to the load through INV first. The function of the inverter is to convert the variable DC output to AC current, which can be used by the load directly. If the system still has the remaining power, the surplus power will be transferred to the electrolyser, which can use this energy to separate the hydrogen from the water and store it in the hydrogen tank for later use. Removed due to copyright restriction (Hakimi, Tafreshi and Kashefi, 2007). Dealing with the solid waste is another method to generate power in the remote areas. Removed due to copyright restriction (Shi et al, 2019) The gas can then be used to generate steam and electricity. This process does not create excess residual sludge that requires complex treatment and cleaning. Removed due to copyright restriction (Hakimi, Tafreshi and Kashefi, 2007). The configuration of the SPV-SWT-FCS system is shown in Figure 1.

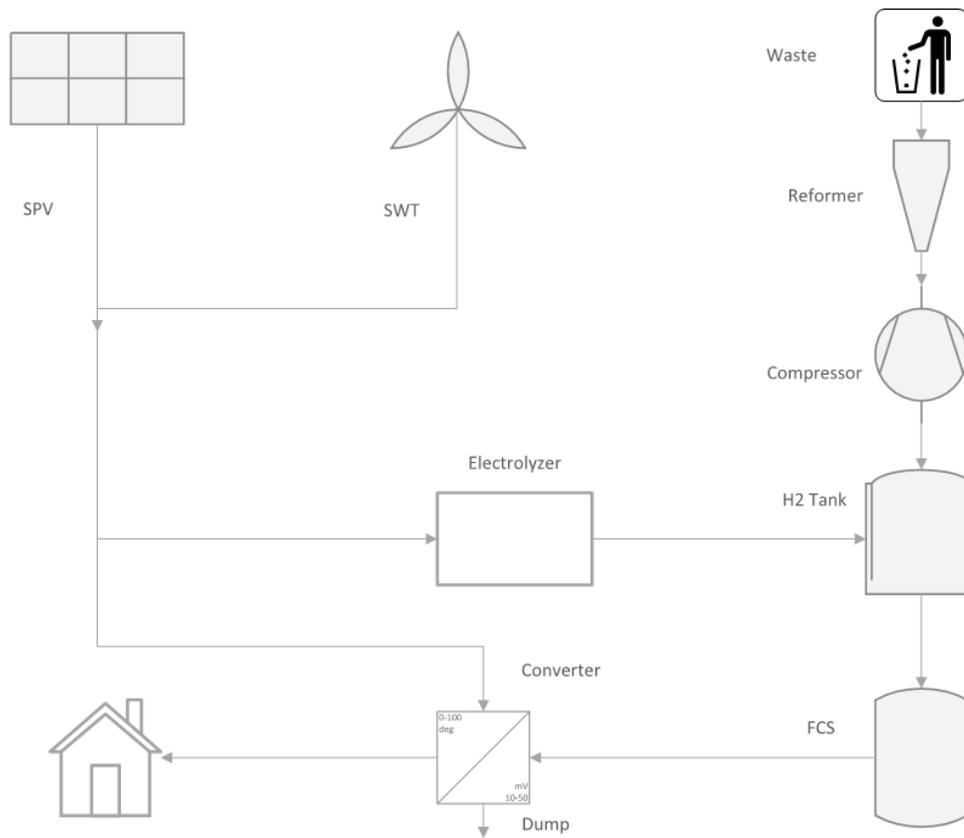


Figure 1. Configuration of SPV-SWT-FCS system.

The terms are as follows:

- P_{re} Power generated by SPV and SWT in total
- P_{re_el} Power delivered from SPV and SWT to electrolyser
- P_{el_tank} Power delivered from electrolyser to hydrogen tank
- P_{tank_fc} Power delivered from hydrogen tank to fuel cell
- P_{fc_inv} Power delivered from fuel cell to inverter
- P_{inv_load} Power delivered from inverter to load
- P_{re_inv} Power delivered from SPV and SWT to inverter
- P_{comp_tank} Power delivered from compressor to hydrogen tank

A. Solar Photovoltaic

The solar energy output depends on the influence of the local climate, array orientation, inclination, total insolation I_c (kW/m^2) and the cell temperature T_{cell} . The total PV array insolation is the sum of beam insolation, diffuse insolation and reflected insolation. The temperature coefficient γ ($\%/^{\circ}\text{C}$) should also be considered in the calculation. The temperature coefficient of the solar array's rated power is the percentage decrease in the rated output power for every 1°C increase in temperature. The power generated by the SPV $P_{pv}(t)$ can be expressed as follows:

$$P_{pv}(t) = P_{p,r} \left(\frac{I_c}{I_{stc}} \right) (1 - \gamma(T_{cell} - T_{stc})) \quad (1)$$

$$P_p(t) = \eta_p * P_{pv}(t) \quad (2)$$

where $P_{p,r}$ is the rated power of the SPV, $P_p(t)$ is the net power generation and η_p is the overall efficiency of the power system.

In the analysis, the following tests are conducted at standard test conditions: $I_{stc} = 1000\text{W}/\text{m}^2$ and temperature $T_{stc} = 25^{\circ}\text{C}$. The SPV system efficiency is considered as 86%, the rated power is 1kW and the temperature coefficient is 0.4.

B. Small Wind Turbine

The output of SWT in winter or rainy and windy days is even higher than that of solar energy. Cut-in wind speed and cut-out wind speed are two key factors that determine SWT output power. If the wind speed is less than the cut-in wind speed or greater than the cut-out wind speed, the output power of the wind turbine will be zero. if the wind speed is greater or equal to the cut-in wind speed and less than the rated nominal wind speed, the wind turbine output power is a cubic approximation of the wind speed vs power curve. Otherwise, if the wind speed is greater than or equal to the rated nominal wind speed and less than or equal to the cut-out wind speed, the wind turbine is operating as rated output power. The power generated by the SWT $P_{wt}(t)$ can be expressed as follows:

$$P_{wt}(t) = \begin{cases} 0 & v < v_c \text{ or } v > v_f \\ P_{w,r} \left(\frac{v-v_c}{v_t-v_c} \right)^3 & v_c \leq v \leq v_t \\ P_{w,r} & v_t \leq v \leq v_f \end{cases} \quad (3)$$

$$P_w(t) = \eta_w * P_{wt}(t) \quad (4)$$

where v_c is the cut-in wind speed, v_f is the cut-out wind speed, v is the wind speed and v_t is the rated nominal wind speed. $P_{w,r}$ is the rated power of the SWT, $P_w(t)$ is the net power generation and η_w is the overall efficiency of the power system.

In the analysis, the rated power is considered as 1kW and the system efficiency is configured as 90%. The cut-in, cut-out, nominal wind speed are set to be 3m/s, 20m/s and 8m/s, respectively.

C. Electrolyser

Removed due to copyright restriction (Xu, Scott and Basu, 2011). The combination of electrolyser and fuel cell plays an important role in energy efficient conversion. As energy is consumed during electrolysis, the efficiency of the electrolyser η_{el} is considered to be 90% in the analysis.

D. Fuel Cell

Removed due to copyright restriction (Zhao, 2019) In this process, the efficiency is high as the fuel does not burn. In addition, there is no mechanical transmission parts, so there is no noise pollution, and the emission of harmful gas is very little. Proton exchange membrane fuel cell (PEMFC) is also equivalent to the reverse device of water electrolysis in principle. The single battery is composed of an anode, a cathode and a proton exchange membrane. The anode is the place where the hydrogen fuel is oxidized, and the cathode is the place where the oxidant is restored. When PEMFC is working, it is equivalent to DC power supply, anode is the negative pole of power supply, cathode is the positive pole of power supply.

Removed due to copyright restriction (Hakimi, Tafreshi and Kashefi, 2007). Hence, the amount of energy that can be converted per kilogram by hydrogen is

$$3.4 \text{ kWh/m}^3 / 0.09\text{kg/m}^3 = 37.8 \text{ kWh/kg.}$$

This is the lower heating value (LHV) of hydrogen. In the analysis, the efficiency of the fuel cell η_{fc} are considered as 50%. So, the electricity generated through fuel cell is

$$E_{fc}(t) = \frac{37.8kWh}{kg} * amount\ of\ hydrogen\ (kg) * \eta_{fc} \quad (5)$$

E. Anaerobic Reactor and Reformer

Removed due to copyright restriction (Li, Wei and Wang, 2008) Hydrogenase is the key enzyme in the whole metabolism. The advantages of anaerobic fermentation are as follows: firstly, solid waste is converted into hydrogen to achieve the reduction of waste; secondly, compared with the aerobic process, the anaerobic digestion process does not need oxygen and reduces power consumption, thus greatly reducing the operating cost.

Removed due to copyright restriction (Hakimi, Tafreshi and Kashefi, 2007). For the remote areas of South Australia, there are on average four people in each family, and each person can generate 600 grams of garbage every day, or 2.4 kilograms of waste per family every day. Although the conversion rate of hydrogen production from solid waste is low, the cost of anaerobic reactor, reformer and other equipment is very low, so, using solid waste to produce hydrogen can also bring more benefits to users. In the simulation, the reformer and the reactor are considered as one component.

F. Inverter

The inverter converts direct current energy into controllable alternating current. In the analysis, the efficiency of the inverter η_{inv} can be considered as 90%. Due to the policy of South Australia region, the capacity of the inverter is limited to 4 kW for one family. Therefore, if the rated output power of 1 kW inverter is selected, 18 inverters are enough for the load of ten family. In the case of the system inverter, a control system to deal with energy dumping needs to be installed. When production exceeds demand and the hydrogen tank is saturated, the remaining energy should be dumped.

G. Hydrogen Tank

The hydrogen electrolyzed from the water and the solid waste will be stored in the hydrogen tank. When the power supply is low, the hydrogen is transferred to the fuel cell and converted into electricity. It is considered that a hydrogen tank of 1 kilogram has an initial storage rate of 0.6. The energy converted from hydrogen to fuel can be expressed as follow:

$$E_{tank}(t) = N_{tank} * M_{tank} * LHV \quad (6)$$

where N_{tank} , M_{tank} are the number and the storage mass of the hydrogen tank.

3.2 SPV-SWT-FCS Hybrid System Analysis

There are three situations in the SPV-SWT-FCS hybrid system: (1) generation = demand (2) generation > demand (3) generation < demand.

A. Generation Matches Demand

In this situation, the power generated by SPV and SWT is transited to the load through the inverter and just enough to support the load. There is no power through the electrolyser and the fuel cell. The hydrogen generated by the waste will be stored in the hydrogen tank. The path of the power is shown in Figure 2. The equations are as follow:

$$P_{re} = P_{pv} + P_{wt} \quad (7)$$

$$P_{re} = P_{re_inv} = P_{inv_load} / \eta_{inv} \quad (8)$$

$$P_{tank(i)} = P_{tank(i-1)} + P_{comp_tank(i)} \quad (9)$$

$$P_{re_el} = P_{el_tank} = P_{tank_fc} = P_{fc_inv} = 0 \quad (10)$$

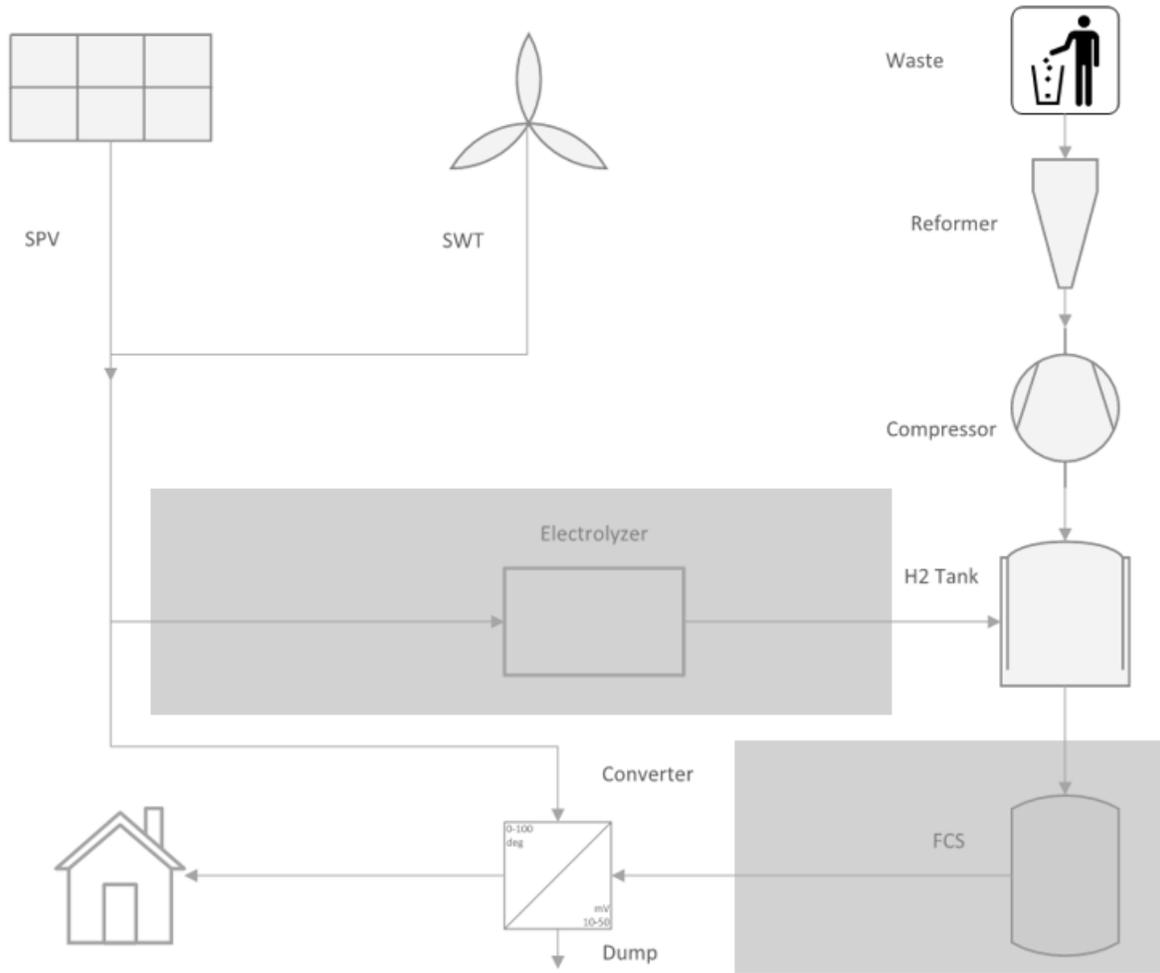


Figure 2. Power path of generation matches demand in SPV-SWT-FCS system.

B. Generation Exceeds Demand

In this situation, the power generated by SPV and SWT is more than demand. In addition to feeding the load, the remaining energy is transferred to the electrolyser. This part of energy breaks down the hydrogen in the water and stores it in the hydrogen tank with the hydrogen produced by the waste. The hydrogen in the tank is not transferred to the fuel cell because the yield is enough to support the load. When the hydrogen tank is filled, the excess power will be dumped. The path of the power is shown in Figure 3. The equations are as follow:

$$P_{re} = P_{pv} + P_{wt} \quad (11)$$

$$P_{re} = P_{re_inv} + P_{re_el} \quad (12)$$

$$P_{re_inv} = P_{inv_load} / \eta_{inv} \quad (13)$$

$$P_{el_tank} = P_{re_el} * \eta_{el} \quad (14)$$

$$P_{tank(i)} = P_{tank(i-1)} + P_{comp_tank(i)} + P_{el_tank(i)} \quad (15)$$

$$P_{tank_fc} = P_{fc_inv} = 0 \quad (16)$$

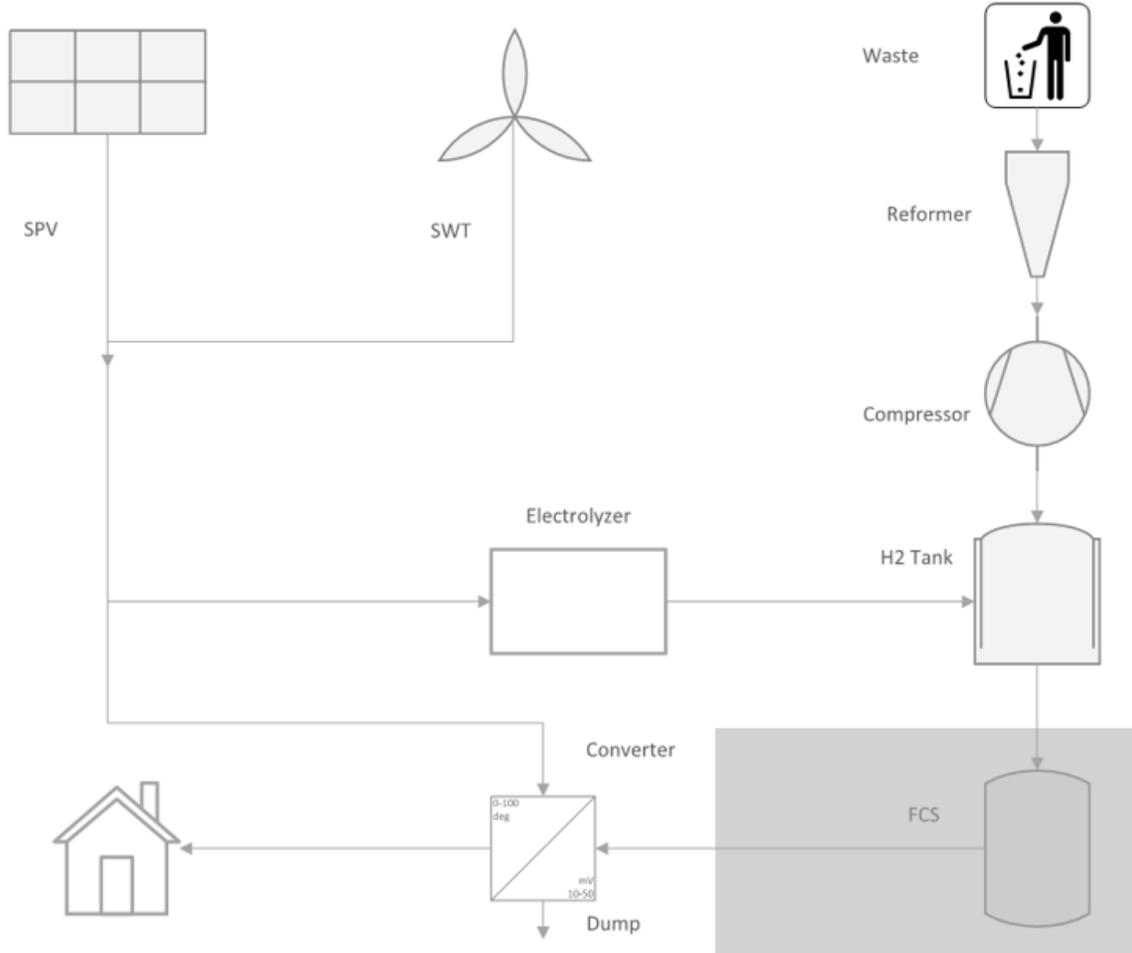


Figure 3. Power path of generation exceeds demand in SPV-SWT-FCS system.

C. Generation is Less than Demand

In this situation, the power generated by SPV and SWT is less than demand. When supply is low, hydrogen stored in the tank is transferred to the fuel cell and converted into power. At this point, all the power generated by the SPV and SWT is used by the load, so, there is no residual power

transferred to the electrolyzer. The path of the power is shown in Figure 4. The equations are as follow:

$$P_{re} = P_{pv} + P_{wt} \quad (17)$$

$$P_{re} = P_{re_inv} \quad (18)$$

$$P_{fc_inv} = \frac{P_{inv_load}}{\eta_{inv}} - P_{re_inv} \quad (19)$$

$$P_{tank_fc} = P_{fc_inv} / \eta_{fc} \quad (20)$$

$$P_{tank(i)} = P_{tank(i-1)} + P_{comp_tank(i)} - P_{tank_fc} \quad (21)$$

$$P_{re_el} = P_{el_tank} = 0 \quad (22)$$

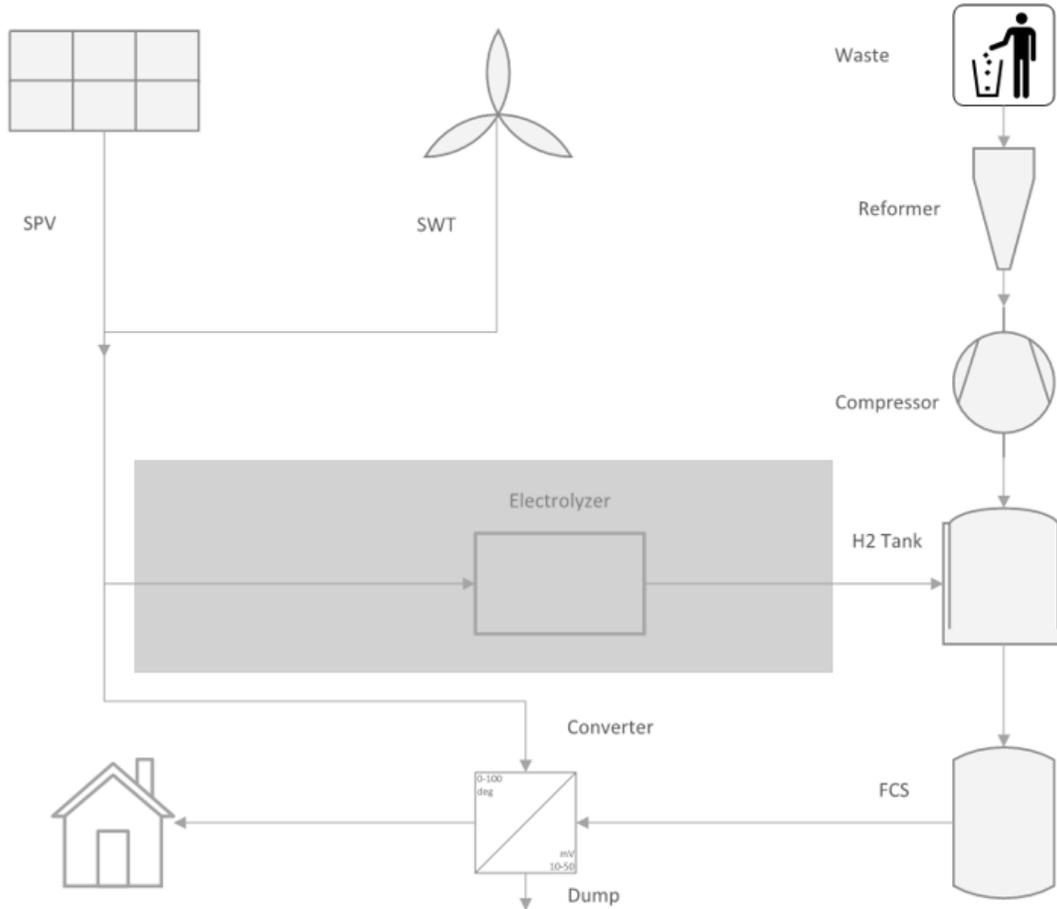


Figure 4. Power path of generation is less than demand in SPV-SWT-FCS system.

3.3 Methodology

System modeling will be carried out in Matlab R2017b and Visual Studio 2019 respectively. As the main data analysis software, Matlab can be used for a variety of data analysis methods, such as line graph analysis. Therefore, in the output results of Matlab model, there is an image output of data such as input and output of each small module. Since Visual Studio has no image output, the interface is much simpler and can be used in a variety of operating systems.

In this part, the optimization method, the objective functions and the system cost are explained. In addition, the initialization parameters and constraints are also included in this section.

A. Optimization Method

Removed due to copyright restriction (Yang, 2010) The goal is to find the optimal solution for all particles in a multi-dimensional hyper-volume. First, all particles in space are assigned initial random positions and initial random velocities. Then the position of each particle is advanced according to the velocity of each particle, the known optimal global position in the problem space and the known optimal position of the particle. As computation progresses, particles gather or aggregate around one or more optima by exploring and exploiting known vantage points in the search space. The mystery of the algorithm design lies in that it retains the best global position and the best-known position of the particle. However, it also has many disadvantages, such as poor local search ability and easy to fall into local extremum.

Removed due to copyright restriction (Hakimi, Tafreshi and Kashefi, 2007):

$$v_{k+1}^i = w_k v_k^i + c_1 r_1 (P_k^i - X_k^i) + c_2 r_2 (P_k^g - X_k^i) \quad (23)$$

The update formula of the d-dimensional position of particle i is as follows:

$$X_{k+1}^i = X_k^i + V_{k+1}^i \quad (24)$$

Removed due to copyright restriction (Yang, 2010). Increasing the speed constant can accelerate the convergence of the algorithm, but it will lead the algorithm to enter the local optimum early. Adding inertia weight can increase the "positivity" of particle detection in the new position, avoid falling into the local optimization too early, but also reduce the convergence speed of the algorithm.

In PSO, a local optimal location will be found by the system firstly and then recorded as a global optimal solution. After randomly moving to the next location, the algorithm compares the two

locations to find the new local optimal location and replaces the previous global optimal solution with the new local optimal location. Through constant comparison, the final global optimal configuration can be obtained.

In this study, the cognitive constant c_1 is assumed as 1 and the social constant c_2 is considered as 3. The inertia weight w is set to be 0.5, the population and generation are 100 and 200, respectively. The flowchart of the algorithm in Visual Studio 2019 is shown in Figure 5.

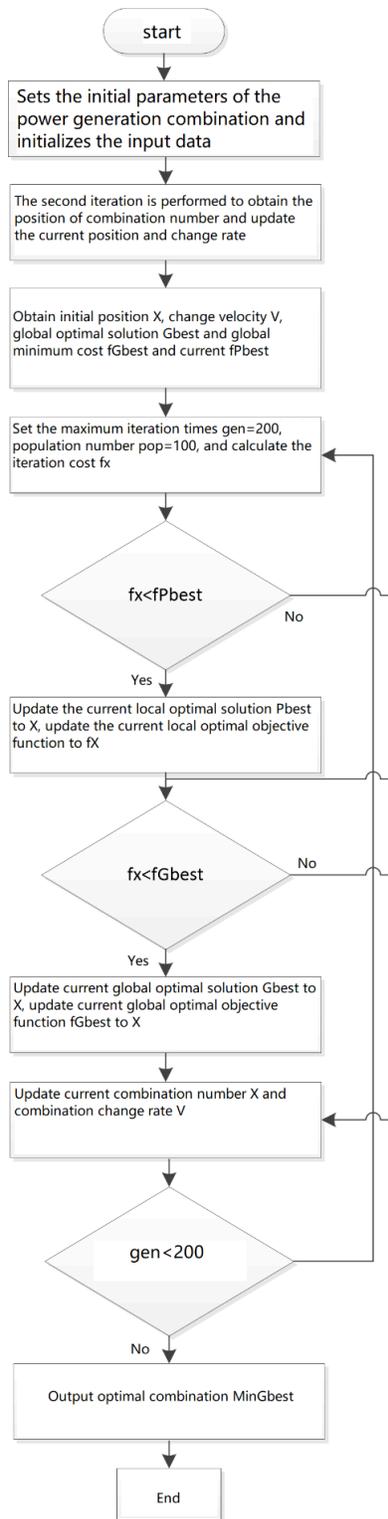


Figure 5. Flowchart of PSO.

B. Objective Functions

The system NPC should consider not only the capital cost of the system, but also the present value of all the costs of installation, replacement, and maintenance, minus the present value of all the revenues over the life of the project.

In this thesis, the expression of the system NPC is shown as follow:

$$NPC = N * (CPC + RPC + MPC) \quad (25)$$

where CPC is the capital present cost, RPC is the replacement present cost and MPC is the maintenance present cost.

For MPC, the interest rate i should be included during the project lifetime n . In the analysis, the interest rate is considered as 8%, and the lifetime of the project is 20 years. The calculation can be expressed as:

$$MPC = M * \frac{1}{CRF(i,n)} \quad (26)$$

where M is the annual maintenance cost. $CRF(i, n)$ is the capital recovery factor, which is the equivalent present value of annual cost. The equation is expressed as follow:

$$CRF(i, n) = \frac{i(i+1)^n}{(i+1)^n - 1} \quad (27)$$

For RPC, the interest rate i should be also included during the project lifetime n . The calculation can be expressed as:

$$RPC = R * \frac{1}{(i+1)^Y} \quad (28)$$

where R is the replacement cost and Y indicates the replacement year.

C. System Costs

Removed due to copyright restriction (Mulligan et al, 2015). The LCOE can be calculated by dividing lifetime costs by energy production. The expression related to the annual electricity demand $P_d(t)$ is shown as follow:

$$LCOE = \left(\frac{NPV}{\sum_1^{8760} P_d(t) * \Delta t} \right) * CRF(i, n) \quad (29)$$

D. Initialization Parameters

The input value of different components is listed in Table 1, including the nominal rated power, capital cost, replacement cost, operation and maintenance (OM) cost and lifetime of the components. Removed due to copyright restriction.

All the prices in this thesis are considered as Australian dollars, and the OM costs are annual payments. The capital cost of a 1-kW SPV is \$1,200 and the lifespan is 25 years. The capital cost of a 1-kW SWT is \$2,500 and the lifespan is 20 years. A 1-kW fuel cell with 5 years lifetime costs \$2,207.5 and the replacement and OM payments are \$1840 and \$44. The capital cost and the replacement cost of a 1-KW INV with 10 years lifespan are \$800 and \$500, respectively. A 1-KW electrolyser costs \$1,472, \$1104 and \$15 as the capital, replacement and OM cost. The lifecycle is around 15 years. The capital cost of a 1kilogram hydrogen tank with 20 years lifetime is \$971 and the OM cost is \$19. The reformer and the compressor are both with 20 years lifespan and the price are cheaper than the above equipment. The capital and replacement cost of a 1-kW reformer are both \$250, and the OM cost is \$12.5. The capital cost, replacement cost and the OM costs of a 1-kW compressor are \$10, \$10 and \$9, respectively.

Table 1. Initialization parameters of the SPV-SWT-FCS system.

	Rated Power	Capital cost	Replacement cost	OM cost	Lifetime
SPV	1 kW	1200	0	25	25 years
SWT	1 kW	2500	0	50	20 years
FCS	1 kW	2207.5	1840	44	5 years
INV	1 kW	800	500	0	10 years
Electrolyser	1 kW	1472	1104	15	15 years
H2 Tank	1 kg	971	0	19	20 years
Reformer	1 kW	250	250	12.5	20 years
Compressor	1 kW	10	10	9	20 years

E. Constraints

The number of components constrains in the system are displayed as follows:

$$0 \leq N_{pv} \leq N_{pv,max} \quad (30)$$

$$0 \leq N_{wt} \leq N_{wt,max} \quad (31)$$

$$0 \leq N_{fc} \leq N_{fc,max} \quad (32)$$

$$0 \leq N_{el} \leq N_{el,max} \quad (33)$$

$$0 \leq N_{tank} \leq N_{tank,max} \quad (34)$$

$$0 \leq N_{ref} \leq N_{ref,max} \quad (35)$$

$$0 \leq N_{comp} \leq N_{comp,max} \quad (36)$$

3.4 SPV-SWT-FCS Simulation Results

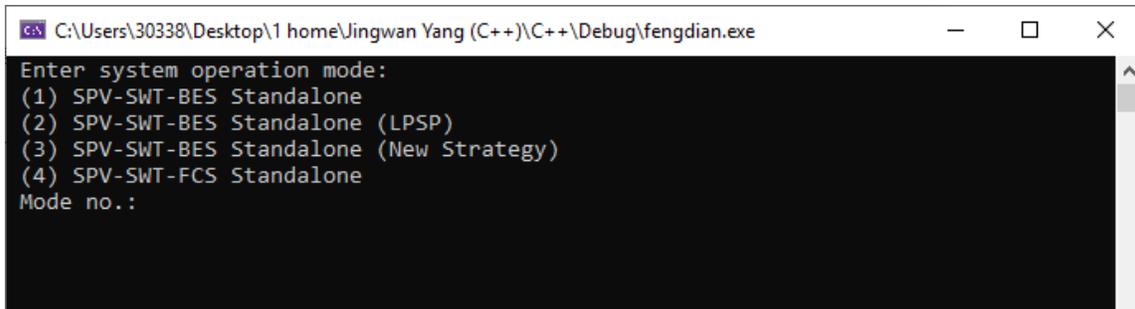
The aim of the project is to achieve an uninterrupted off-grid power supply in typical standalone households. Removed due to copyright restriction (Khezri, 2019).

A. Software Introduction

In the modeling process, MATLAB is used to model the configurations for ten households. The Visual Studio is for one household. Matlab can output data in the form of pictures to achieve data visualization, which is conducive to data analysis. Visual Studio has much faster computing power, which can get the simulation results faster.

The Visual Studio interface is simple. For the single energy storage system, there are four parts in the main program, including SPV-SWT-BES standalone, SPV-SWT-BES Standalone (LPSP), SPV-SWT-BES Standalone (New Strategy) and SPV-SWT-FCS Standalone configurations. Only case 1 and 4 are used in this simulation. Configuration 1 is for the battery system and configuration 4 is for the fuel cell system. The other two cases are reserved for future additional research.

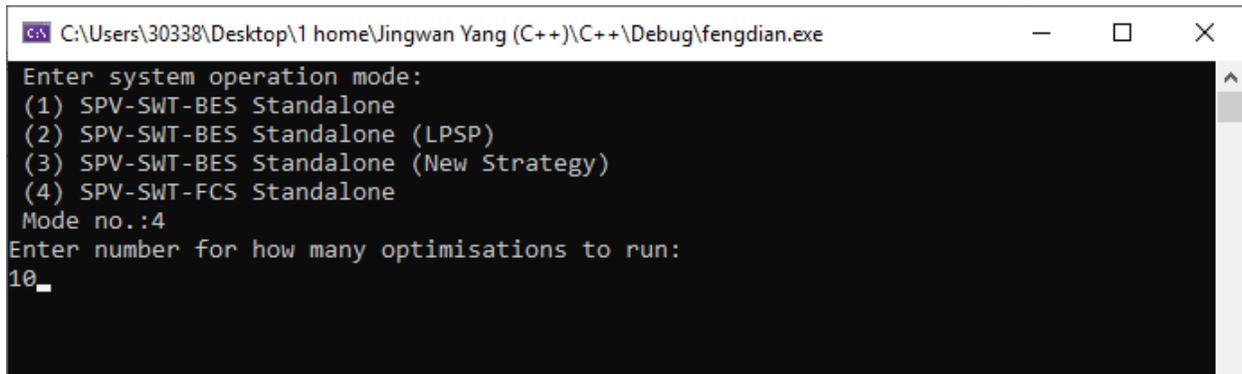
Firstly, after clicking 'Local Windows Debugger' in the software, these four options will be displayed in the command window.



```
C:\Users\30338\Desktop\1 home\Jingwan Yang (C++)\C++\Debug\fengdian.exe
Enter system operation mode:
(1) SPV-SWT-BES Standalone
(2) SPV-SWT-BES Standalone (LPSP)
(3) SPV-SWT-BES Standalone (New Strategy)
(4) SPV-SWT-FCS Standalone
Mode no.:
```

Figure 6. Visual Studio system selection operation interface.

The users can select either mode 1 or 4 and enter the number after ‘Mode no.’ After pressing enter on the keyboard, the system will prompt the user to select the number of iterations. The number of iterations is generally changed according to the scale calculated by the system. In this project, it is better to run ten times to get more accurate results.



```
C:\Users\30338\Desktop\1 home\Jingwan Yang (C++)\C++\Debug\fengdian.exe
Enter system operation mode:
(1) SPV-SWT-BES Standalone
(2) SPV-SWT-BES Standalone (LPSP)
(3) SPV-SWT-BES Standalone (New Strategy)
(4) SPV-SWT-FCS Standalone
Mode no.:4
Enter number for how many optimisations to run:
10_
```

Figure 7. Visual Studio iteration times selection interface.

The system will automatically calculate in the background and display the result in the operation window.

```

-----
Optimised System Energy Balance
-----
PV Generation          = 1.57 MWh
Wind turbine Generation = 12.31 MWh
Compressor Generation  = 1.50 MWh
Reformer Generation    = 1.50 MWh
-----
Electricity Load Demand = 6.15 MWh
Electricity Charging Fuel Cell = 5.03 MWh
Electricity Discharging Fuel Cell = 2.51 MWh
Electricity Fuel Cell Losses = 2.51 MWh
Electricity Dump        = 3.88 MWh
-----
Net Electricity Energy Balance = 5.22 MWh
-----

Optimised System Configuration
-----
No. of PV          = 1.00
No. of WT          = 6.00
No. of Fuel Cells   = 2.00
No. of Inverters    = 4.00
No. of Electrolyzers = 1.00
No. of Tanks       = 1.00
No. of Reformers    = 1.00
No. of Compressors  = 1.00

```

Figure 8. Visual Studio result interface.

Matlab has an operation interface similar to Visual Studio. The operation interface is shown in Figure 9 below. Detailed operation methods are described in the Appendix A and Appendix B.

```

Command Window
Enter system operation mode:
(1) SPV-SWT-BES Standalone
(2) SPV-SWT-BES Standalone (LPSP)
(3) SPV-SWT-BES Standalone (New Strategy)
(4) SPV-SWT-FCS Standalone
Mode no.: 4
Enter number for how many optimisations to run:
fx 10|

```

Figure 9. Matlab operation interface.

B. Optimization Results

The results of different components are listed in Table 2. The left side of the table shows the input values of the system, and the right side is the simulation outputs. The load data in the simulation

is based on the real electricity utilization of 10 family in remote area of SA. From the table, to achieve an uninterruptible off-grid power supply, the SPV, SWT and FCS have capacities of 37 kW, 16 kW and 17 kW, respectively. In the simulation, the INV's capacity is set to 18 kW due to South Australian policy limitations. The capacities of the electrolyser, reformer and compressor are all 40 kW. The storage mass of the hydrogen tank is 65 kilograms. The annual energy generation of SPV and SWT are 75.92MWh and 25.14MWh. The energy from the solid waste is 15MWh per year. The NPCs of SPV and SWT are \$53,481.79 and \$47,854.52. The NPC of the fuel cell is \$90,509.57. \$18,568.74, \$78,691.96, \$75,240.41, \$745.45 and \$196.73 are for the inverter, electrolyser, hydrogen tank, reformer and compressor, respectively. The total system NPC is \$365,289.17 and the LCOE of the hybrid system is cents 60.52/kWh.

Table 2. Simulation results of SPV-SWT-FCS configuration.

	Rated Power	Capital cost	Replacement cost	OM cost	Lifetime	Capacity	Energy generation	NPC
SPV	1 kW	1,200	0	25	25 years	37 kW	75.92MWh	\$ 53481.79
SWT	1 kW	2500	0	50	20 years	16 kW	25.14MWh	\$ 47854.52
FCS	1 kW	2207.5	1840	44	5 years	17 kW	N/A	\$ 90509.57
INV	1 kW	800	500	0	10 years	18 kW	N/A	\$ 18568.74
Electrolyser	1 kW	1472	1104	15	15 years	40 kW	N/A	\$ 78691.96
Tank	1 kg	971	0	19	20 years	65 kg	N/A	\$ 75240.41
Reformer	1 kW	250	250	12.5	20 years	2 kW	15.00MWh	\$ 745.45
Compressor	1 kW	10	10	9	20 years	2 kW	N/A	\$ 196.73
Total	N/A	N/A	N/A	N/A	N/A	N/A	N/A	\$ 365289.17
LCOE	N/A	N/A	N/A	N/A	N/A	N/A	N/A	¢ 60.52/kWh
Dump Energy	N/A	N/A	N/A	N/A	N/A	33.22MWh	N/A	N/A

In the simulation, the more complex the calculation, the more iterations are required. If there are not enough iterations, the system may fall into a local optimal solution. As shown in Figure 10, after ten times of iterations, the smallest NPC will be selected as the global optimal solution.

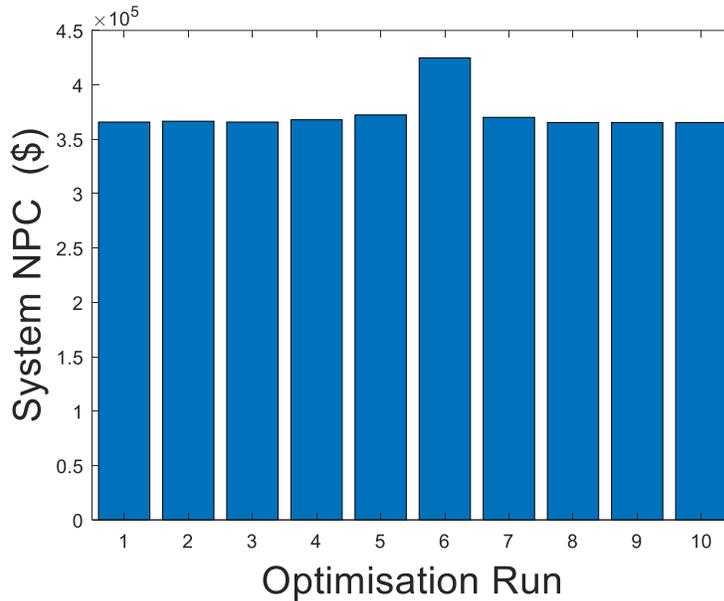


Figure 10. Ten iterations of the system NPC in SPV-SWT-FCS system.

Figure 11 and Figure 12 show the information of the simulation results of the power demand and the generation related to 8,760 hours (1 year) and 24 hours (1 day). The average annual electricity consumption is around 61.48MWh. It can be seen from the distribution diagram of the yearly consumption that, in winter and summer, due to the use of air conditioning and other electric appliances that consume a lot of electricity, the electricity consumption of the family increases significantly. Annual SPV production drops to less than 10 kW in winter and increases to nearly 13 kW in summer. Since wind speeds are relatively stable throughout the year in remote areas of South Australia, the power of SWT is very stable, maintaining around 32 kW. The annual power of renewable indicates the sum of SPV and SWT power generation, about 45 kW. This figure is much higher than the total annual demand, so it is clear that some of the output will be dumped. As can be seen from the 24-hour average demand chart, the highest consumption occurs between 17pm and 20pm, with a maximum of 11 kW. During that time, however, the SPV's output drops almost to 1 kW due to a lack of solar insolation. SWT generates more power during these two hours due to higher night wind speeds, up to nearly 10 kW. By comparing the two charts of average

daily demand and renewable output, the daily electricity output basically meets the electricity demand of users. It can be seen that the hybrid power generation system can make up for the disadvantages caused by the different time periods of solar and wind power generation and make the power supply more stable.

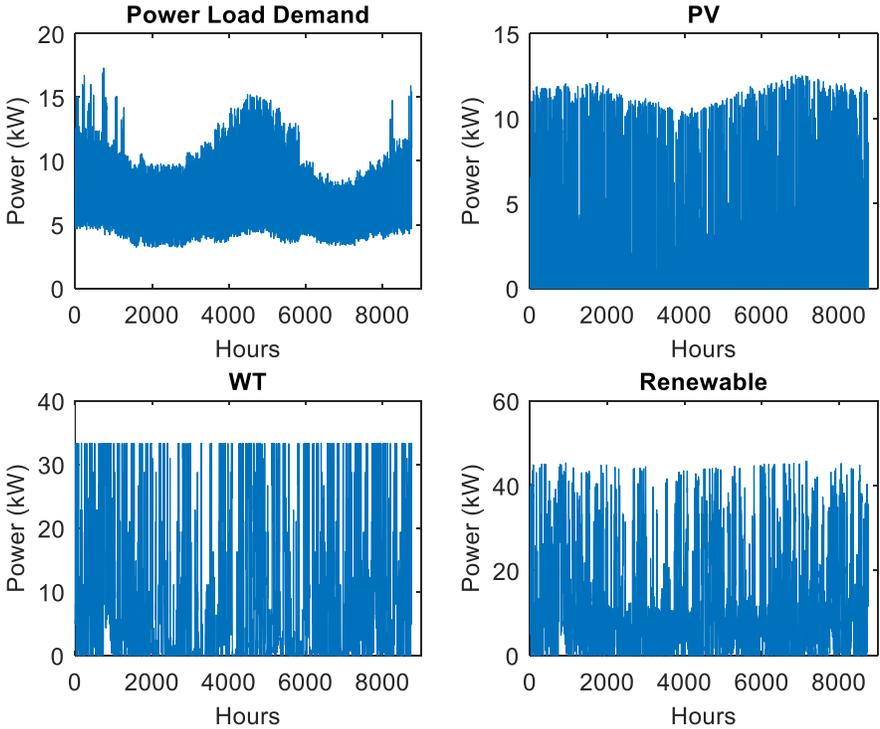


Figure 11. Simulation results of demand, SPV, SWT and renewable generation (8760 hours) in SPV-SWT-FCS system.

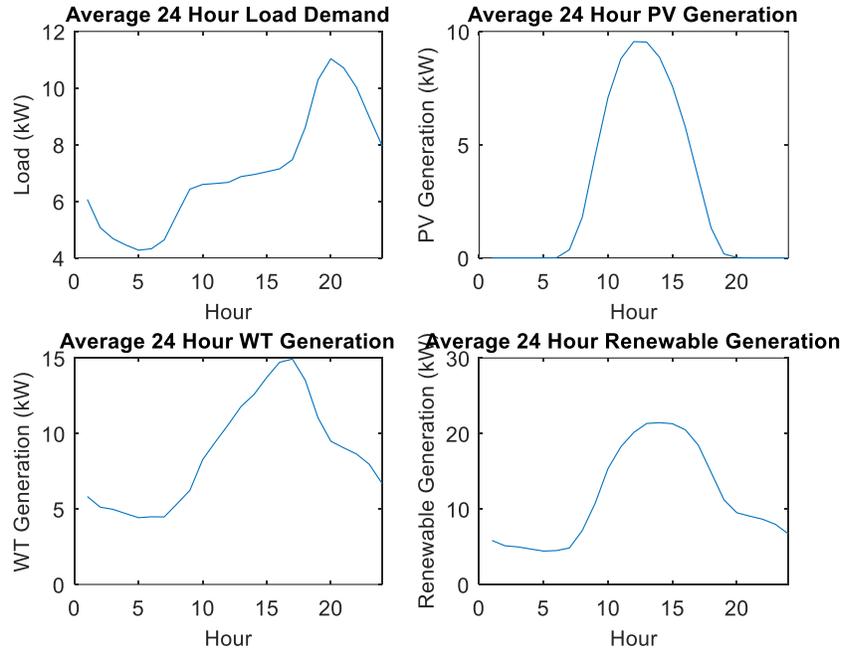


Figure 12. Simulation results of demand, SPV, SWT and renewable generation (24 hours) in SPV-SWT-FCS system.

Figure 13 shows the trend of the system NPC with the generation, which is the maximum number of iterations. In the analysis, the generation is set to be 200. The system NPC decreases from a high level to less than \$500,000 after 40 generations. The drop of the system NPC represents that the PSO algorithm is comparing to find the optimal configuration. As the system selects random numbers by default for calculation in PSO, if the number of iterations is insufficient, the result may fall into the local optimal solution instead of the global optimal solution. When the NPC arrived at a constant level, it means the PSO algorithm found the global optimal combination.

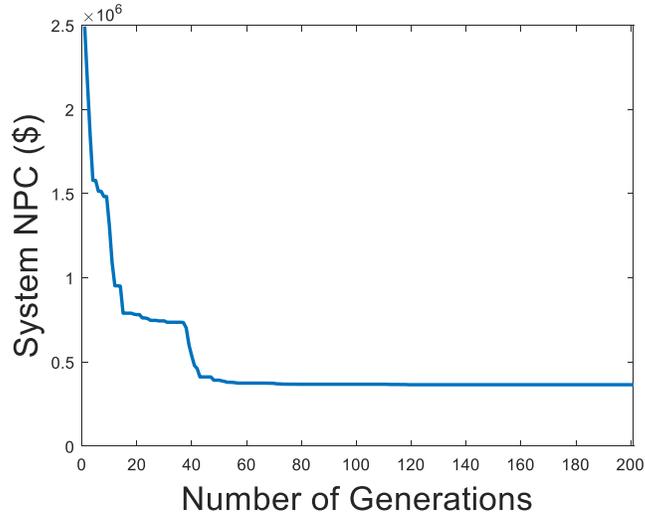


Figure 13. Relationship between generations and system NPC in the simulation in SPV-SWT-FCS system.

Figure 14 shows the comparison between the power consumed by the load and the power output from the inverter to the load. It can be seen that the two results are consistent, which proves that the system meets the requirements of uninterrupted power supply.

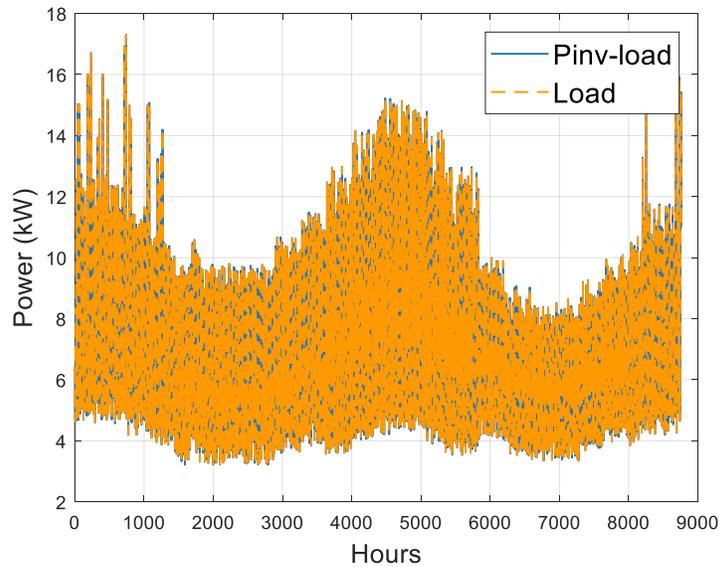


Figure 14. Simulation results of load consumption and the output of inverter in SPV-SWT-FCS system.

Figure 15 shows the relationship between total generation power, fuel cell output power and load consumption power. As can be seen from the diagram, the total power generation is around 40 kW and is on average higher than the load demand, which is approximately 15 kW. The extra power

of the system will be dumped. From the simulation result, the dumped power keeps at a low level, and the dump energy is only 33.22MWh per year, which is around 28.6% of the total generation. The dumped power can be found in Figure 16.

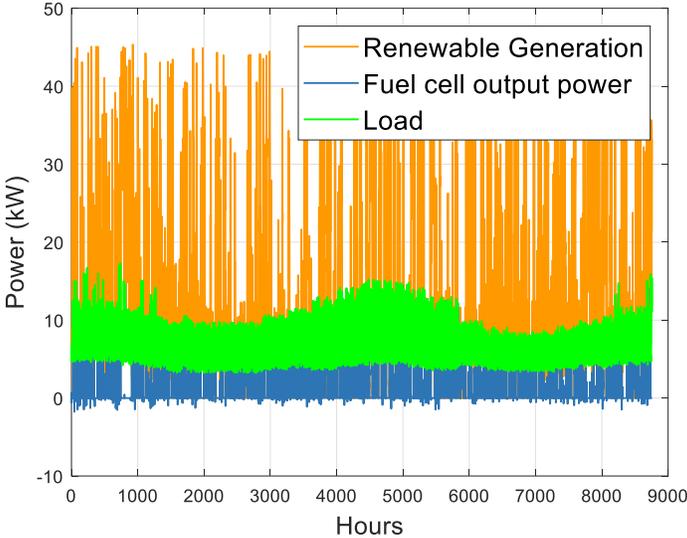


Figure 15. Simulation results of generation, fuel cell output and the load power in SPV-SWT-FCS system.

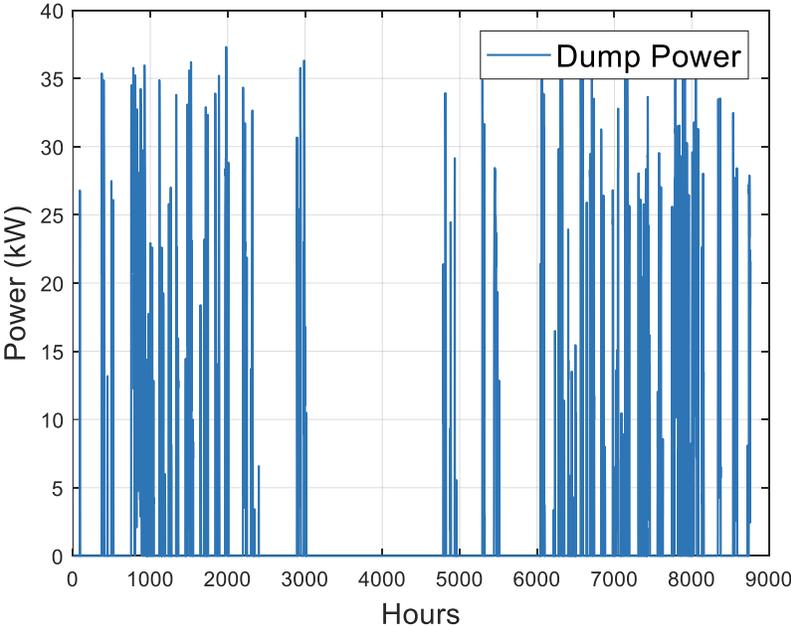


Figure 16. Simulation results of dumped power in SPV-SWT-FCS system.

The following four figures show the information of the power delivered from SPV, SWT to electrolyser, from electrolyser to hydrogen tank, from hydrogen tank to fuel cell and from fuel cell to inverter, respectively. Since the value of the load reserve is set in the model, you can see in Figure 19 and Figure 20 that the power is less than zero. It can be seen from Figure 20 that the output of fuel cells increases significantly in summer and winter, which is the same as the growth trend of load demand power.

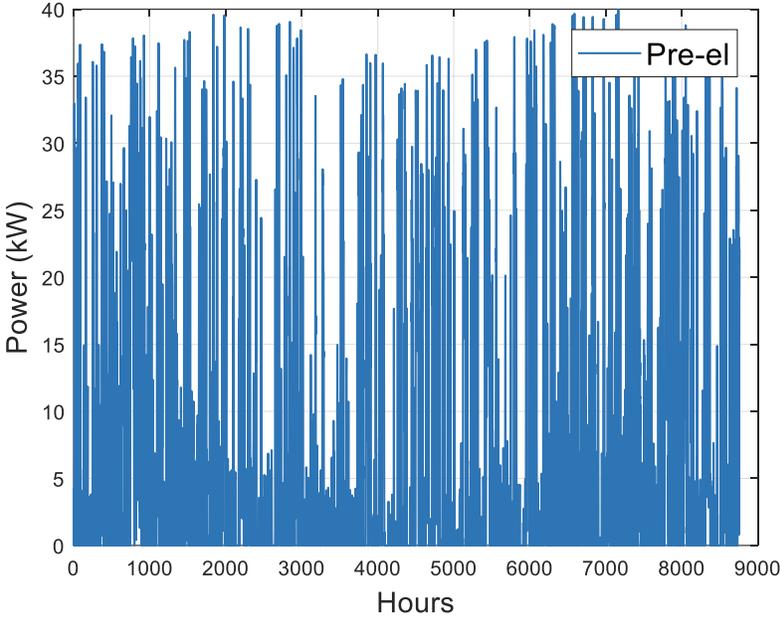


Figure 17. Power delivered from SPV, SWT to electrolyser in SPV-SWT-FCS system.

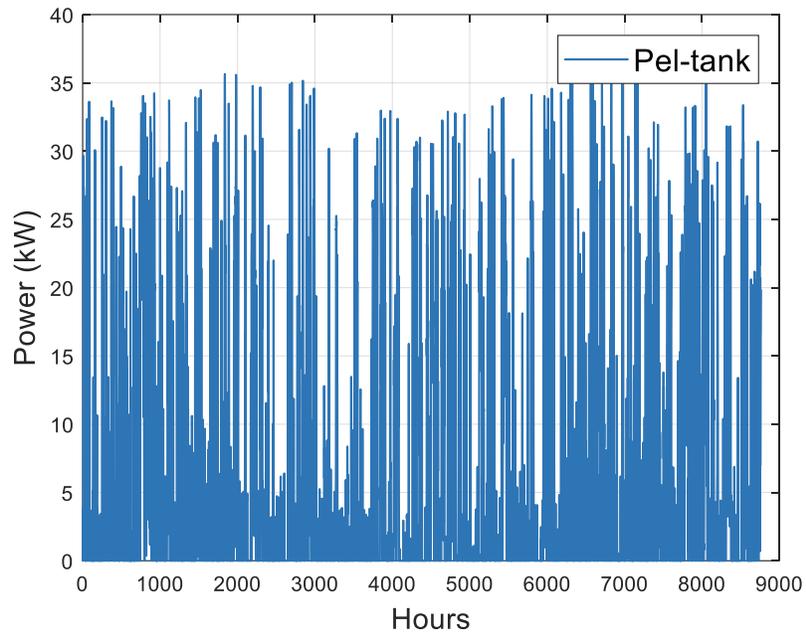


Figure 18. Power delivered from electrolyser to hydrogen tank in SPV-SWT-FCS system.

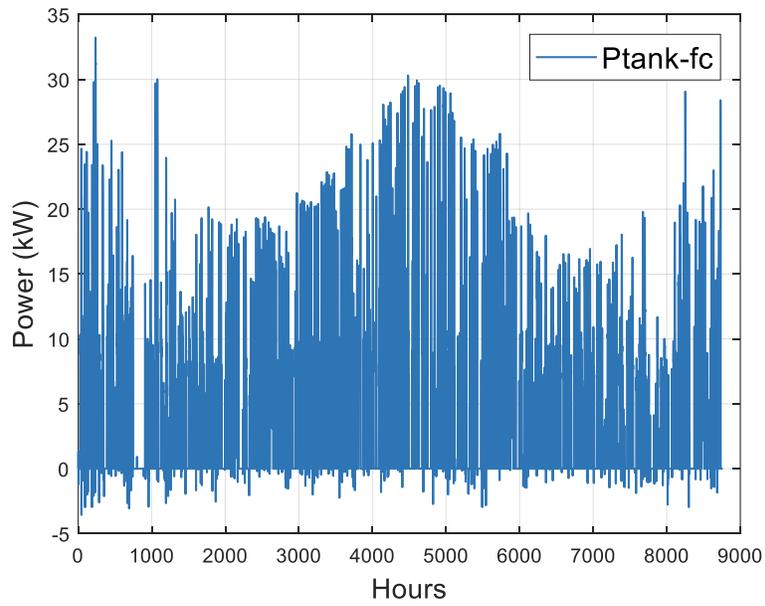


Figure 19. Power delivered from hydrogen tank to fuel cell in SPV-SWT-FCS system.

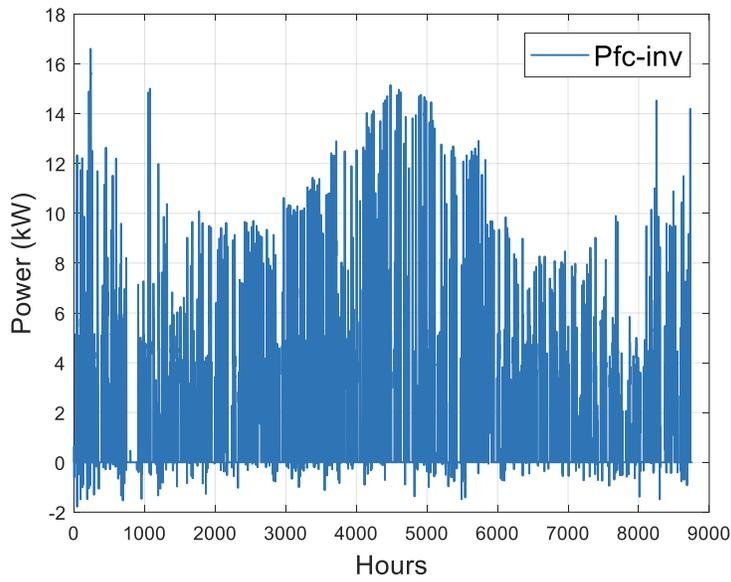


Figure 20. Power delivered from fuel cell to inverter in SPV-SWT-FCS system.

Figure 21 shows the NPCS for each component of the system. SWT and FCS account for more than half of the system's total NPC. Following by the INV, which accounts for almost a quarter of the total. Compared to these three, the proportions of other components are small. Especially for reformer and compressor, it takes only about five percent. From the NPC ratio of these components, SWT and FCS have the greatest impact on the NPC of the system. Therefore, reducing the price of these two items is especially important to improve the cost performance of the system.

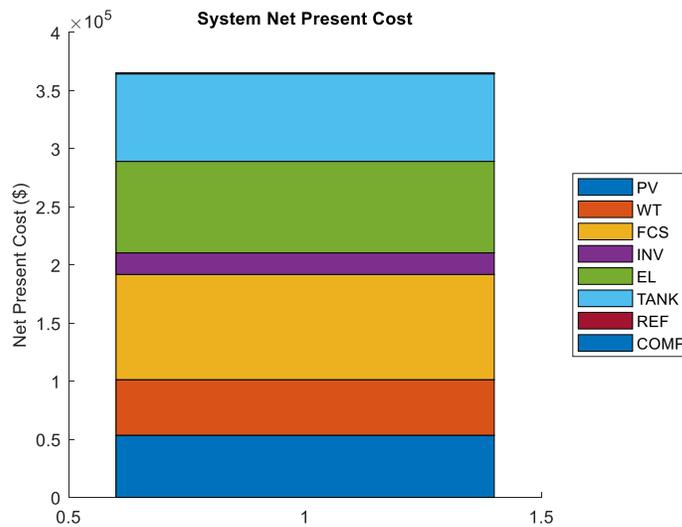


Figure 21. Simulation results of system NPC in SPV-SWT-FCS system.

C. Sensitivity Analysis

The sensitivity analysis of the system LCOE will be displayed by changing the costs of the main components in this section.

When the cost of SPV, SWT and FCS component in the system is reduced, the impact on the system LCOE is different. In the sensitivity analysis, the change in price is from a 50% reduction in the base price to 40% increase. The sensitivity analysis graph is shown below. As can be seen from Figure 22, the biggest impact on the system LCOE is the fuel cell, followed by the SPV unit. SWT components have the least effect on the system.

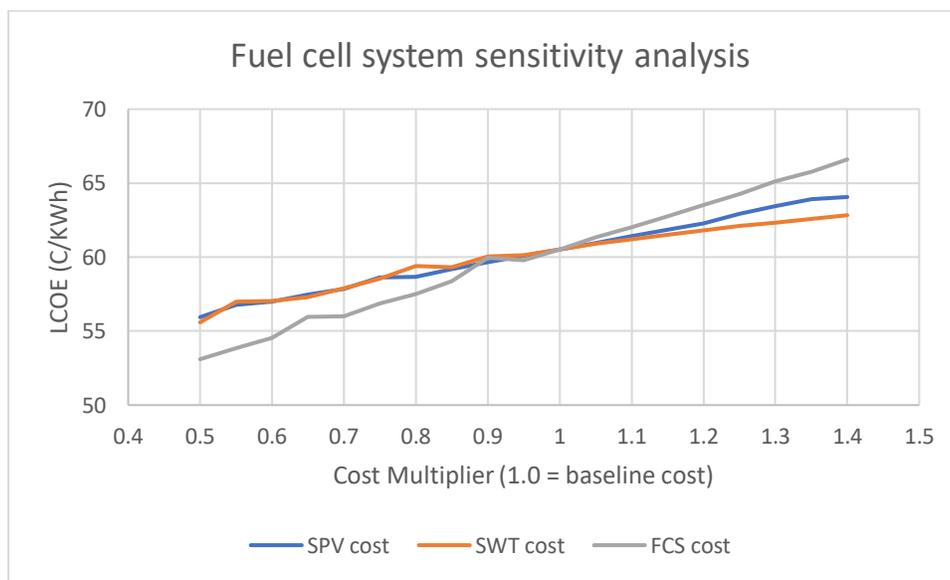


Figure 22. System LCOE sensitivity analysis of fuel cell configuration.

3.5 SPV-FCS and SWT-FCS Systems

In the configuration of fuel cell storage system, a single power generation method, namely SPV-FCS and SWT-FCS, can be used. This part will simulate the above two configurations and the comparison with the SPV-SWT-FCS system will be displayed in the later section. In this part, the components number limitations are ignored, and the results are only for data comparison.

A. SPV-FCS system

When the number of SWT in the system is limited to 0, only SPV is used to generate electricity. According to the 24-hour demand analysis in Figure 12 in the previous section, the average peak household electricity consumption is between 5 p.m. and 8 p.m. If the number of SPV remains the

same, the power supply will be insufficient. Therefore, the capacity of storage system will be increased to support the load. Due to the high number of hydrogen tanks, the NPC of the system will also increase significantly. The simulation results of the SPV-FCS configuration are shown in Table 3. The NPC of the hydrogen tanks is increased to a high level, which \$129,645.02. The total system NPC is up to \$394,564.75. However, due to the increase of the hydrogen tank, the dumped energy decreases to 27.6MWh. The following results are obtained after 10 iterations of the system.

Table 3. Simulation results of SPV -FCS configuration.

	Rated Power	Capital cost	Replacement cost	OM cost	Lifetime	Capacity	NPC
SPV	1 kW	\$1200	0	25	25 years	50 kW	\$ 72272.68
SWT	1 kW	\$2500	0	50	20 years	N/A	N/A
FCS	1 kW	2207.5	1840	44	5 years	17 kW	\$ 90509.57
INV	1 kW	800	500	0	10 years	18 kW	\$ 18568.74
Electrolyser	1 kW	1472	1104	15	15 years	42 kW	\$ 82626.56
Tank	1 kg	\$971	0	\$19	20 years	112 kg	\$ 129645.02
Reformer	1 kW	\$250	\$250	\$12.5	20 years	2 kW	\$ 745.45
Compressor	1 kW	\$10	\$10	\$9	20 years	2 kW	\$ 196.73
Total	N/A	N/A	N/A	N/A	N/A	N/A	\$ 394564.75
LCOE	N/A	N/A	N/A	N/A	N/A	N/A	¢ 65.37/kWh
Electricity dump	N/A	N/A	N/A	N/A	N/A	27.60MWh	N/A

B. SWT-FCS system

As can be seen from the simulation results in Table 4, the total system NPC is increased to \$557,544.93, comparing with the SPV-SWT-FCS system. The dumped energy also becomes more, which is 60.62MWh per year. The following results are obtained after 10 iterations of the system.

Table 4. Simulation results of SWT -FCS configuration.

	Rated Power	Capital cost	Replacement cost	OM cost	Lifetime	Capacity	NPC
SPV	1 kW	\$1200	0	25	25 years	N/A	N/A
SWT	1 kW	\$2500	0	50	20 years	90 kW	\$ 269181.66
FCS	1 kW	2207.5	1840	44	5 years	18 kW	\$ 95833.66
INV	1 kW	800	500	0	10 years	18 kW	\$ 18568.74
Electrolyser	1 kW	1472	1104	15	15 years	65 kW	\$ 127874.44
Tank	1 kg	\$971	0	\$19	20 years	39 kg	\$ 45144.25
Reformer	1 kW	\$250	\$250	\$12.5	20 years	2 kW	\$ 745.45
Compressor	1 kW	\$10	\$10	\$9	20 years	2 kW	\$ 196.73
Total	N/A	N/A	N/A	N/A	N/A	N/A	\$ 557544.93
LCOE	N/A	N/A	N/A	N/A	N/A	N/A	¢92.37/kWh
Electricity dump	N/A	N/A	N/A	N/A	N/A	60.62MWh	N/A

Chapter 4

IV. SPV-SWT-BES System Modelling

4.1 SPV-SWT-BES System Configuration

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To store the remaining charge, another efficient configuration is to use a battery. This configuration has fewer components and is easier to install. The system is mainly composed of SPV, SWT, BES and INV, as shown in Figure 23. The difference between the two configurations is that when there is excess power, the fuel cell system converts it into hydrogen and stores it in a hydrogen tank. When the supply is insufficient, the hydrogen is delivered from hydrogen tank to fuel cell and converted into power by the fuel cell. Hence, the fuel cell system is one-way transmission. However, in the method that the battery is configured, the remaining power is charged to the battery first. When the supply is insufficient, the battery discharge to replenish the load consumption. The battery is in the state of repeated charging and discharging, and it is a two-way transmission.

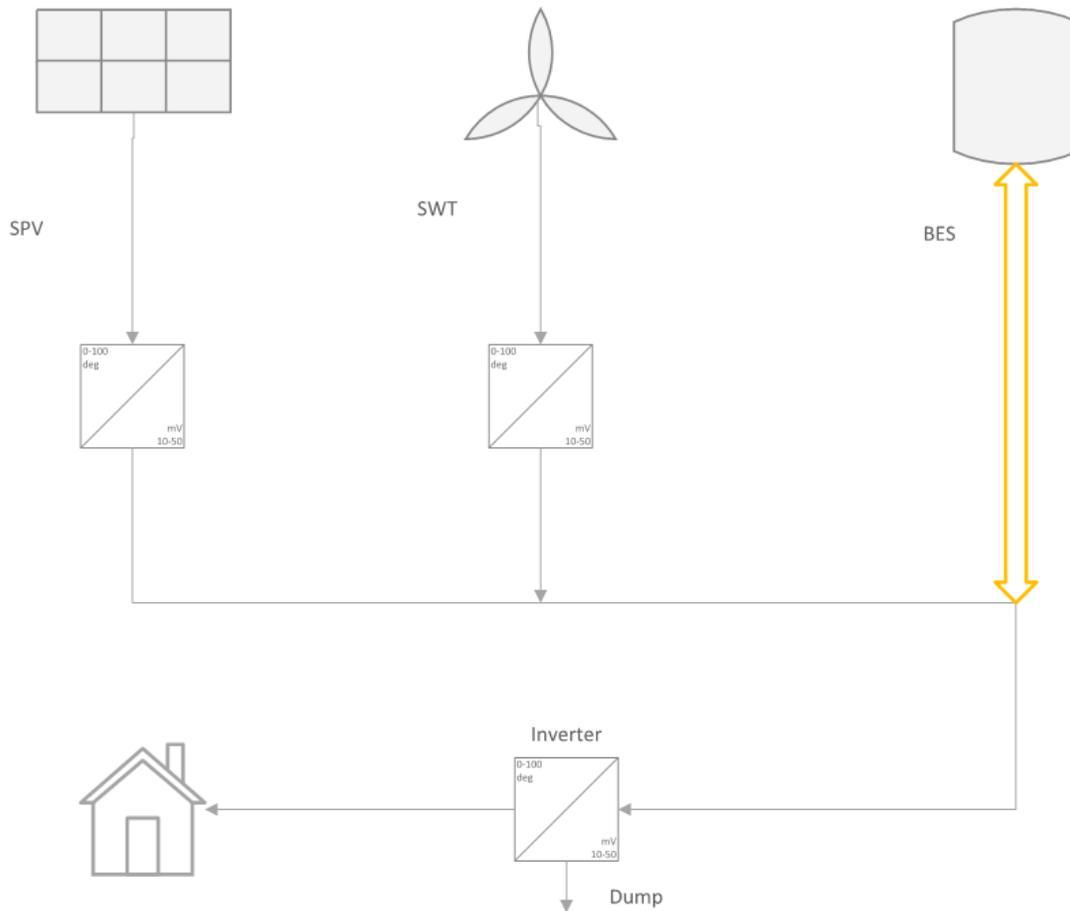


Figure 23. Configuration of SPV-SWT-BES system.

4.2 SPV-SWT-BES Hybrid System Analysis

The SPV-SWT-BES system can also be divided into three situations: (1) generation = demand (2) generation > demand (3) generation < demand.

A. Generation Matches Demand

In this situation, the power generated by SPV and SWT is transited to the load through the inverter and just enough to support the load. There is no power through the battery. The path of the power is shown in Figure 24.

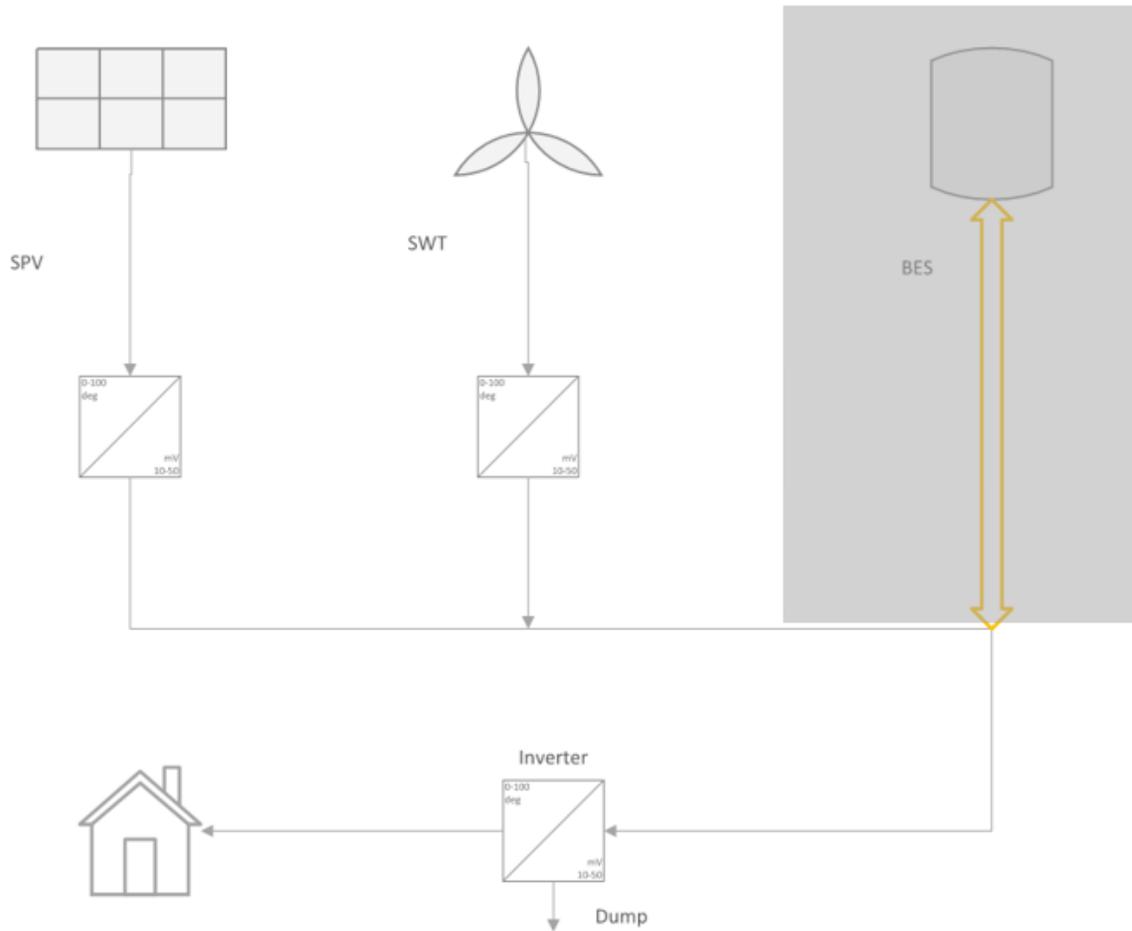


Figure 24. Power path of generation matches demand in SPV-SWT-BES system.

B. Generation Exceeds Demand

In this situation, the power generated by SPV and SWT is more than demand. In addition to feeding the load, the remaining energy is to charge the battery. When battery is filled, the excess power will be dumped. The path of the power is shown in Figure 25.

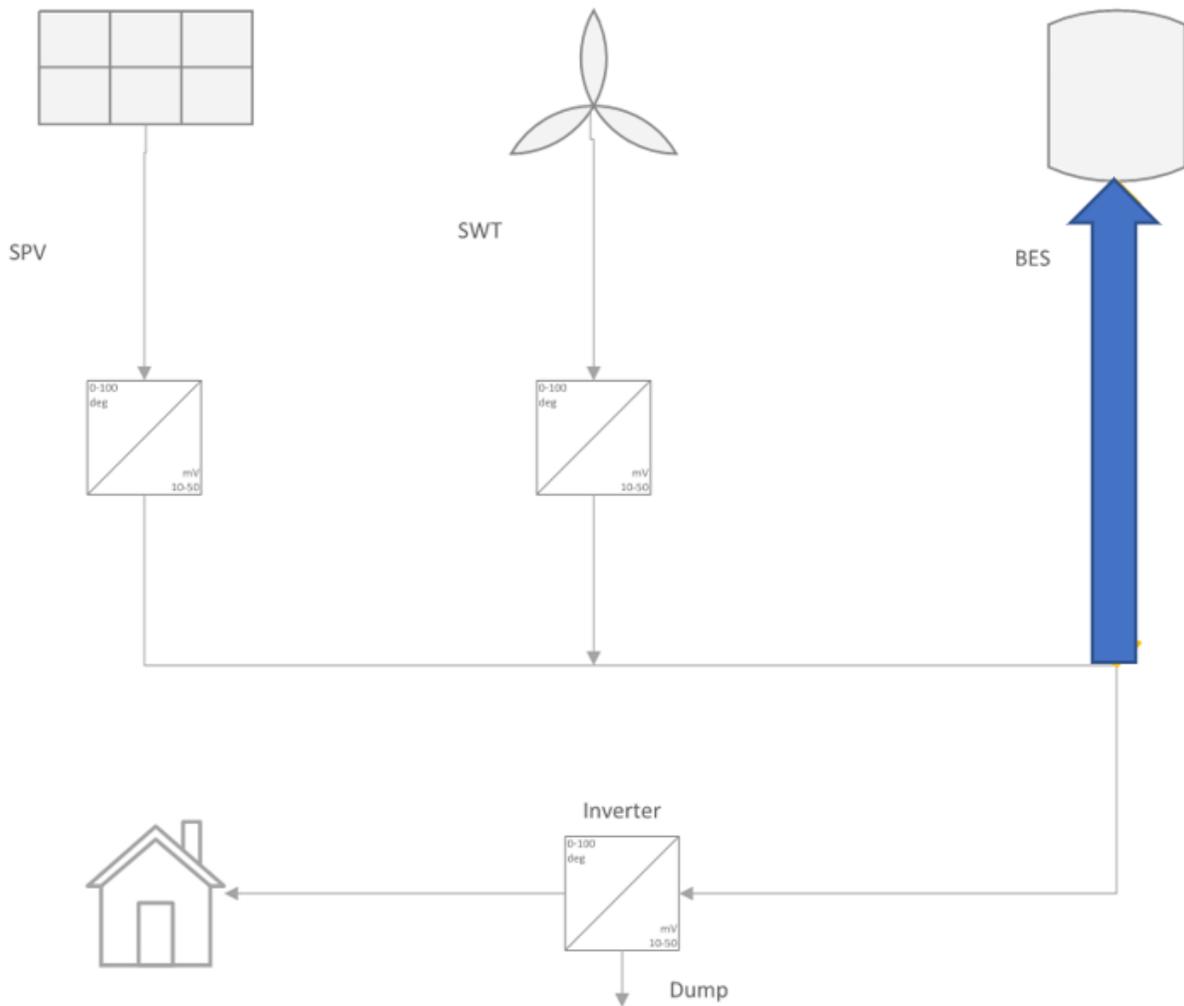


Figure 25. Power path of generation exceeds demand in SPV-SWT-BES system.

C. Generation is Less than Demand

In this situation, the power generated by SPV and SWT is less than demand. When supply is low, the battery is discharging to support the load. The path of the power is shown in Figure 26.

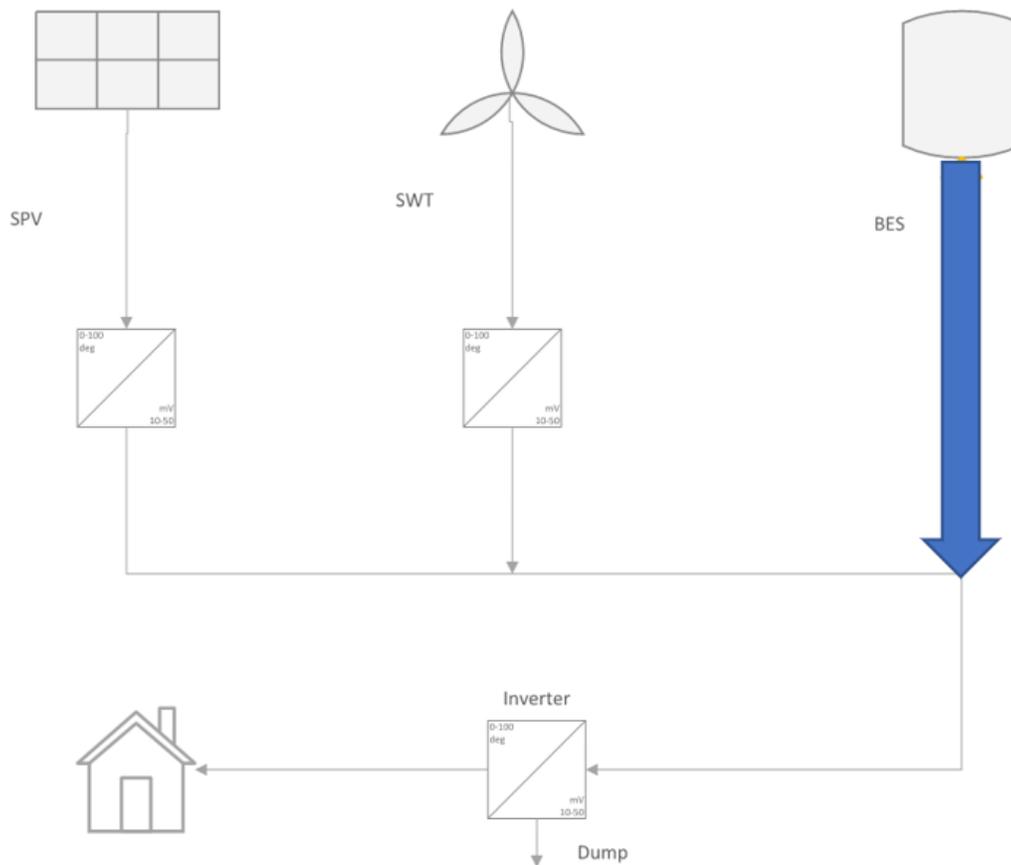


Figure 26. Power path of generation is less than demand in SPV-SWT-BES system.

4.3 SPV-SWT-BES Simulation Results

A. Optimization Results

The input data and the simulation results of different components are listed in Table 5. The left side of the table shows the input values of the system, and the right side is the simulation outputs. Since the SPV and the SWT are with a lifetime of 20 years, which is the same as the project lifespan, no replacement costs are incurred during this time. Removed due to copyright restriction (2019).

The capital cost of a 1-kW SPV is \$1,200 and the lifespan is 25 years. The capital cost of a 1-kW SWT is \$2,500 and the lifespan is 20 years. A 1-kW battery with 10 years lifetime costs \$600 and

the replacement payment is \$400. The capital cost and the replacement cost of a 1-kW INV with 10 years lifespan are \$800 and \$500, respectively.

From Table 5, to achieve an uninterruptible off-grid power supply, the SPV, SWT and BES have capacities of 62 kW, 18 kW and 288 kW, respectively. In the simulation, the INV's capacity is set to 18 kW. The NPCs of SPV and SWT are \$89,618.13 and \$53,836.33. The NPC of the battery is the highest, which is \$254,436.15. The NPC of inverters is \$18,568.74. The total system NPC is \$416,459.36 and the LCOE of the hybrid system is cents69.00/kWh. The dump energy is up to 69.74MWh, which leads to more electricity generation components and a high system NPC.

Table 5. Simulation results of the SPV-SWT-BES system.

	Rated Power	Capital cost	Replacement cost	OM cost	Lifetime	Capacity	NPC
SPV	1 kW	1200	0	25	25 years	62 kW	\$ 89618.13
SWT	1 kW	2500	0	50	20 years	18 kW	\$ 53836.33
BES	1 kW	600	400	10	10 years	288 kW	\$ 254436.15
INV	1 kW	800	500	0	10 years	18 kW	\$ 18568.74
Total	N/A	N/A	N/A	N/A	N/A	N/A	\$ 416459.36
LCOE	N/A	N/A	N/A	N/A	N/A	N/A	¢69.00/kWh
Dump Energy	N/A	N/A	N/A	N/A	N/A	69.74 MWh	N/A

Figure 27 shows the relationship between total generation power, battery output power and load consumption power. As can be seen from the diagram, the total power generation is around 60 kW and is much higher than the load demand, which is approximately 13 kW. The extra power of the system will be dumped. From the simulation result, the dumped power is around 50kW, and the dumped energy is 69.74 MWh per year. The dumped power can be found in Figure 28.

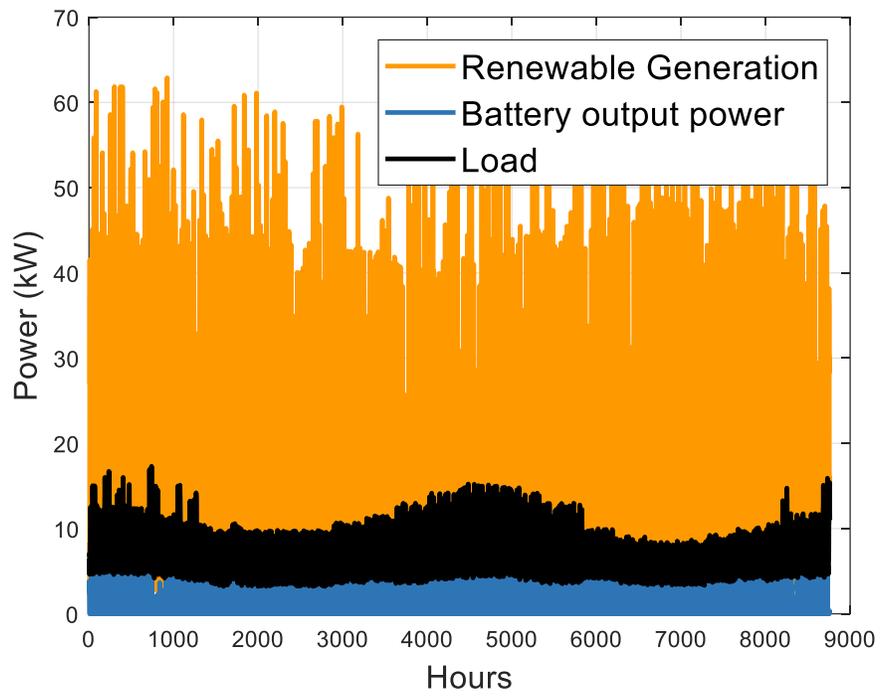


Figure 27. Simulation results of generation, battery output and the load power.

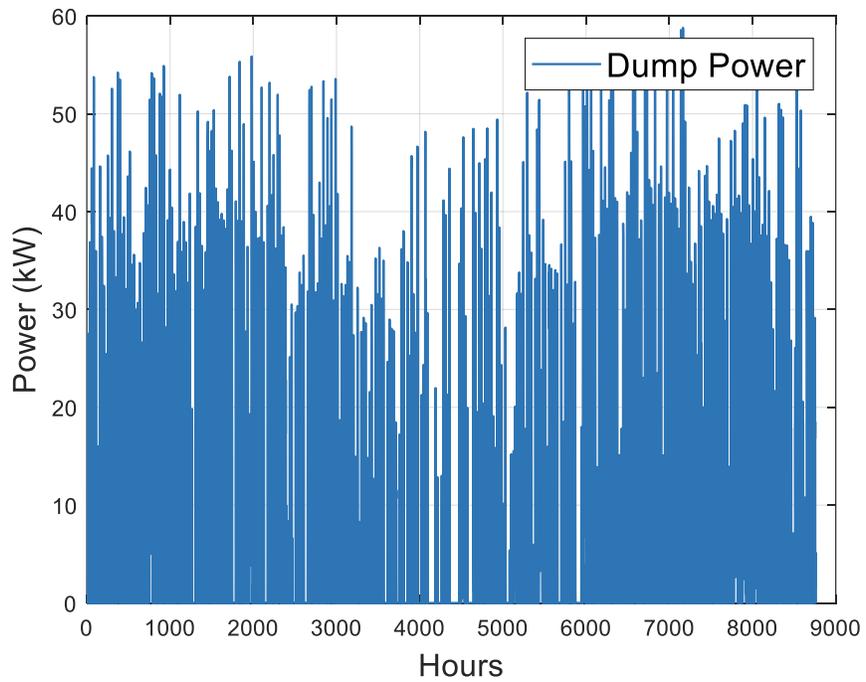


Figure 28. Simulation results of dumped power in SPV-SWT-BES system

Figure 29 shows the NPCS for each component of the system. FCS accounts for nearly half of the system's total NPC. The second largest number can be found in SPV, following by the INV.

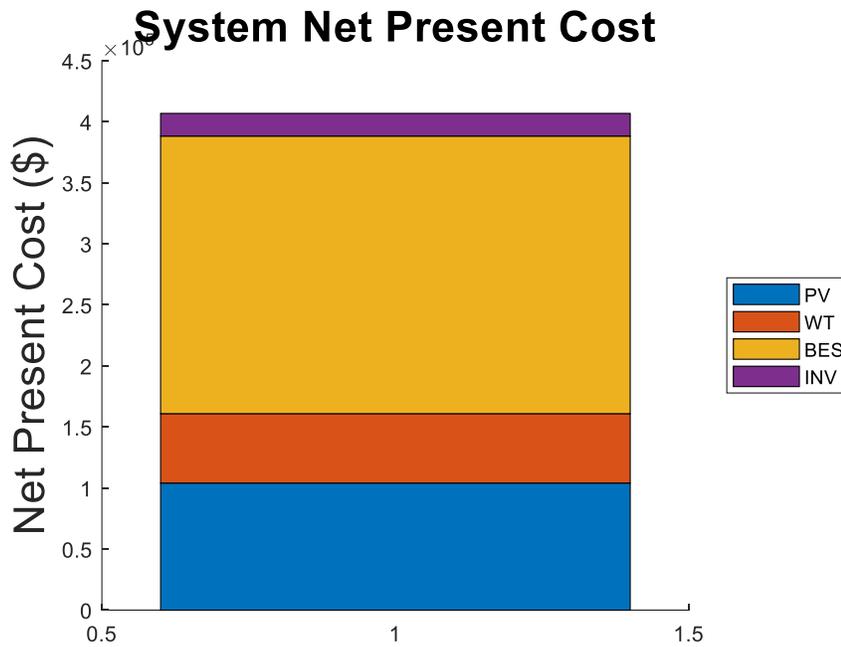


Figure 29. Simulation results of system NPC in SPV-SWT-BES system.

B. Sensitivity Analysis

The sensitivity analysis of the system LCOE will be displayed by changing the costs of the main components in this section.

When the cost of SPV, SWT and FCS component in the system is reduced, the impact on the system LCOE is different. In the sensitivity analysis, the change in price is from a 50% reduction in the base price to 40% increase. The sensitivity analysis graph is shown below. As can be seen from Figure 30, the biggest impact on the system LCOE is the battery, followed by the SPV unit. SWT components have the least effect on the system.

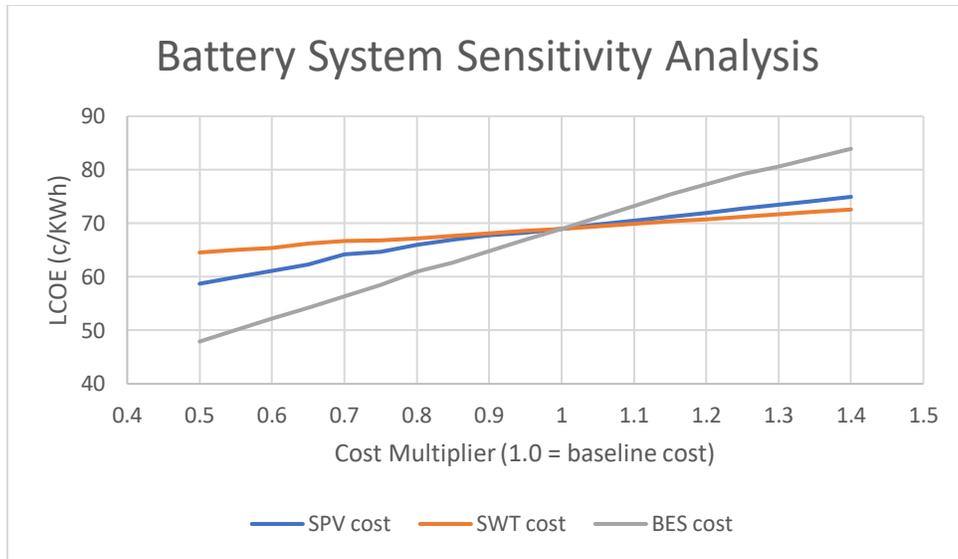


Figure 30. System LCOE sensitivity analysis of battery configuration.

4.4 SPV-BES and SWT-BES Systems

In the configuration of the battery storage system, a single power generation method, namely SPV-BES and SWT-BES, can be used. This part will simulate the above two configurations and the comparison with the SPV-SWT-BES system will be displayed in the next section. In this part, the components number limitations are ignored, and the results are only for data comparison.

A. SPV-BES system

When the number of SWT in the system is limited to 0, only SPV is used to generate electricity. According to the 24-hour demand analysis in Figure 12 in the last section, the average peak household electricity consumption is around 8 p.m. If the number of SPV remains the same, the power supply will be insufficient. Therefore, the capacity of storage system will be increased to support the load. Due to the high cost of BES, the NPC of the system will also increase significantly. From the simulation results in Table 6, the NPCs of the SPV, BES and INV are \$439,417.92, \$263,270.74 and \$18,568.74, respectively. The total system NPC is \$721,257.40 and the system LCOE is increased to 119.49 cents per kWh. The dumped energy is up to 412.01MWh.

Table 6. Simulation results of SPV -BES configuration.

	Rated Power	Capital cost	Replacement cost	OM cost	Lifetime	Capacity	NPC
SPV	1 kW	\$1200	0	25	25 years	304kW	\$ 439417.92
SWT	1 kW	\$2500	0	50	20 years	N/A	N/A
BES	1 kW	\$600	\$400	10	10 years	298 kW	\$ 263270.74
INV	1 kW	\$800	\$500	0	10 years	18 kW	\$ 18568.74
Total	N/A	N/A	N/A	N/A	N/A	N/A	\$ 721257.40
LCOE	N/A	N/A	N/A	N/A	N/A	N/A	¢119.49/kWh
Electricity dump	N/A	N/A	N/A	N/A	N/A	412.01MWh	N/A

B. SWT-BES system

When the number of SPV in the system is limited to 0, only SWT is used to generate electricity. In this case, since the SPV is not generating power and the SWT is producing less during the day, the system needs to store more power at night to support the load's uninterrupted power supply. Therefore, the capacity of BES and NPC will be significantly increased. As can be seen from the simulation results in Table 7, the capacity of the battery is increased to 1,844 kW, which results in the total system NPC reaching \$1,886,939.49. The system LCOE is up to 312.62 cents per kWh.

Table 7. Simulation results of SWT -BES configuration.

	Rated Power	Capital cost	Replacement cost	OM cost	Lifetime	Capacity	NPC
SPV	1 kW	\$1200	0	25	25 years	N/A	N/A
SWT	1 kW	\$2500	0	50	20 years	80 kW	\$ 239272.59
BES	1 kW	\$600	\$400	10	10 years	1844kW	\$ 1629098.16
INV	1 kW	\$800	\$500	0	10 years	18 kW	\$ 18568.74
Total	N/A	N/A	N/A	N/A	N/A	N/A	\$ 1886939.49
LCOE	N/A	N/A	N/A	N/A	N/A	N/A	¢312.62/kWh
Electricity dump	N/A	N/A	N/A	N/A	N/A	98.58MWh	N/A

Chapter 5

V. Comparison

In this section, the SPV-SWT-BES configuration is compared with the SPV-SWT-FCS configuration. In addition, the advantages and disadvantages of these two systems will be researched through the simulation results. Secondly, the hybrid and the single power supply system will be compared as well.

5.1 SPV-SWT-FCS and SPV-SWT-BES

A battery is an energy storage device that stores electrical energy and releases it when needed. A fuel cell, on the other hand, is strictly an electricity-generating device. Like a power plant, it is an electrochemical generator that converts chemical energy directly into electricity.

There are advantages and disadvantages to these two configurations. For fuel cell system, first, the electricity consumed by decomposing water to get hydrogen is also generated by renewable energy, so the whole power generation system is completely green and pollution-free, which plays a crucial role in environmental protection. Second, the dumping energy in fuel cell configuration is lower, which is only 33.22MWh. Less energy dumping reduces the waste of resources, which is beneficial for both the government and the nature. A small amount of the dumped energy can be used to heat water and recycle electricity. Third, make full use of waste in the system to generate electricity, not only reduce the cost of power generation, but also make a contribution to the waste treatment. Last but not least, fuel cell systems are cheaper than battery systems in SA. So, regardless of government subsidies, fuel cell configurations are more cost-effective than battery configurations for the same amount of electricity demand. However, this configuration requires more components and needs higher requirements for component installation, which increases the usefulness of the system. In addition, the entire power supply system has more equipment, so it has a larger footprint, which will bring inconvenience to the small family. Finally, hydrogen storage also has some security risks, such as hydrogen leakage.

For battery system, the components are less, so that the installation is relatively simple. Market prices for batteries have fallen steadily over the past decade, which makes the market price of the battery lower than that of the fuel cell in the future. In terms of safety, batteries take longer to

develop than fuel cells and the technology is mature, so they are safer than fuel cells. But because of this, battery development will be slow, with limited room for performance improvements. In addition, the SPV-SWT-BES system will dump far more energy than the fuel cell system, resulting in excessive resource waste.

The output data of these two configurations is listed in Table 8. Both configurations can provide uninterruptible off-grid power to standalone households. From the table, the total system NPC of the SPV-SWT-FCS configuration is less than the SPV-SWT-BES configuration. Besides, the dumped energy of the battery system is more than twice as much energy as the fuel cell system.

Table 8. Comparison of SPV-SWT- FCS and SPV-SWT- BES configurations.

SPV-SWT-FCS				SPV-SWT-BES			
	Capacity	Dump energy	NPC		Capacity	Dump energy	NPC
SPV	37 kW	N/A	\$ 53481.79	SPV	62 kW	N/A	\$ 89618.13
SWT	16 kW	N/A	\$ 47854.52	SWT	18 kW	N/A	\$ 53836.33
FCS	17 kW	N/A	\$ 90509.57	BES	288 kW	N/A	\$ 254436.15
INV	18 kW	N/A	\$ 18568.74	INV	18 kW	N/A	\$ 18568.74
Electrolyzer	40 kW	N/A	\$ 78691.96	N/A	N/A	N/A	N/A
H ₂ Tank	65 kg	N/A	\$ 75240.41	N/A	N/A	N/A	N/A
Reformer	2 kW	N/A	\$ 745.45	N/A	N/A	N/A	N/A
Compressor	2 kW	N/A	\$ 196.73	N/A	N/A	N/A	N/A
Total	N/A	33.22MWh	\$ 365289.17	N/A	N/A	69.74MWh	\$ 416459.36
LCOE	N/A	N/A	¢60.52/kWh	N/A	N/A	N/A	¢69.00/kWh

5.2 SPV-SWT-FCS and SPV-FCS and SWT-FCS

From the comparison of SPV-SWT-FCS, SPV-FCS and SWT-FCS configurations in Table 9, the total NPC of the SPV-SWT-FCS hybrid system is the lowest, although dumping a little bit more energy than SPV-FCS system. For the SWT-FCS system, both the system NPC and the dumping energy are the highest. Thus, SPV plays an important role in the hybrid power supply system.

Table 9. Comparison of SPV-SWT-FCS, SPV-FCS and SWT-FCS configurations.

	SPV-SWT-FCS		SPV-FCS		SWT-FCS	
	Capacity	NPC	Capacity	NPC	Capacity	NPC
SPV	37 kW	\$ 53481.79	50 kW	\$ 72272.68	N/A	N/A
SWT	16 kW	\$ 47854.52	N/A	N/A	90 kW	\$ 269181.66
FCS	17 kW	\$ 90509.57	17 kW	\$ 90509.57	18 kW	\$ 95833.66
INV	18 kW	\$ 18568.74	18 kW	\$ 18568.74	18 kW	\$ 18568.74
Electrolyser	40 kW	\$ 78691.96	42 kW	\$ 82626.56	65 kW	\$ 127874.44
H2 Tank	65 kg	\$ 75240.41	112 kg	\$ 129645.02	39 kg	\$ 45144.25
Reformer	2 kW	\$ 745.45	2 kW	\$ 745.45	2 kW	\$ 745.45
Compressor	2 kW	\$ 196.73	2 kW	\$ 196.73	2 kW	\$ 196.73
Total	N/A	\$365289.17	N/A	\$ 394564.75	N/A	\$ 557544.93
LCOE	N/A	¢60.52/kWh	N/A	¢65.37/kWh	N/A	¢92.37/kWh
Dump energy	33.22MWh	N/A	27.60MWh	N/A	60.62MWh	N/A

5.3 SPV-SWT-BES and SPV-BES and SWT-BES

From the comparison of SPV-SWT-BES, SPV-BES and SWT-BES configurations in Table 10, the total NPC of the SPV-SWT-BES hybrid system is much lower than the other two single energy systems. Additionally, the dumped energy is also the lowest.

Table 10. Comparison of SPV-SWT-BES, SPV-BES and SWT-BES configurations.

	SPV-SWT-BES		SPV-BES		SWT-BES	
	Capacity	NPC	Capacity	NPC	Capacity	NPC
SPV	62 kW	\$ 89618.13	304kW	\$ 439417.92	N/A	N/A
SWT	18 kW	\$ 53836.33	N/A	N/A	80 kW	\$ 239272.59
BES	288 kW	\$ 254436.15	298 kW	\$ 263270.74	1844kW	\$ 1629098.16
INV	18 kW	\$ 18568.74	18 kW	\$ 18568.74	18 kW	\$ 18568.74
Total	N/A	\$ 416459.36	N/A	\$ 721257.40	N/A	\$ 1886939.49
LCOE	N/A	¢69.00/kWh	N/A	¢119.49/kWh	N/A	¢312.62/kWh
Dump energy	69.74MWh	N/A	412.01MWh	N/A	98.58MWh	N/A

Chapter 6

VI. SPV-SWT-BES System Modelling

In this section, a mixed energy storage configuration consisted with both battery and fuel cells is analyzed.

6.1 SPV-SWT-BES-FCS Hybrid System Configuration

In a hybrid energy storage system configuration, batteries and fuel cells work together and share common inverters. Due to the lower cost of the fuel cell system, in the hybrid system algorithm, the control mode will be designed to charge and discharge the fuel cell first. When the hydrogen is full, the surplus power will go to the battery. The configuration of the mixed energy storage system is only simulated in Matlab and the model is shown in Figure 31.

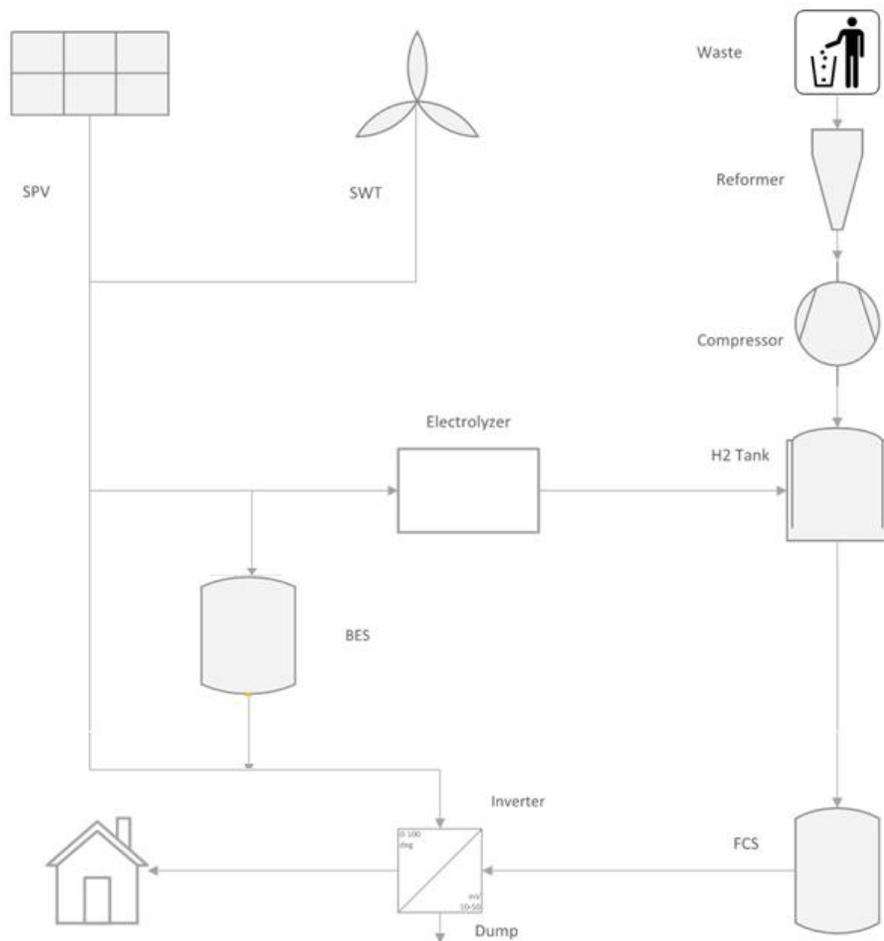


Figure 31. Mixed energy storage system configuration.

6.2 SPV-SWT-BES-FCS Hybrid System Analysis

The SPV-SWT-BES-FCS system can also be divided into three situations: (1) generation = demand (2) generation > demand (3) generation < demand.

A. Generation Matches Demand

In this situation, the power generated by SPV and SWT is transited to the load through the inverter and just enough to support the load. There is no power through the battery and the electrolyzer. There is energy producing by the waste. But the energy is transformed to be hydrogen and restored in the hydrogen tank. The path of the power is shown in Figure 32.

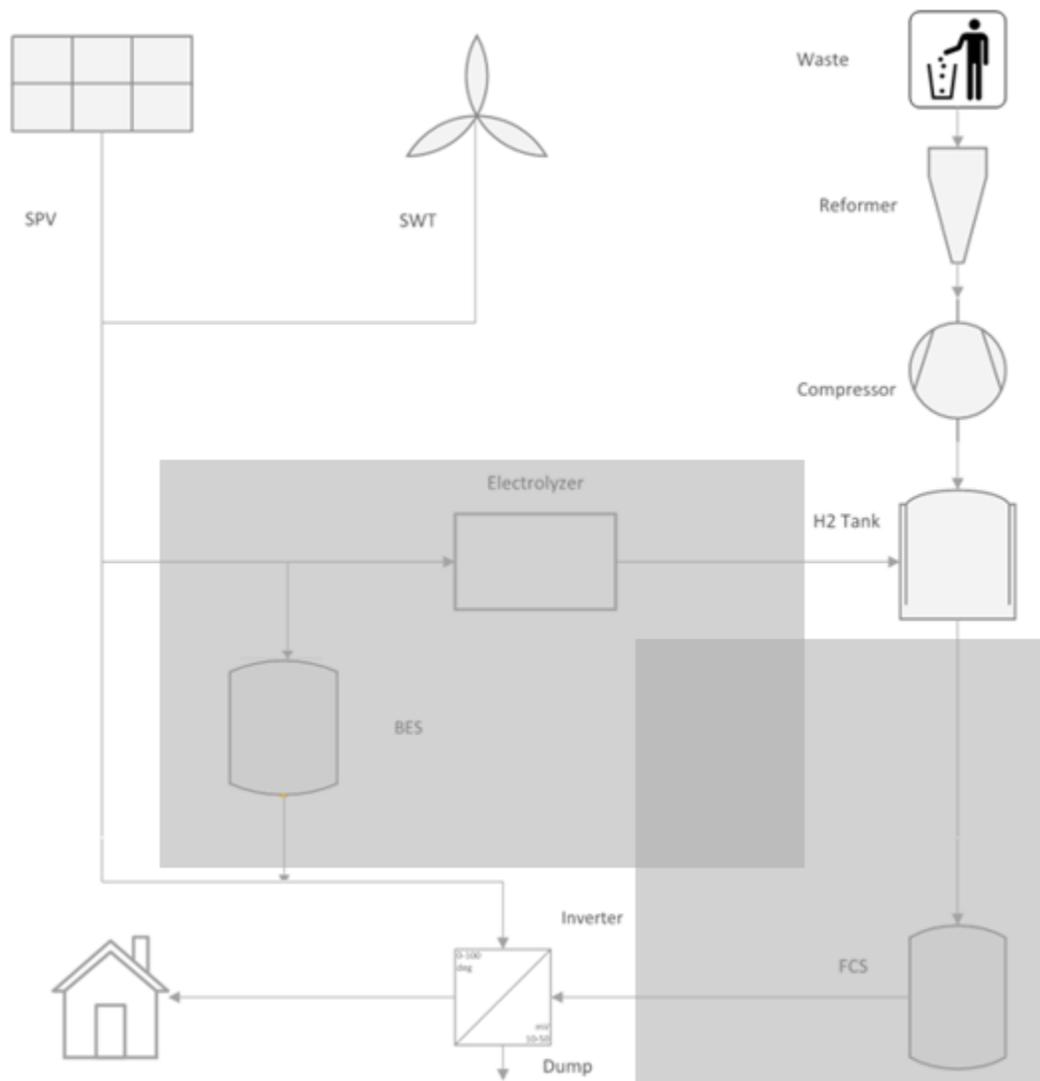


Figure 32. Power path of generation matches demand in SPV-SWT-BES-FCS system.

B. Generation Exceeds Demand

In this situation, the power generated by SPV and SWT is more than demand. In addition to feeding the load, the remaining power is to be transformed to hydrogen through electrolyzer and stored in the tank. When the tank is filled, the excess power will be sent to the battery. If the battery is also filled, the surplus power will be dumped by the control system. In this situation, there is no output from the tank and battery. The path of the power is shown in Figure 33.

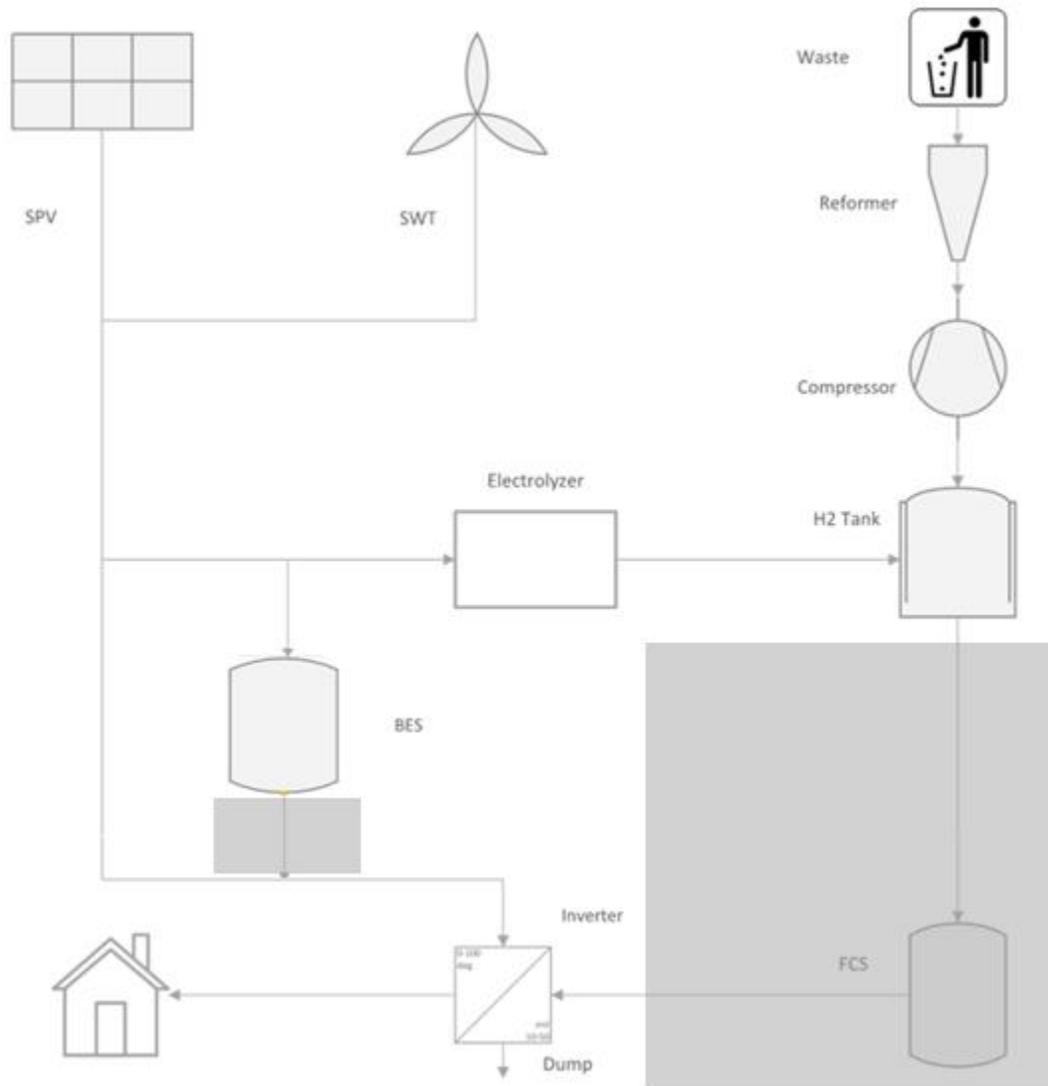


Figure 33. Power path of generation exceeds demand in SPV-SWT-BES-FCS system.

C. Generation is Less than Demand

In this situation, the power generated by SPV and SWT is less than demand. When supply is low, the hydrogen will be sent to the fuel cell and transformed to power for the load usage. If it is still not enough for the load, the battery will discharge. The path of the power is shown in Figure 34.

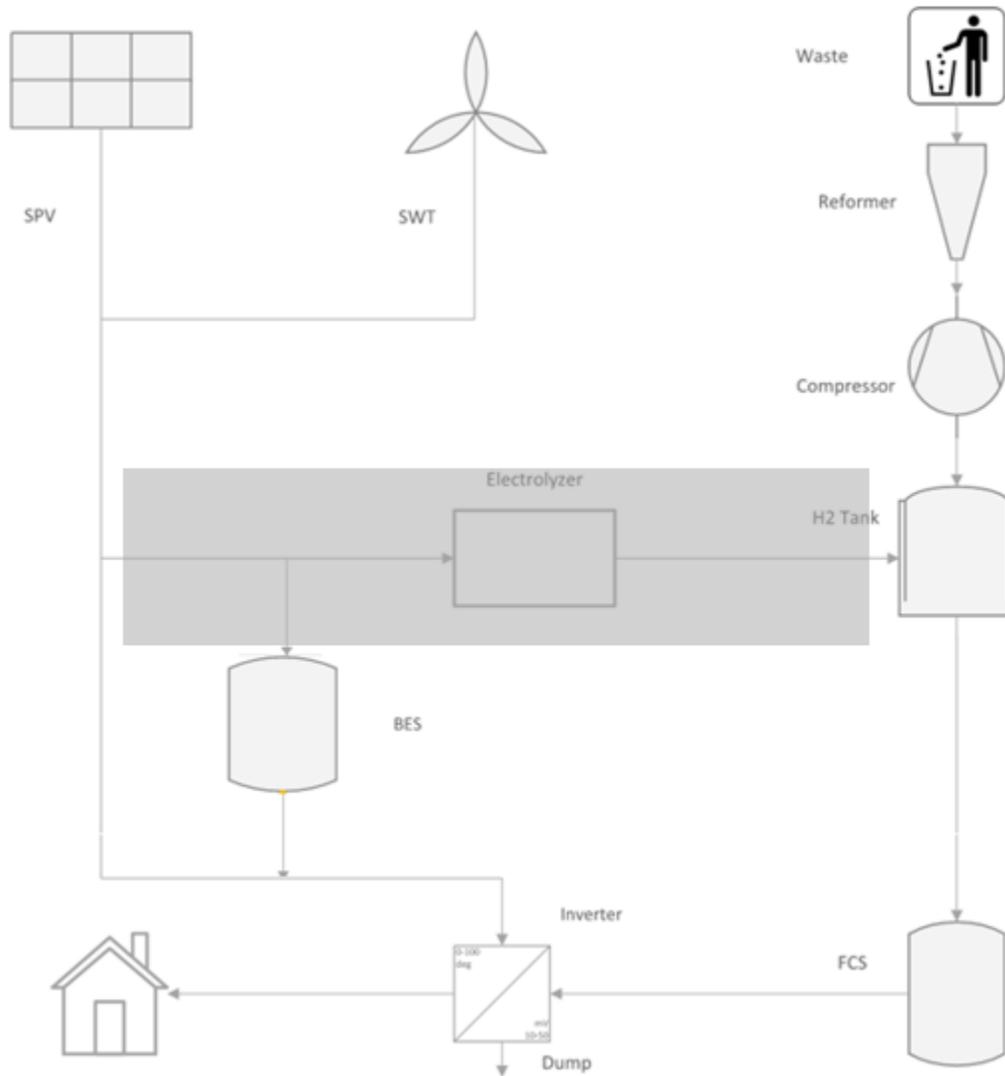


Figure 34. Power path of generation is less than demand in SPV-SWT-BES system.

6.3 SPV-SWT-BES-FCS Simulation Results

A. Optimization Results

The results of different components are listed in Table 11. The left side of the table shows the input values of the system, and the right side is the simulation outputs. From the table, to achieve an

uninterruptible off-grid power supply, the SPV, SWT, BES and FCS have capacities of 67kW, 20 kW, 281kW and 3kW, respectively. In the simulation, the INV's capacity is set to 18kW. The capacity of the electrolyser is 1kW. The reformer and compressor are all 2kW. The storage mass of the hydrogen tank is 3kg. The annual energy generation of SPV and SWT are 105.29MWh and 41.04MWh. The energy from the solid waste is 15MWh per year. The NPCs of SPV and SWT are \$96,845.40 and \$59,818.15. The NPC of the battery is the most, which is \$248,251.94. The fuel cell is lower, which is \$15,972.28. \$18,568.74, \$1,967.30, \$3,472.63, \$745.45 and \$196.73 are for the inverter, electrolyser, hydrogen tank, reformer and compressor, respectively. The total system NPC is \$445,838.62 and the LCOE of the hybrid system is cents73.86/kWh. It can be seen from the simulation data that since the price of the battery system is lower than that of the fuel cell system, the optimization algorithm chooses to use more batteries. The following data is the result of 10 iterations.

Table 11. Simulation results of SPV-SWT-BES-FCS configuration.

	Rated Power	Capital cost	Replacement cost	OM cost	Lifetime	Capacity	Energy generation	NPC
SPV	1 kW	1200	0	25	25 years	67 kW	105.29MWh	\$96845.40
SWT	1 kW	2500	0	50	20 years	20 kW	41.04MWh	\$59818.15
BES	1 kW	600	400	10	10 years	281 kW	N/A	\$248251.94
FCS	1 kW	2207.5	1840	44	5 years	3 kW	N/A	\$15972.28
INV	1 kW	800	500	0	10 years	1 kW	N/A	\$18568.74
Electrolyser	1 kW	1472	1104	15	15 years	1 kW	N/A	\$1967.30
Tank	1 kg	971	0	19	20 years	3 kg	N/A	\$3472.63
Reformer	1 kW	250	250	12.5	20 years	2 kW	15.00MWh	\$745.45
Compressor	1 kW	10	10	9	20 years	2 kW	N/A	\$196.73
Total	N/A	N/A	N/A	N/A	N/A	N/A	N/A	\$445838.62
LCOE	N/A	N/A	N/A	N/A	N/A	N/A	N/A	¢73.86/kWh
Dump Energy	N/A	N/A	N/A	N/A	N/A	N/A	67.31 MWh	N/A

Figure 35 is the simulation result of Matlab after 10 iterations. One of the results of the five iterations is higher than others, which proves that the local optimal solution is obtained. The final result of the system selects the lowest of all the results. The more times it runs, the more accurate the results will be obtained.

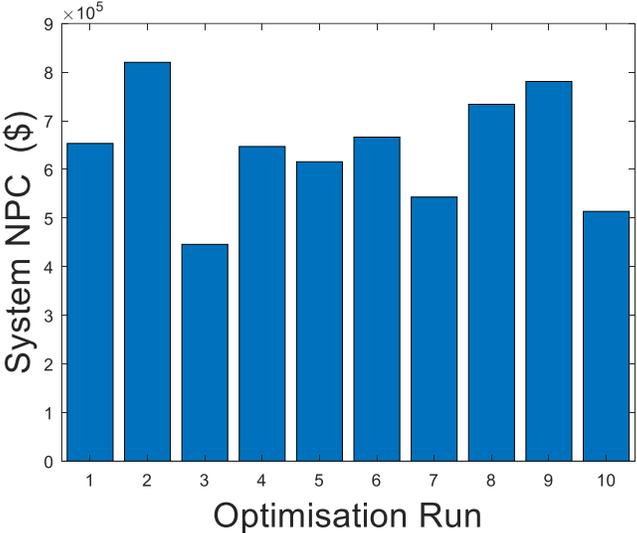


Figure 35. Five iterations of the system NPC in SPV-SWT-BES-FCS system.

Figure 36 shows the information about the fuel cell and battery input power. Due to the low number of fuel cell, the input power of fuel cells is also less than the battery input power.

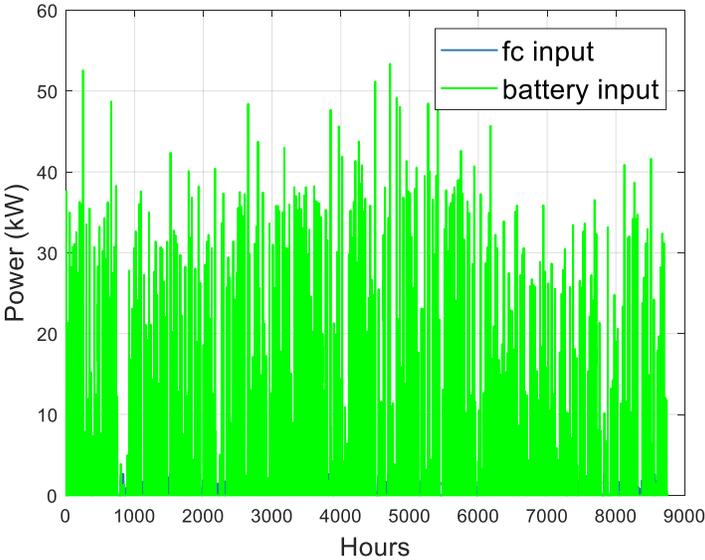


Figure 36. The fuel cell and battery input power.

In Matlab, the way energy storage is managed is that when the output exceeds the consumption, the excess electricity will be stored in the hydrogen tank in the form of hydrogen. If the hydrogen tank is already full, charge it to the battery. As can be seen from Figure 37, the input power of the battery system is greater than the output power. The extra power will be dumped. Since the parameters of the hydrogen tank have initial values, it may occur that the dumped energy is negative. The dumped power can be found in Figure 16. The dumped power is around 45kW, which is 67.31MWh.

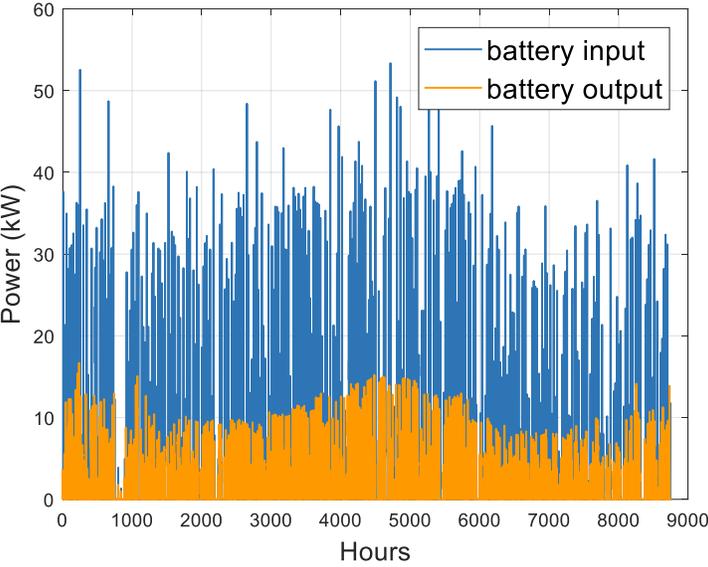


Figure 37. The output power of battery and fuel cell.

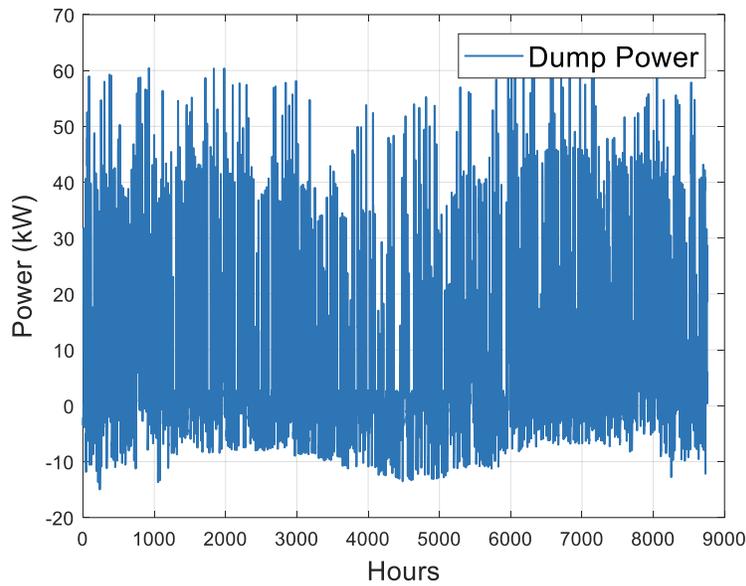


Figure 38. Dump power in SPV-SWT-BES-FCS configuration.

Figure 39 shows the 24-hour battery power. As can be seen from the figure, the battery is basically in charging state from 9 am to 12 am. After 7 pm, the battery is always discharging because of the high load at this period.

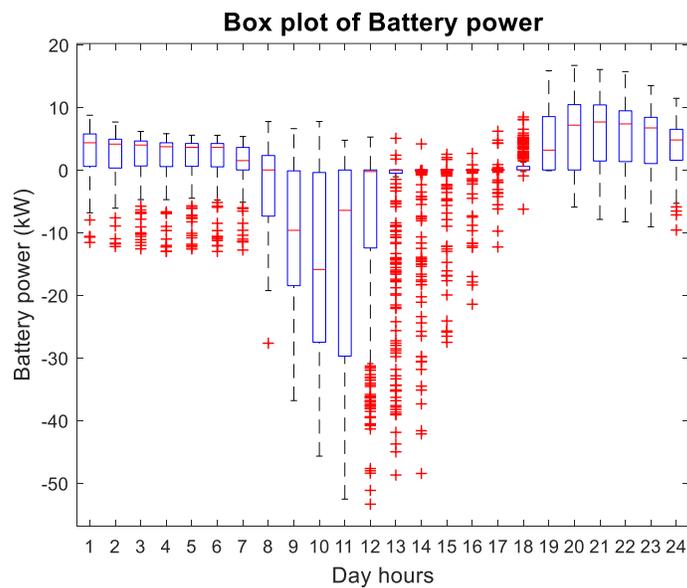


Figure 39. Battery power in SPV-SWT-BES-FCS configuration.

According to the simulation results of system NPC as shown in Figure 40, the NPC of battery still occupies the largest proportion, followed by SWT.

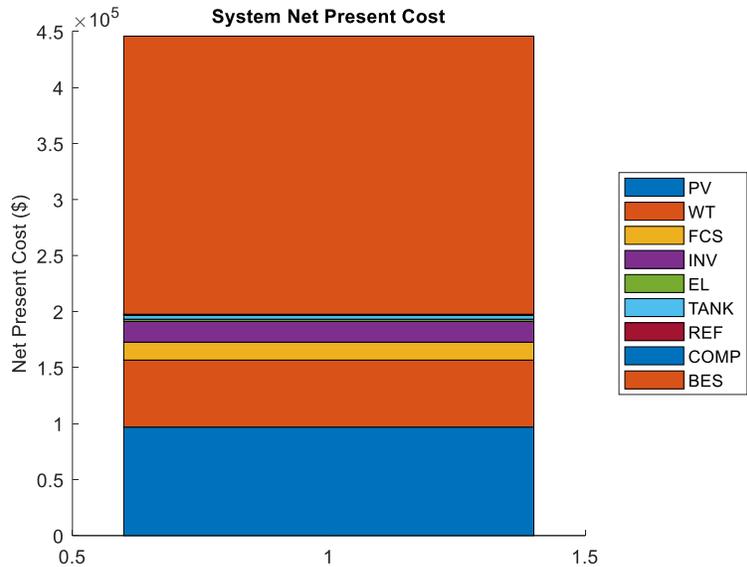


Figure 40. System NPC of SPV-SWT-BES-FCS configuration.

B. Sensitivity Analysis

The sensitivity analysis of the system LCOE will be displayed by changing the costs of the main components in this section.

When the cost of each component in the system is reduced, the impact on the system LCOE is different. In the sensitivity analysis, the change in price is from a 5% reduction in the base price to 50%. The sensitivity analysis graph is shown below. As can be seen from Figure 41, the biggest impact on the system LCOE is the battery, followed by the SPV and the SWT unit.

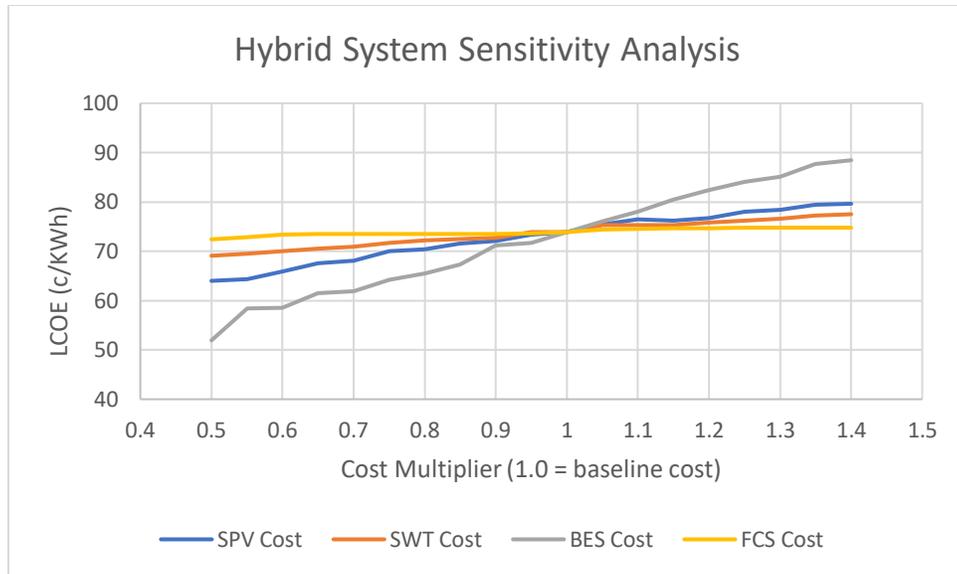


Figure 41. System LCOE sensitivity analysis of hybrid energy storage configuration.

6.4 SPV-BES-FCS and SWT-BES-FCS Systems

In the configuration of the hybrid energy storage system, a single power generation method, namely SPV-BES-FCS and SWT-BES-FCS, can be used. In this part, the components number limitations are ignored, and the results are only for data comparison.

A. SPV-BES-FCS system

The simulation results of the SPV-BES-FCS configuration are shown in Table 12. The NPC of the battery is increased to a high level, which \$346,315.88, as well as SPV's system NPC. The total system NPC is up to \$726,920.62. However, as the huge amount of generation, the dumped energy is increased to 280.30MWh.

Table 12. Simulation results of SPV-BES-FCS configuration.

	Rated Power	Capital cost	Replacement cost	OM cost	Lifetime	Capacity	Energy generation	NPC
SPV	1 kW	1200	0	25	25 years	235 kW	369.3MWh	\$339681.62
SWT	1 kW	2500	0	50	20 years	N/A	N/A	N/A
BES	1 kW	600	400	10	10 years	392 kW	N/A	\$346315.88
FCS	1 kW	2207.5	1840	44	5 years	3 kW	N/A	\$15972.28
INV	1 kW	800	500	0	10 years	18 kW	N/A	\$18568.74
Electrolyser	1 kW	1472	1104	15	15 years	1 kW	N/A	\$1967.30
Tank	1 kg	971	0	19	20 years	3 kg	N/A	\$3472.63
Reformer	1 kW	250	250	12.5	20 years	2 kW	15MWh	\$745.45
Compressor	1 kW	10	10	9	20 years	2 kW	N/A	\$196.73
Total	N/A	N/A	N/A	N/A	N/A	N/A	N/A	\$726920.62
LCOE	N/A	N/A	N/A	N/A	N/A	N/A	N/A	¢120.43/kWh
Electricity dump	N/A	N/A	N/A	N/A	N/A	N/A	280.30MWh	N/A

B. SWT-BES-FCS system

When the number of SPV in the system is limited to 0, only SWT is used to generate electricity. As can be seen from the simulation results in Table 13, the total system NPC reaching \$1,825,355.36 due to the increase of battery capacity.

Table 13. Simulation results of SWT -BES-FCS configuration.

	Rated Power	Capital cost	Replacement cost	OM cost	Lifetime	Capacity	Energy generation	NPC
SPV	1 kW	1200	0	25	25 years	N/A	N/A	N/A
SWT	1 kW	2500	0	50	20 years	130 kW	266.74MWh	\$ 388817.96
BES	1 kW	600	400	10	10 years	1575kW	N/A	\$ 1391447.72
FCS	1 kW	2207.5	1840	44	5 years	4 kW	N/A	\$ 21296.37
INV	1 kW	800	500	0	10 years	18 kW	N/A	\$ 18568.74
Electrolyser	1 kW	1472	1104	15	15 years	1 kW	N/A	\$ 1967.30
Tank	1 kg	971	0	19	20 years	2 kg	N/A	\$ 2315.09
Reformer	1 kW	250	250	12.5	20 years	2 kW	15MWh	\$ 745.45
Compressor	1 kW	10	10	9	20 years	2 kW	N/A	\$ 196.73
Total	N/A	N/A	N/A	N/A	N/A	N/A	N/A	\$ 1825355.36
LCOE	N/A	N/A	N/A	N/A	N/A	N/A	N/A	¢302.41/kWh
Electricity dump	N/A	N/A	N/A	N/A	N/A	N/A	185.76MWh	N/A

Chapter 7

VII. Discussion

In this section, the comparison of battery and fuel cells on other aspects will be mentioned. Additionally, the result comparison of SPV-SWT-FCS, SPV-SWT-BES and SPV-SWT-BES-FCS configurations, SPV-SWT-BES-FCS, SPV-BES-FCS and SWT-BES-FCS configurations will be also included.

Apart from the capacity and system NPC data analysis in the previous chapter, the other aspects of these two energy storage modes are also important. Removed due to copyright restriction (Xia, 2019). Secondly, from the perspective of low temperature performance, because the electrolyte viscosity increases and the conductivity decreases at low temperature, the polarization resistance of the battery increases sharply. Generally, manufacturers do not recommend the discharge behavior below zero. Therefore, batteries need external heating to solve the problem of low temperature. Third, it is from the perspective of cost. In general, both fuel cells and batteries are more expensive than conventional energy. In particular, the complexity and rigor of hydrogen source, storage and safe use lead to the high cost of hydrogen fuel cell, which makes it difficult to gain advantages in a short term. Fourth, it is the time it takes to recharge. Long charging time is always an indelible pain point of lithium-ion batteries. But fuel cells are much more convenient. Therefore, it will play an important role in the optimization of the system if the two energy storage methods are combined to play their respective advantages.

7.1 Result Comparison

In this section, the SPV-SWT-BES-FCS configuration is compared with the SPV-BES-FCS and SWT-BES-FCS configurations, as well as the SPV-SWT-FCS and the SPV-SWT-BES configurations.

A. SPV-SWT-FCS and SPV-SWT-BES and SPV-SWT-BES-FCS

The comparison of SPV-SWT-FCS, SPV-SWT-BES and SPV-SWT-BES-FCS configurations is thrown in Table 14. SPV-SWT-FCS system has outstanding performance in both reducing energy dumping and system NPC, which is the main metric for most users to evaluate the operating system. Although the hybrid energy storage system has the highest total NPC, the dumped energy is lower

than the battery system. Thus, the fuel cell configuration has the advantage in remote areas of south Australia.

Table 14. Comparison of SPV-SWT-FCS, SPV-SWT-BES and SPV-SWT-BES-FCS configurations.

	SPV-SWT-FCS		SPV-SWT-BES		SPV-SWT-BES-FCS	
	Capacity	NPC	Capacity	NPC	Capacity	NPC
SPV	37 kW	\$ 53481.79	62 kW	\$ 89618.13	67 kW	\$ 96845.40
SWT	16 kW	\$ 47854.52	18 kW	\$ 53836.33	20 kW	\$ 59818.15
BES	N/A	N/A	288 kW	\$ 254436.15	281 kW	\$ 248251.94
FCS	17 kW	\$ 90509.57	N/A	N/A	3 kW	\$ 15972.28
INV	18 kW	\$ 18568.74	18 kW	\$ 18568.74	18 kW	\$ 18568.74
Electrolyser	40 kW	\$ 78691.96	N/A	N/A	1 kW	\$ 1967.30
H2 Tank	65 kg	\$ 75240.41	N/A	N/A	3 kg	\$ 3472.63
Reformer	2 kW	\$ 745.45	N/A	N/A	2 kW	\$ 745.45
Compressor	2 kW	\$ 196.73	N/A	N/A	2 kW	\$ 196.73
Total	N/A	\$ 365289.17	N/A	\$ 416459.36	N/A	\$ 445838.62
LCOE	N/A	¢60.52/kWh	N/A	¢69.00/kWh	N/A	¢73.86 /kWh
Dump energy	N/A	33.22MWh	N/A	69.74 MWh	N/A	67.31 MWh

In the previous simulation, the fuel cell included low-cost components that break down waste to produce electricity. But in practice, there are some households that are unable to produce large amounts of waste that can be broken down into hydrogen or that are unable to install the garbage disposal equipment. Table 15 shows the comparison of the three configurations without compressor and reformer. The system NPC of the fuel cell system increases slightly, but still less than the other two configurations.

Table 15. Comparison of SPV-SWT-FCS, SPV-SWT-BES and SPV-SWT-BES-FCS configurations without reformers and compressors.

	SPV-SWT-FCS		SPV-SWT-BES		SPV-SWT-BES-FCS	
	Capacity	NPC	Capacity	NPC	Capacity	NPC
SPV	48 kW	\$ 69381.78	62 kW	\$ 89618.13	64 kW	\$ 92509.04
SWT	12 kW	\$ 35890.89	18 kW	\$ 53836.33	19 kW	\$ 56827.24
BES	N/A	N/A	288 kW	\$ 254436.15	316 kW	\$ 279173
FCS	17 kW	\$ 90509.57	N/A	N/A	1 kW	\$ 5324.09
INV	18 kW	\$ 18568.74	18 kW	\$ 18568.74	18 kW	\$ 18568.74
Electrolyser	47 kW	\$ 92463.06	N/A	N/A	1 kW	\$ 1967.30
H2 Tank	91 kg	\$ 105336.58	N/A	N/A	1 kg	\$ 1157.54
Total	N/A	\$ 412150.61	N/A	\$ 416459.36	N/A	\$ 455526.96
LCOE	N/A	¢68.28/kWh	N/A	¢69.00/kWh	N/A	¢75.47/kWh
Dump energy	N/A	34.90 MWh	N/A	69.74 MWh	N/A	49.79 MWh

B. SPV-SWT-BES-FCS and SPV-BES-FCS and SWT-BES-FCS

From the comparison of SPV-SWT-BES-FCS, SPV-BES-FCS and SWT-BES-FCS configurations in Table 16, compared with the other two single power systems, the total NPC and the dumped energy of the SWT-BES-FCS hybrid system are the lowest.

Table 16. Comparison of SPV-SWT-BES-FCS, SPV-BES-FCS and SWT-BES-FCS configurations.

	SPV-SWT-BES-FCS		SPV-BES-FCS		SWT-BES-FCS	
	Capacity	NPC	Capacity	NPC	Capacity	NPC
SPV	37 kW	\$ 53481.79	235 kW	\$339681.62	N/A	N/A
SWT	16 kW	\$ 47854.52	N/A	N/A	130 kW	\$ 388817.96
BES	N/A	N/A	392 kW	\$346315.88	1575kW	\$ 1391447.72
FCS	17 kW	\$ 90509.57	3 kW	\$15972.28	4 kW	\$ 21296.37
INV	18 kW	\$ 18568.74	18 kW	\$18568.74	18 kW	\$ 18568.74
Electrolyser	40 kW	\$ 78691.96	1 kW	\$1967.30	1 kW	\$ 1967.30
H2 Tank	65 kg	\$ 75240.41	3 kg	\$3472.63	2 kg	\$ 2315.09
Reformer	2 kW	\$ 745.45	2 kW	\$745.45	2 kW	\$ 745.45
Compressor	2 kW	\$ 196.73	2 kW	\$196.73	2 kW	\$ 196.73
Total	N/A	\$ 365289.17	N/A	\$726920.62	N/A	\$ 1825355.36
LCOE	N/A	¢60.52/kWh	N/A	¢120.43/kWh	N/A	¢302.41/kWh
Dump energy	N/A	33.22MWh	N/A	280.30MWh	N/A	185.76MWh

Chapter 8

VIII. Conclusions

8.1 Conclusion

This thesis is focused on the capacity optimization analysis of renewable energy generation components for standalone households in remote areas of South Australia. It is based on a case study in South Australia applying real data. The time of the data is accurate to the hour, which makes the simulation results more accurate.

This thesis first analyzes the current situation of power supply in remote areas of south Australia and the disadvantages of using power grid in remote areas. The results show that the use of renewable energy to power standalone households in remote areas of south Australia is feasible and beneficial. It not only has a price advantage, but also greatly reduces environmental pollution. In this thesis, six different configurations, namely SPV-SWT-FCS, SPV-FCS, SWT-FCS, SPV-SWT-BES, SPV-BES and SWT-BES, are used for simulation and comparison. In the discussion section, the mixed energy storage SPV-SWT-BES-FCS configuration is simulated, as well as compared with the SPV-SWT-BES and SPV-SWT-FCS configurations.

In the modeling process, MATLAB is used to model the configurations for ten households. The Visual Studio is for one household. Matlab can output data in graph results to achieve data visualization, which is conducive to data analysis. Visual Studio has much faster computing power, which can get the simulation results faster.

In the simulation, PSO algorithm is used in Matlab and Visual Studio software to obtain the optimal configuration of the system, to minimize the NPC of the system configurations. All the configurations can meet the requirements of uninterruptible off-grid power supply. From the simulation results, the fuel cell configuration has the least system NPC and dumped energy in the remote areas of South Australia. After 10 iterations of particle swarm optimization, the LCOE of the fuel cell configuration is only $\$ 60.52/\text{kWh}$, and the dumped energy is 33.22MWh, which is almost half as much as the other two configurations. As can be seen from the comparison of the data, the system NPC of the hybrid energy storage configuration reaches $\$445838.62$, which is the highest. However, the dumped energy of the battery configuration is higher than the hybrid energy

storage system. The report also provides a sensitivity analysis of the system LCOE for the SPV-SWT-FCS, SPV-SWT-BES and SPV-SWT-BES-FCS configurations. In SPV-SWT-FCS system, the sensitivity analysis shows that the biggest impact on the system LCOE is the fuel cell, followed by the hydrogen tank and the electrolyzer unit. Reformer and compressor have almost no effect on the system. For the battery and the hybrid energy storage system, the impact of the battery components on the system LCOE is obvious. In the simulation, if only SPV or SWT is used in the system, the total NPC and the dumped energy will be increased greatly. In particular, in the case of battery-stored power supply systems, when SWT is disabled, the energy dumped is 412.01MWh, almost six times that of hybrid power generation systems. With the SPV disabled, the LCOE even reaches $\$ 312.62/\text{kWh}$.

The low cost of generating electricity from waste contributes to the low LCOE of fuel cell systems. This thesis also takes into account the situation that waste products cannot be used to produce electricity. In this case, the LCOE of the fuel cell system increases slightly, which is $\$ 68.28/\text{kWh}$, but still less than the battery and the hybrid energy storage configurations, which are $\$ 69.00/\text{kWh}$ and $\$ 75.47/\text{kWh}$, respectively.

In summary, both economically and in terms of energy conservation, the SPV-SWT-FCS configuration in remote areas of south Australia has advantages.

8.2 Future Work

In this report, the research on hybrid energy storage system is still in the initial stage. In future research, the proportion of batteries and fuel cells used could be adjusted according to the needs of different regions, not just the lowest system NPC as the calculation standard. For example, if the user's available installation area is insufficient, more battery storage systems can be used. If users want to cause less energy loss, they can choose a larger percentage of the fuel cells. The later work can analyze the economy and advantages of the mixed energy storage system with different components.

Secondly, in the hybrid energy storage system studied in this study, the default setting is to use the fuel cell energy storage system first and then the battery system. In subsequent studies, the order of use can also be adjusted to use the battery system first and then the fuel cell system. Then, the two configuration methods can be compared and analyzed.

In the process of using Visual Studio to model the system, only the power supply of a single household is simulated. In future studies, the number of simulations can be adjusted to expand to 10 households or larger.

Finally, the configuration of the hybrid energy storage system can also be modeled based on the C++ language. The results of the two software simulations should be consistent.

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Appendix A: User manual of single energy storage configuration in Matlab

The following is an introduction to how users can use the Matlab software.

The first step is to click the "run" button at the top of the program.

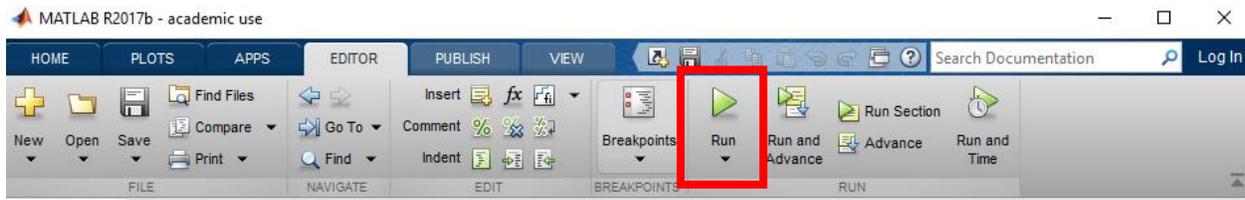


Figure 42. The start interface of Matlab.

For the single energy storage system, there are four parts in the main program, including SPV-SWT-BES standalone, SPV-SWT-BES Standalone (LPSP), SPV-SWT-BES Standalone (New Strategy) and SPV-SWT-FCS Standalone configurations. Only case 1 and 4 are used in this simulation. Configuration 1 is for the battery system and configuration 4 is for the fuel cell system. The other two cases are reserved for future additional research. The following illustration shows a fuel cell system as an example.

Firstly, after clicking Run in Matlab, these four options will be displayed in the command window.

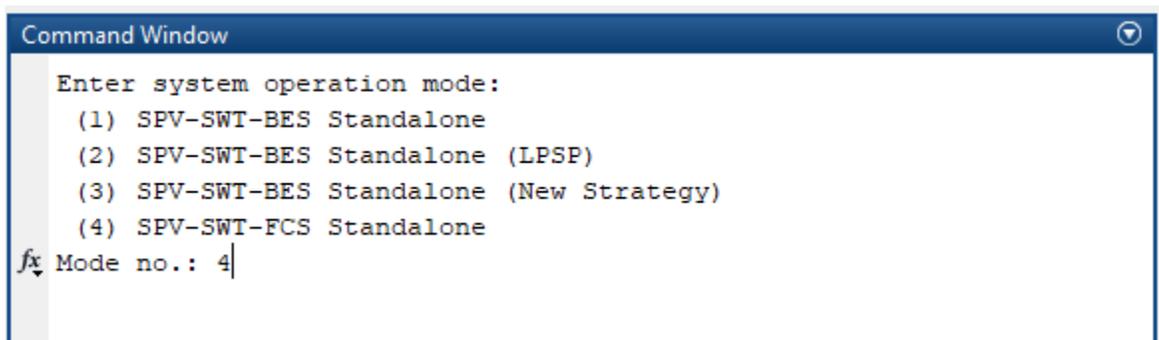


Figure 43. System selection operation interface of single energy storage system in Matlab.

The users can select either mode 1 or 4 and enter the number after 'Mode no.' After pressing enter on the keyboard, the system will prompt the user to select the number of iterations. The number of iterations is generally changed according to the scale calculated by the system. In this project, it is better to run ten times to get more accurate results.

```
Command Window
Enter system operation mode:
(1) SPV-SWT-BES Standalone
(2) SPV-SWT-BES Standalone (LPSP)
(3) SPV-SWT-BES Standalone (New Strategy)
(4) SPV-SWT-FCS Standalone
Mode no.: 4
Enter number for how many optimisations to run:
fx 10|
```

Figure 44. Iteration times selection interface of single energy storage system in Matlab.

After pressing enter to confirm, the system will automatically enter the calculation process. The system NPC result calculated from each random combination will be displayed in the command window.

```
Command Window
Run: 1, Generation: 65, NPC: $41915.95
Run: 1, Generation: 66, NPC: $41915.95
Run: 1, Generation: 67, NPC: $41915.95
Run: 1, Generation: 68, NPC: $41915.95
Run: 1, Generation: 69, NPC: $41915.95
Run: 1, Generation: 70, NPC: $41915.95
Run: 1, Generation: 71, NPC: $41915.95
Run: 1, Generation: 72, NPC: $41915.95
Run: 1, Generation: 73, NPC: $41915.95
Run: 1, Generation: 74, NPC: $41915.95
Run: 1, Generation: 75, NPC: $41915.95
Run: 1, Generation: 76, NPC: $41915.95
Run: 1, Generation: 77, NPC: $41915.95
Run: 1, Generation: 78, NPC: $41915.95
Run: 1, Generation: 79, NPC: $41915.95
fx |
```

Figure 45. System computing interface of single energy storage system in Matlab.

The final calculation results will be displayed in the command window, including the number of each module, the peak load of the system, and so on.

Command Window

```
No. of PV      = 1
No. of WT      = 6
No. of Fuel Cells      = 2
No. of Inverters      = 4
No. of Electrolyzers  = 1
No. of Tanks      = 1
No. of Reformers     = 1
No. of Compressors   = 1

-----

Rated PV Output = 1.00 kW
Rated Wind Turbine Output = 6.00 kW
Rated Fuel Cell Output = 2.00 kW
Rated Inverter Output = 4.00 kW
Rated Electrolyzers Output = 1.00 kW
Rated Tanks Output = 1.00 kg
Rated Reformers Output = 0.17 kW
Rated Compressors Output = 0.17 kW

-----

Peak System Load      = 1.73 kW
Minimum System Load   = 0.32 kW
Average System Load    = 0.70 kW

-----

Optimised System Net Present Costs

-----

PVs NPC = 1200.00 $
Wind Turbines NPC = 15000.00 $
Fuel Cells NPC = 10648.18 $
Inverters NPC = 7871.83 $
Electrolyzers NPC = 1967.30 $
Tanks NPC = 1157.54 $
Reformers NPC = 372.73 $
Compressors NPC = 98.36 $

-----

Total System NPC = 38315.95 $

-----

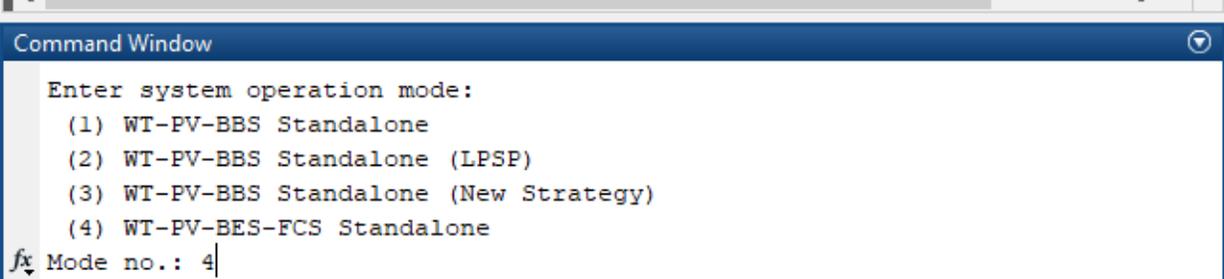
Levelised cost of energy = 634.80$ per MWh
Levelised cost of energy = 63.48c per kWh

-----
```

Figure 46. Result interface of single energy storage system in Matlab.

Appendix B: User manual of hybrid energy storage configuration in Matlab

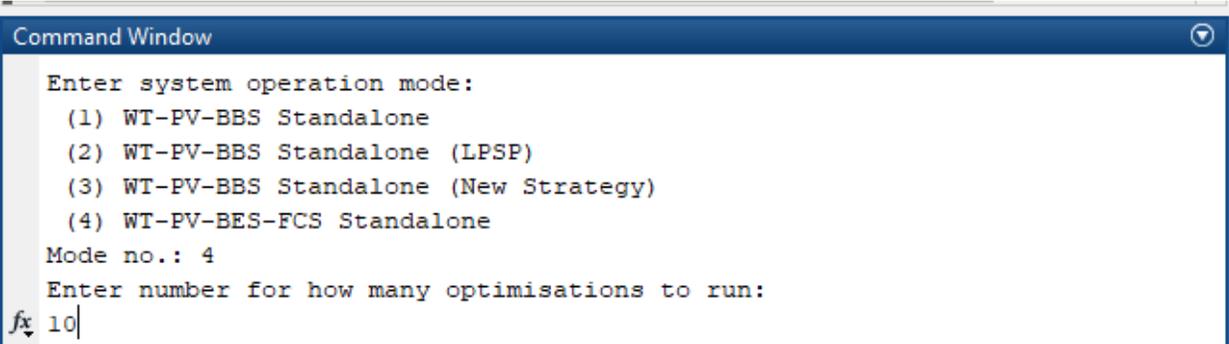
In the hybrid energy storage system, the operation interface is similar with the single energy storage system. Only the fourth option is changed to SPV-SWT-BES-FCS system. The first option is the battery system. The second and third selections are still reserved options. Users only need to select mode 1 or 4 after running. Mode 1 is for the battery system and mode 4 is for the hybrid energy storage system.



```
Command Window
Enter system operation mode:
(1) WT-PV-BBS Standalone
(2) WT-PV-BBS Standalone (LPSP)
(3) WT-PV-BBS Standalone (New Strategy)
(4) WT-PV-BES-FCS Standalone
fx Mode no.: 4
```

Figure 47. System selection operation interface of hybrid energy storage system in Matlab.

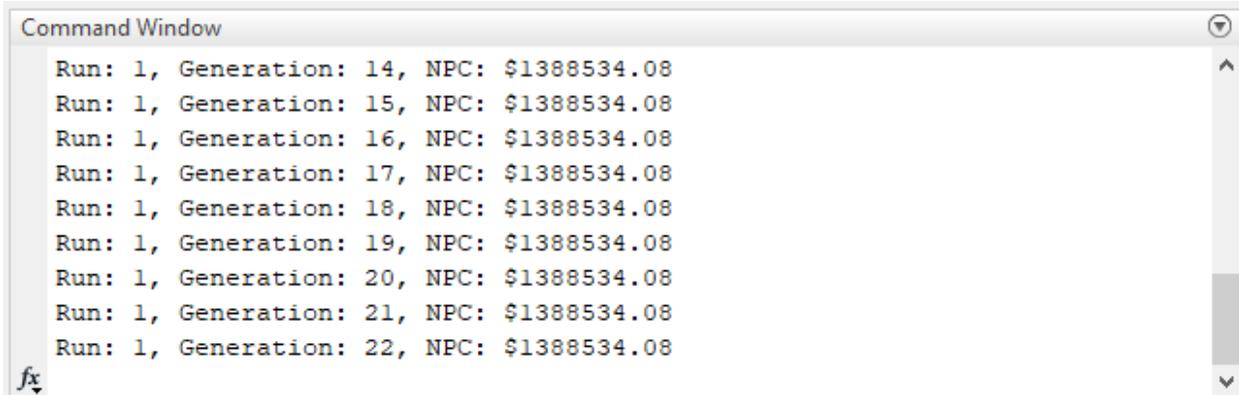
After pressing enter on the keyboard, the system will prompt the user to select the number of iterations. The number of iterations is generally changed according to the scale calculated by the system. In this project, it is better to run ten times to get more accurate results. Because the calculation of hybrid energy storage system is more complex, the optimal solution cannot be found in the specified range in the operation of fewer times. If there is no result at the end of the calculation, it is better to run more times to get the optimal solution.



```
Command Window
Enter system operation mode:
(1) WT-PV-BBS Standalone
(2) WT-PV-BBS Standalone (LPSP)
(3) WT-PV-BBS Standalone (New Strategy)
(4) WT-PV-BES-FCS Standalone
Mode no.: 4
Enter number for how many optimisations to run:
fx 10
```

Figure 48. Iteration times selection interface of hybrid energy storage system in Matlab.

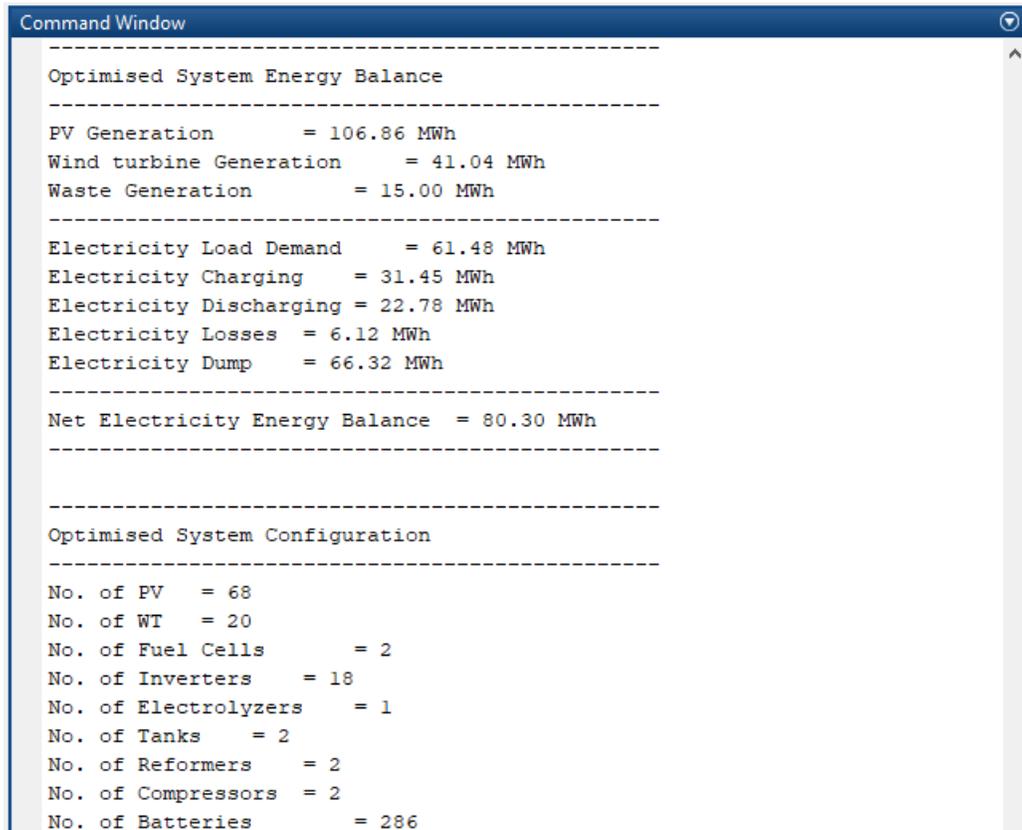
After pressing enter to confirm, the system will automatically enter the calculation process. The system NPC result calculated from each random combination will be displayed in the command window.



```
Command Window
Run: 1, Generation: 14, NPC: $1388534.08
Run: 1, Generation: 15, NPC: $1388534.08
Run: 1, Generation: 16, NPC: $1388534.08
Run: 1, Generation: 17, NPC: $1388534.08
Run: 1, Generation: 18, NPC: $1388534.08
Run: 1, Generation: 19, NPC: $1388534.08
Run: 1, Generation: 20, NPC: $1388534.08
Run: 1, Generation: 21, NPC: $1388534.08
Run: 1, Generation: 22, NPC: $1388534.08
```

Figure 49. System computing interface of hybrid energy storage system in Matlab.

The final calculation results will be displayed in the command window, including the number of each module, the peak load of the system, and so on.



```
Command Window
-----
Optimised System Energy Balance
-----
PV Generation          = 106.86 MWh
Wind turbine Generation = 41.04 MWh
Waste Generation       = 15.00 MWh
-----
Electricity Load Demand = 61.48 MWh
Electricity Charging    = 31.45 MWh
Electricity Discharging = 22.78 MWh
Electricity Losses     = 6.12 MWh
Electricity Dump       = 66.32 MWh
-----
Net Electricity Energy Balance = 80.30 MWh
-----

Optimised System Configuration
-----
No. of PV      = 68
No. of WT      = 20
No. of Fuel Cells = 2
No. of Inverters = 18
No. of Electrolyzers = 1
No. of Tanks   = 2
No. of Reformers = 2
No. of Compressors = 2
No. of Batteries = 286
```

Figure 50. Result interface of hybrid energy storage system in Matlab.

Appendix C: User manual of single energy storage configuration in Visual Studio

The following is an introduction to how users can use the Visual Studio software. In this research, Visual Studio is used to simulate the SPV-SWT-BES and SPV-SWT-FCS configurations based on one household data.

Visual Studio's operation interface is basically consistent with Matlab. First, click "Local Windows Debugger" to start the simulation.

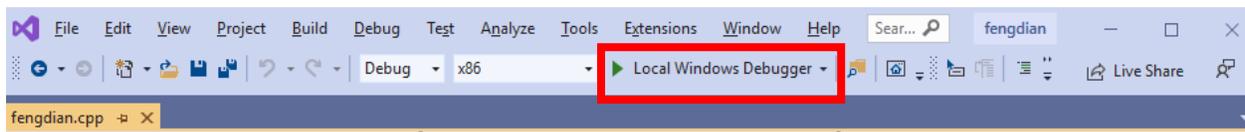


Figure 51. The start interface of Visual Studio.

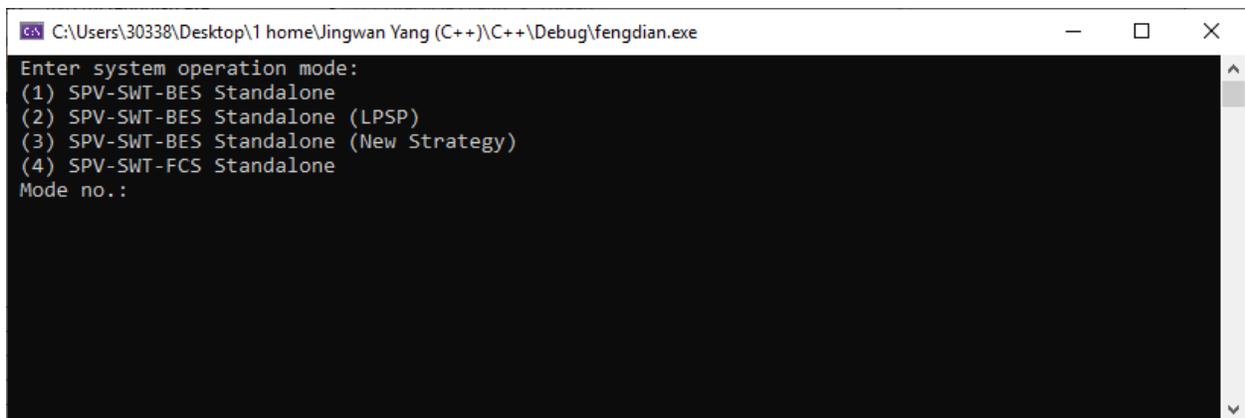
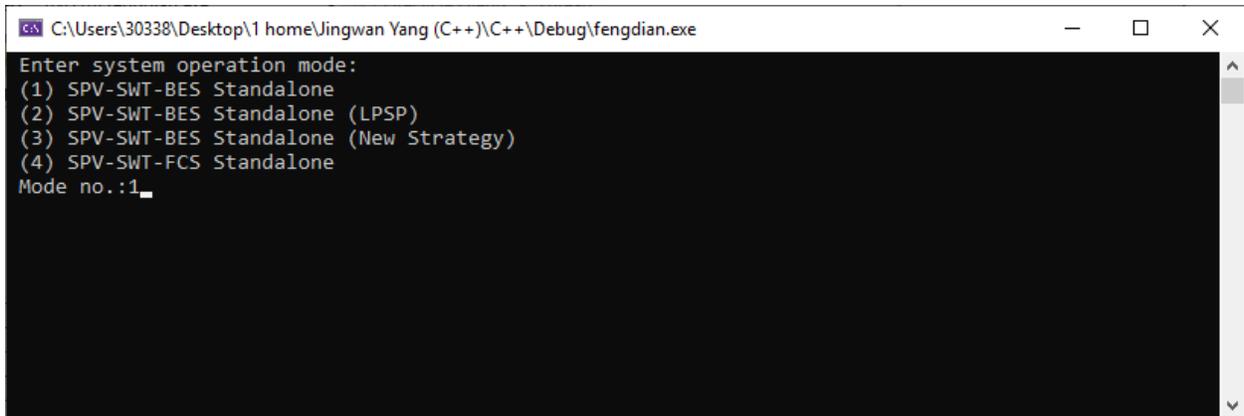


Figure 52. The mode selection interface of Visual Studio.

The same options as the Matlab software are displayed in the command window that pops up. There are four parts in the main program, including SPV-SWT-BES standalone, SPV-SWT-BES Standalone (LPSP), SPV-SWT-BES Standalone (New Strategy) and SPV-SWT-FCS Standalone configurations. Only case 1 and 4 are used in this simulation. Configuration 1 is for the battery system and configuration 4 is for the fuel cell system. The other two cases are reserved for future additional research. The following illustration shows a battery system as an example.

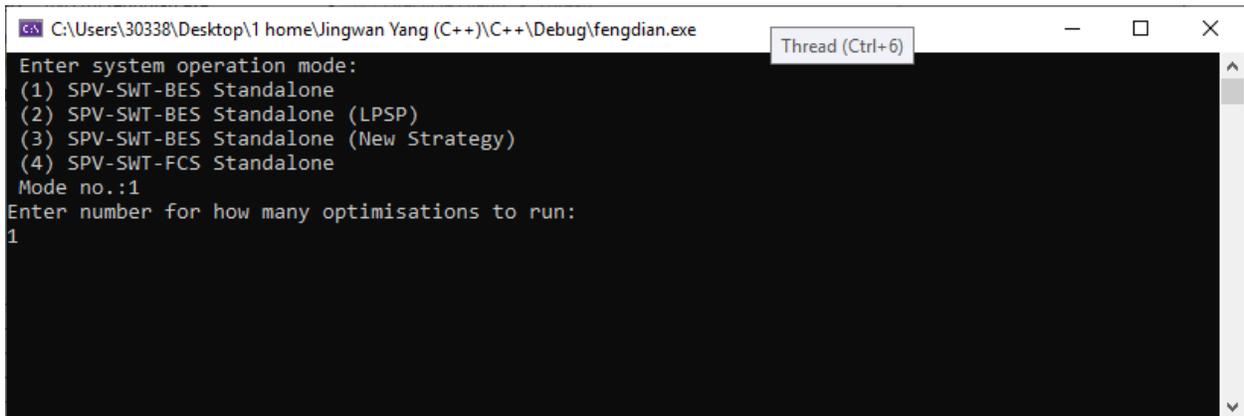
In this step, users should select mode 1 to simulate the SPV-SWT-BES configuration.



```
C:\Users\30338\Desktop\1 home\Jingwan Yang (C++)\C++\Debug>fengdian.exe
Enter system operation mode:
(1) SPV-SWT-BES Standalone
(2) SPV-SWT-BES Standalone (LPSP)
(3) SPV-SWT-BES Standalone (New Strategy)
(4) SPV-SWT-FCS Standalone
Mode no.:1_
```

Figure 53. Battery configuration mode selection of Visual Studio.

After pressing enter on the keyboard, the system will prompt the user to select the number of iterations. The number of iterations is generally changed according to the scale calculated by the system. In the battery configuration, the operation time could be 1, because the calculation it is not complex. After many tests, in the battery system, the optimal solution of the system can be obtained after one iteration. However, more iterations lead to more accurate results.



```
C:\Users\30338\Desktop\1 home\Jingwan Yang (C++)\C++\Debug>fengdian.exe
Enter system operation mode:
(1) SPV-SWT-BES Standalone
(2) SPV-SWT-BES Standalone (LPSP)
(3) SPV-SWT-BES Standalone (New Strategy)
(4) SPV-SWT-FCS Standalone
Mode no.:1
Enter number for how many optimisations to run:
1
```

Figure 54. Operation times selection interface of battery configuration in Visual Studio.

Unlike Matlab, Visual Studio does not display the results of each calculation. After pressing enter and waiting for a while, the system will automatically display the results. The operation time is less than that of Matlab. Finally, press any key twice can close the result window.

```

Select C:\Users\30338\Desktop\1 home\Jingwan Yang (C++)\C++\Debug\fengdian.exe
Optimised System Energy Balance
-----
PV Generation           = 14.24 MWh
Wind turbine Generation = 12.31 MWh
-----
Electricity Load Demand   = 6.15 MWh
Electricity Charging Battery = 2.17 MWh
Electricity Discharging Battery = 1.74 MWh
Electricity Battery Losses = 0.19 MWh
Electricity Dump         = 19.99 MWh
-----
Net Electricity Energy Balance = 20.2 MWh
-----

Optimised System Configuration
-----
No. of PV           = 9.00
No. of WT           = 6.00
No. of Batteries    = 22.00
No. of Inverters    = 4.00
-----
Rated PV Output = 9.00 kW
Rated Wind Turbine Output = 6.00 kW
Rated Battery Bank Output = 22.00 kW
Rated Inverter Output = 4.00 kW
Rated Battery Bank Storage = 6.00 kWh
-----
System Power Output = 9.00 kW
System Energy Storage = 4.80 kWh
-----
Peak System Load = 1.73 kW
Minimum System Load = 0.32 kW
Average System Load = 0.70 kW
-----

Optimised System Net Present Costs
-----
PVs NPC = 10800.00 $
Wind Turbines NPC = 15000.00 $
Battery Banks NPC = 13547.56 $
Inverters NPC = 7871.83 $
-----
Total System NPC = 47219.40 $
-----
Levelised cost of energy = 782.31$ per MWh
Levelised cost of energy = 78.23c per kWh
-----
Press any key to continue . . .

```

Figure 55. Result interface of battery configuration in Visual Studio.

Configuration 4 is for the fuel system. To operate the SPV-SWT-FCS configuration, users should select mode 4 in the mode selection step.

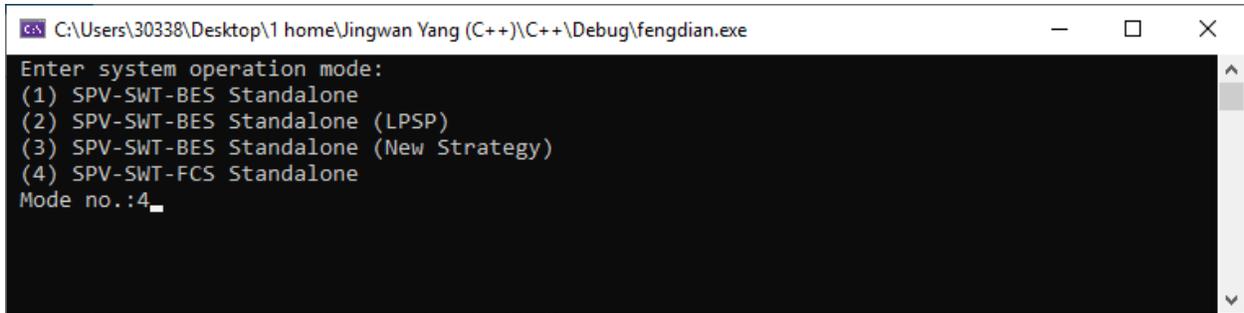


Figure 56. Fuel cell configuration mode selection of Visual Studio.

After pressing enter on the keyboard, the system will prompt the user to select the number of iterations. The number of iterations is generally changed according to the scale calculated by the system. In the battery configuration, the operation time could be 1, because the calculation it is not complex. After many tests, in the battery system, the optimal solution of the system can be obtained after one iteration. However, more iterations lead to more accurate results.

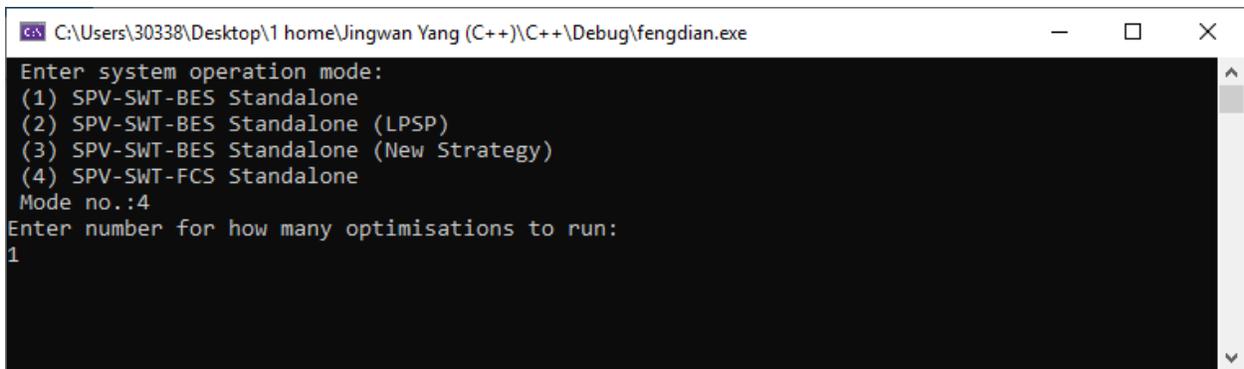


Figure 57. Operation times selection interface of fuel cell configuration in Visual Studio.

Unlike Matlab, Visual Studio does not display the results of each calculation. After pressing enter and waiting for a while, the system will automatically display the results. The operation time is less than that of Matlab. Finally, press any key twice can close the result window.

```

C:\Users\30338\Desktop\1 home\Jingwan Yang (C++)\C++\Debug\fengdian.exe
Optimised System Energy Balance
-----
PV Generation           = 1.57 MWh
Wind turbine Generation = 12.31 MWh
Compressor Generation  = 1.50 MWh
Reformer Generation    = 1.50 MWh
-----
Electricity Load Demand = 6.15 MWh
Electricity Charging Fuel Cell = 5.03 MWh
Electricity Discharging Fuel Cell = 2.51 MWh
Electricity Fuel Cell Losses = 2.51 MWh
Electricity Dump       = 3.88 MWh
-----
Net Electricity Energy Balance = 5.22 MWh
-----

Optimised System Configuration
-----
No. of PV           = 1.00
No. of WT           = 6.00
No. of Fuel Cells   = 2.00
No. of Inverters    = 4.00
No. of Electrolyzers = 1.00
No. of Tanks        = 1.00
No. of Reformers    = 1.00
No. of Compressors  = 1.00
-----
Rated PV Output = 1.00 kW
Rated Wind Turbine Output = 6.00 kW
Rated Fuel Cell Output = 2.00 kW
Rated Inverter Output = 4.00 kW
Rated Electrolyzers Output = 1.00 kW
Rated Tanks Output = 1.00 kg
Rated Reformers Output = 0.17 kW
Rated Compressors Output = 0.17 kW
-----
Peak System Load = 1.73 kW
Minimum System Load = 0.32 kW
Average System Load = 0.70 kW
-----

Optimised System Net Present Costs
-----
PVs NPC = 1200.00 $
Wind Turbines NPC = 15000.00 $
Fuel Cells NPC = 10648.18 $
Inverters NPC = 7871.83 $
Electrolyzers NPC = 1967.30 $
Tanks NPC = 1157.54 $
Reformers NPC = 372.73 $
Compressors NPC = 98.36 $
-----
Total System NPC = 38315.95 $
-----
Levelised cost of energy = 634.80$ per MWh
Levelised cost of energy = 63.48c per kWh
-----
Press any key to continue . . .

```

Figure 58. Result interface of fuel cell configuration in Visual Studio.