International Conference on Renewable Energies and Power Quality (ICREPQ'18)
Salamanca (Spain), 21th to 23th March, 2018
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.16 April 2018

Multi-Energy Management System for Chungming Island in China

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Abstract. The Shanghai government intends to transform Chungming Island in China into a green ecological base. As a part of this idea, vehicles on this island are preferred to be electric or fuel cell vehicles in order to achieve zero emissions. The design will use SAIC fuel cell buses and commercial vehicles (minibuses) to serve as tour buses and shuttle minibuses. A multi-energy management system was studied for use on this island. This system will support a fuel cell transit bus tour and a shuttle minibus route. The island's demand for hydrogen, according to the parameters of the vehicles and the routes, was determined to be 100 kg/day. The hydrogen will be produced through electrolysis on location. A 750 kW wind generator set and a PV roof can be used as the energy supply system. This system can meet the fuel cell bus energy demand (950 MWh/year) and serve the local community as well. The total cost of the system is estimated to be 3.0 Million $US.

Key words

Energy Management, Fuel Cells, Hydrogen Economy, Sustainable Energy

1. Introduction

This study reports the results of a team project completed by three Chinese scholars employed by SAIC and enrolled in a 500-level *Energy and the Environment* course at Kettering University during the Fall Term, 2016.

China's vehicle ownership exceeded 200 million recently. Facing excessive air pollution and an overuse of resources, automobile companies are under pressure to reduce fuel consumption and emissions. As a socially responsible company, *Shanghai Automotive Industry Corporation (SAIC)* started to research and develop alternatively fueled vehicles in 2001. As these vehicles are continually brought to market, users and enterprises face infrastructural problems.

Purely electric vehicles and some hybrid vehicles need charging stations and fuel cell vehicles require hydrogen refueling stations. The process of electricity and hydrogen production has always been controversial in terms of environmental protection. Considering total carbon emissions during the whole life cycle of a vehicle, SAIC intends to design a clean, low-carbon management system to ensure that the steps of vehicle manufacturing, distribution, use and recycle are all environmentally friendly. This system will service not only new-energy vehicles, but will also benefit the surrounding communities, buildings and residents. Chungming Island, at a distance of 50 km from

Table I. – Nomenclature

c	specific heat
CHP	combined heat and power
FC	fuel cell
HHV	higher heating value

m	mass
N	number of moles
p	pressure
PV	photovoltaic
Q	heat
R_u	universal gas constant
T	temperature (K)
V	volume
ρ	density of hydrogen

Shanghai mainland, is China's third largest island. It is connected to Shanghai through a bridge and a tunnel. The island is located in the Yangtze River estuary where wind and sunshine are abundant. The Shanghai government intends to transform the island into a green ecological base. As a part of this idea, vehicles on this island are preferred to be electric or fuel cell vehicles in order to achieve zero emissions. Renewable energy will be used as the main source of electricity for electrolysis of water and hydrogen production. Hydrogen bottles, batteries and hot water packages are used as energy storage units.

2. System Design

In order to effectively begin designing the system and the location and capability of the charging station, it was necessary to set some design parameters. Eight (8) popular spots on the island were chosen to set up a green line tour (Fig. 1) such as the Chong Ming National Forest Park, Wetland Park and so on, and set up yellow line tour (Fig. 1) between the island's major inside transfer center and the transport hub.

Fig. 1. Green line tour (transit bus) and yellow line tour (shuttle vehicle)

A. Parameters

Google Maps were used to measure the distance for these two routes (Table II).

Table II. – Parameters of Operation

Bus Tour		Minibus Tour	
Distance(km/tour)	127	Distance(km/tour)	52

It was determined that our design would use SAIC fuel cell buses and commercial vehicles to serve as tour buses and shuttle vehicles (Fig. 2). Using data for these two types of vehicles, the fuel demand was calculated (Table III).

Table III. – Vehicle Design Parameters

Fuel Cell Transit Bus		**Fuel Cell Shuttle Vehicle**	
H_2 Consumption (kg/100 km)	7.7	H_2 Consumption (kg/100 km)	2.7
Number of buses	4	Number of Vehicles	8
Speed (km/hr)	40	Speed (km/hr)	55

Fig. 2. FC transit bus (L) and FC shuttle vehicle (R)

B. Schedule

Once the location of the lines and their respective lengths had been determined, it was necessary to determine operation requirements including operation time and number of shifts. The operation time was determined from the distance and the speed of vehicles:

$$\text{OperationTime} = \text{Distance/Speed}$$

Operation time of the fuel cell bus per tour = 127/40 ~ 3 hours . Operation time of the fuel cell commercial vehicle per tour = 52/55 ~ 1 hour

Assuming the operation times are from 7:00 to 18:00, the schedules for these two lines were developed as shown in Table IV.

Table IV. – Schedule for the Two Lines

Bus	Schedule of Transit Bus		Shuttle	Schedule of Shuttle Bus			
#1	7:00 — 10:30	13:00 — 16:30	#1 #2	7:00 — 8:00	10:00 — 11:00	13:30 — 14:30	15:30 — 16:30
#2	7:30 — 11:00	13:30 — 17:00	#3 #4	7:30 — 8:30	10:30 — 11:30	14:00 — 15:00	16:00 — 17:00
#3	8:00 — 11:30	14:00 — 17:30	#5 #6	8:00 — 9:00	11:00 — 12:00	14:30 — 15:30	16:30 — 17:30
#4	8:30 — 12:00	14:30 — 18:00	#7 #8	9:30 — 10:30	13:00 — 14:00	15:00 — 16:00	17:00 — 18:00

Operation parameters are shown in Table V.

Table V. – Operation Parameters

Operation Parameters of Fuel Cell Transit Bus		Operating Parameters of Fuel Cell Shuttle Bus	
Operation time (hr/Tour)	3.5	Operation time (hr/Tour)	1
Shift (Tour/Day)	8	Shift (Tour/Day)	16

3. Hydrogen Demand

To ensure that the operation of fuel cell buses and shuttle vehicles is executed under schedule, the hydrogen consumption needed to be calculated. The equation used to calculate this value is:

Hydrogen consumption = number of shifts x hydrogen consumption/100 km x operation distance/100

Hydrogen consumption of fuel cell buses = 8*7.7*(127/100) = 78 kg /day

Hydrogen consumption of fuel cell commercial vehicles = 16*2.7*(52/100) =22 kg/day

Total hydrogen demand = 78+22 = 100 kg/day

The combination of a tunnel and a bridge are the only way connecting the island and the mainland. *They cannot be used for hydrogen transportation due to a prohibition issued by the government for safety reasons.* The island is to be established as a "green island" hence no chemical industry will be developed on this island. *The hydrogen needed (100 kg/day) should be produced through electrolysis on location.*

4. System Specifications

In order to verify the feasibility of the system, a *small-scale simulated physical system* was set up in an office building. This building belongs to a fuel cell system assembly company (Re-Fire Technology). The simulation system includes 6 modules: solar power, electrolysis, fuel cell CHP (combined heat and power), hydrogen storage, batteries and a test bench. It was assumed that solar power, as a renewable and primary source, is used to generate electricity. Electrolysis is used to produce hydrogen, and hydrogen storage and batteries are used as storage units. Considering that one of the businesses of this company is testing power systems, an existing test bench they already own is arranged as the load of the simulation system which can be simply regarded as the hydrogen charging station in the real system. The basic circuit and architecture shown in Fig. 3 was created. This allowed us to easily determine the electricity demand for electrolysis as well as other power requirements. Simulation system layout on the building is shown in Fig. 4.

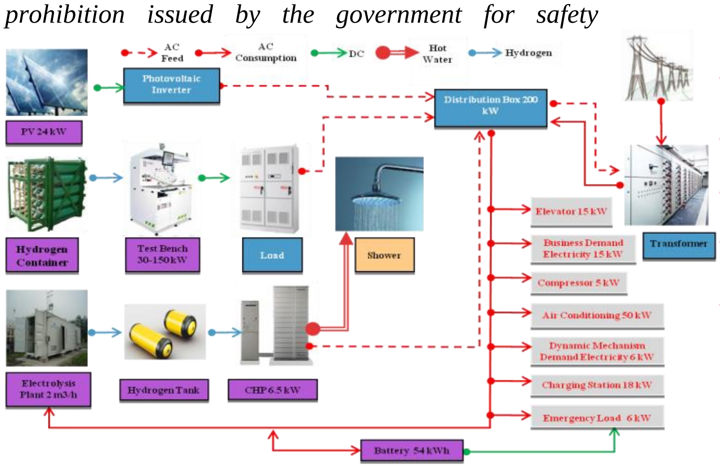

Fig. 3. Circuit and architecture of the building multi-energy management system

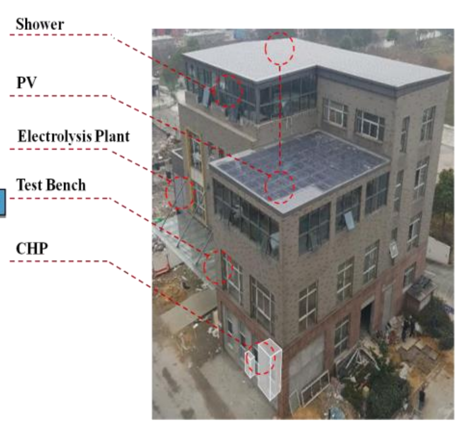

Fig. 4. Simulation system layout on the building

5. Calculations

A. Module 1: Solar power

Two hundred ninety eight (298) 80-W (each) polycrystalline silicon photovoltaic panels have been installed on the roof of the building.

Roof area = 600 m^2
Area of one panel = 1 m x 1 m = 1 m^2
Effective roof area = 50% of actual roof area = 300 m^2

The number of photovoltaic panels that could actually be installed is 298.

According to the Renewable Energy Data Manual, released by China National Renewable Energy Centre (2015), the effective (annual average) sunshine time is 3.08 hours per day in Shanghai.
The theoretical power of total photovoltaic panel = 298 *80 W*3.08= 73.4 kW.h/day

The electric power consumption of the auxiliary equipment is 9 kW.

Figs. 5 and 6 show the employee gym equipment with solar panels as well as the electrolysis equipment and its specifications.

Fig. 5. GYM with photovoltaic panel roof

Fig. 6. Electrolysis equipment and its specifications

B. Module 2: Electrolysis

As shown in Fig. 6, the *electrolysis equipment capability is 2.0 m^3/h of hydrogen*. Its electric power consumption is 4.2 kW.

For an ideal gas, the number of moles and volume are related by the ideal gas equation of state:

$$PV=NR_uT$$

At standard conditions, 101.3 kPa and 0 °C, the molar volume is:

Molecular mass of Hydrogen is 2.0158 kg/kmol. The density of hydrogen is calculated as:

$$\rho = 0.0899 \text{ kg/m}^3$$

Operation time of the equipment for each day is 16 hours (two 8-hour shifts). The amount of hydrogen it can produce is:

$$2.0 \text{ m}^3\text{/h x 16 h/day x 0.0899 kg/m}^3 = 2.88 \text{ kg/day}$$

Actual hydrogen required by the vehicles is 100 kg/day.

The power consumed by the electrolysis equipment is 4.2 kW, Electricity demand per day is:

4.2 x 16 = 67.2 kWh

C. Module 3: Fuel Cell CHP

A PEM fuel cell is an electrochemical device which brings hydrogen and air together and produces direct electricity, water and heat. The Fuel Cell module used in the *small-scale simulated system* (not pictured) has an output power of 6.5 kW, and an output voltage of 40-75 Volts. Hydrogen consumption is 0.325 kg/hr.

The basic fuel cell reactions are [1],[2]:

At the anode: $H_2 \rightarrow 2H^+ + 2e^-$
At the cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$

The overall reaction is the same as the reaction of hydrogen combustion, which means that there is energy released in the process:

Overall: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ + heat + electricity

At standard conditions, that is 101.3 kPa and 0°C, the heat released is:

$$HHV = 141.8 \text{ MJ/kg}$$

Total heat supplied by fuel cell CHP is:

$$141.8 \times 0.325 = 46.12 \text{ MJ/h} = 12.8 \text{ kW}$$

Specific heat of water is 4.186 kJ/(Kg °C). This means that to heat 1 kg water by 1°C, 4.186 KJ of heat is needed. It was assumed that the water inlet temperature is 15 °C, and suitable shower temperature should be around 37 °C which is close to the human body temperature. We need to heat the water by 22 °C. *One kg of hydrogen* can release 141.8 MJ of heat, which can heat the water by 22 °C:

$$Q = mc\,\Delta T$$

$$46.12*1000 = m*4.186*22$$

$m = 501$ *kg of water*

The hot water tank is shown in Fig. 7 (L).

Fig. 7. Hot water tank (L) and Main hydrogen storage tanks (R)

D. Module 4: Hydrogen storage

Figs. 7 (R) and 8 show the main and the spare hydrogen storage tanks.

Fig. 8. Spare hydrogen storage tanks

The two 6-m^3 main tanks shown in Fig. 7 (R) store hydrogen produced by electrolysis, especially at night during the off-peak hours. The electric power consumed to keep the two tanks pressurized is 1 kW.

E. Module 5: Battery

Three (3) battery packages were used. One of them is shown in Fig. 9 (L). Each can store 18 kWh. Together, they can store 54 kWh at the night. The control box is shown in Fig. 9 (R).

Fig. 9. Battery (L) and Control box (R)

F. Module 6: Test bench

The test bench and a fuel cell stack are shown in Fig. 10. *Re-Fire Technology* uses the test bench to test performance of different fuel cell stacks with an output power of 30-150 kW. Hydrogen consumption for 30 kW of power is 1.5 kg/h. The heat produced is:

$$141.8 \times 1.5 = 212.7 \text{ MJ/h} = 59 \text{ kW}$$

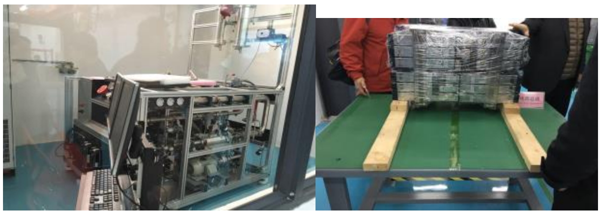

Fig. 10. Test bench (L) and a fell cell stack (R)

The parameters used for the simulation are shown in Table VI. It is obvious that solar energy can support the electricity demand of electrolysis, but the capacity of electrolysis does not meet the demand for hydrogen.

Table VI. – System Specifications

	Electrolysis	Batt.	FC CHP	Solar Power	H_2 Storage	Test bench
Power			6.5 kW	73.4 kW.h /day		
Capacity	2.0 m^3/hr or 2.88 kg/day	54 kWh	6.5 kW		12 m^3 or 1.08 kg	30-150 kWh
Consu-mption	4.2 kW (16 h/day)		0.325 kg/h	9 kWh/ day (accessories)	1 kWh/ day	1.5 kg/h @ 30 kW
Avail. Heat			12.8 kW			59 kW

6. Test Data

The *physically simulated system* was operated and data for October 3-23, 2016 were recorded. The data included solar energy supply, fuel cell supply, and hydrogen supply. The data is shown in Fig. 11.

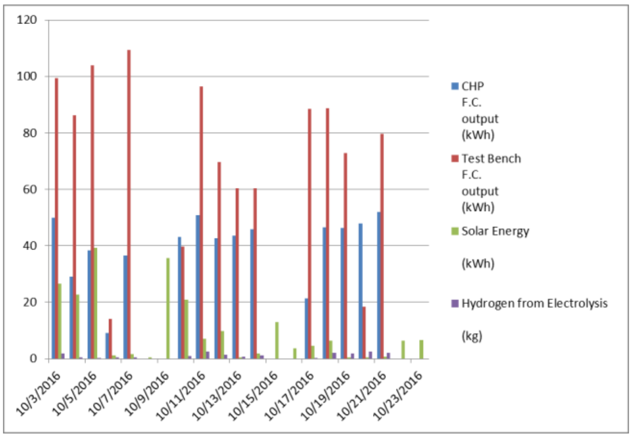

Fig. 11. Test data for October 3-23, 2016

Table VII shows the physically-simulated system specifications. The hydrogen needed (100 kg/day) should be produced through electrolysis on location.

Table VII. – Specifications of the actual system in Chungming Island

	Electrolysis	Solar Power	H_2 Storage	Wind & Grid Accessor-ies
Capacity	100 kg/day	73.4 kWh/day	20 kg	2638 kWh/day
Consu-mption	2333 kWh per day	20% of capacity is used by accessori-es	20 kWh/day used for H_2 compress-ion	15% of capacity

Solar power with a photovoltaic panel area of 298 m^2 can only supply 73.4 out of 2333 kWh/day (3%) of the electricity demand for electrolysis if the energy needed to serve the community is to be supplied. Wind power and the grid should be used as the main sources of energy. The capacity of wind power and the grid should be at least (2333-73.4+14+20)*1.15 = 2638 kWh/day to satisfy the energy demand of fuel cell vehicles running on the two routes.

These results show that PV based power is not reasonable for the scale of the real system in Chungming Island. As an Island with abundant wind, wind power and the grid should be used as main sources of energy. Hydrogen produced by electrolysis is not economical because of the double conversion of electrical energy. Power density and efficiency should be considered when choosing an energy storage unit [3].

7. Energy Source Data for the Island

Nine wind farms have been built on Chungming Island since 2007, with a total installed capacity of 291 MW. The annual generating capacity is up to 0.6 TWh. Wind speed in the Chungming inland area is approximately 3.5-4.0 m/s. Wind speed around Chungming-Dongtan, Hengsha Island and the Yangtze River Estuary is 5.5-6.0 /s.

The total annual generation can be calculated through the ampere-hour of the wind power generator by gathering data systematically. According to the records of *Changxing Power Company*, Island wind power generation operating time was more than 2700 hours last year.

Chungming photovoltaic applications started earlier than any other area. China's first commercial operation of photovoltaic 1 MW *avant-garde photovoltaic power station* was located in Chungming Island in 2007. During the past two years, with the national and Shanghai PV subsidy policy being introduced, 8 enterprise distributed PV projects and 50 personal distributed photovoltaic projects have been built, with a total installed capacity of 3400 kW. Chungming Island has been categorized as a Class-3 type area for solar energy. According to the local government, a PV system with 1 kW of power can generate 1100 kWh of electric energy per year in this area.

8. Economic Analysis

According to [5], the 2013 cost to build a solar power station in China is as shown in Table VIII:

Table VIII. – 2013 cost of a solar power station in China

Item	**US$ /kW**	**Decrease Relative to Previous Year**	**Equipment**	**Price**
Equipment & Installation	1952	8.4%	PV Module	0.99 US$/W
Constructional Engineering	240	9.7%	Inverter System	490,000 US$/set
Other Expenses	157	52.1%		
Basic Reserve Funds	36	94.3%		
Loan Interest in a Construction Cycle	43	28.5%		
Total Investment	2430	13.0%		

(Source: [5] The statistics assessment report of construction of solar power generation in China 2013, page 35, page 39, National Energy Administration of China, US Dollar vs. China Yuan = 1:7)

Based on the calculations, the electricity consumption for running fuel cell vehicles in Chungming Island is 2638 kWh/day. Assume running 360 days per year; the total consumption is:

2638 kWh/day * 360/1000 = 950 MWh/year

A fully operational wind generating set with a power capacity of 750 kW (operating 2700 hours/year) can generate:

750 kW * 2700 hr*(1MW/1000 kW) = 2025 MWh /year

In this study, a roof area of 600 m^2 was used, resulting in 73.4 kW.h/day:

73.4 kW.h/day * 1100 operating hours/year = 80.7 MWh/year

A 750 kW wind generator set and the PV roof can be used as the energy supply system. This system can meet the fuel cell bus operation demand (950 MWh/year) and can serve the local community as well.

Taking 1304 $US/kW as unit cost of wind power generation, 471 $US/kW as unit cost of additional wind power equipment, with a 75-ton tower ($US 1460/ton) [4],[5] the cost of the wind power system is estimated to be:

(1304*750) + (471*750) + (1460*75) = 1.44 Million $US

Cost for procurement of the solar power system and construction of the facility is:

2430 US$/kW *298 panels *80 W/panel / 1000 = 0.06 Million $US.

The breakdown of the total cost of the multi-energy power system in Chungming is shown in Table IX.

Table IX. – Cost and lifetime of the multi-energy system in Chungming Island

ITEM	**COST**	**UNIT**
Compressor	228,571	US$
Compressor Life	10	years
Medium Pressure Storage	214,285	US$
Storage Life	20	years
High Pressure Storage	214,285	US$
Storage Life	20	years
Dispenser Cost	128,571	US$
Dispenser Life	10	years
Electrolysis Cost	428,571	US$
Electrolysis Life	10	years
Controller Cost~ ¥ 100,000	142,857	US$
Building Cost	71,428	US$
Construction Cost~ ¥ 100,000	142,857	US$
Other~ ¥ 100,000	142,857	US$
Hydrogen Station Life	20	years
Battery Cost	571	$US/kWh
Battery Capacity	54	kWh
Battery Package Cost	30,834	US$
Wind Power System	1.44 million	US$
Wind System Life	20	Years
Solar Power system	0.06 million	US$
Solar System Life	25	Years
Total Cost	**3.0 million**	**US$**

9. Summary and Conclusions

- The Shanghai government intends to transform Chungming Island in China into a green ecological base. As a part of this idea, vehicles on this island are preferred to be electric or fuel cell vehicles in order to achieve zero emissions. The design will use SAIC fuel cell buses and commercial vehicles (minibuses) to serve as tour buses and shuttle minibuses.

- A multi-energy management system was studied for use on this island. This system will support a fuel cell transit bus tour and a shuttle minibus route. The island's demand for hydrogen, according to the parameters of the vehicles and the routes, was determined to be 100 kg/day. The hydrogen will be produced through electrolysis on location.

- In order to verify the feasibility of the system, a *small-scale simulated physical* system was set up in an office building. This simulated physical system consists of 298 solar PV panels, an electrolysis module, a hydrogen storage module, a battery module, and a test bench used for data collection. Two hundred ninety eight 80-W, 1 m x 1 m (each) polycrystalline silicon photovoltaic panels have been installed on the roof of the building. The total maximum capacity of the PV system is 73.4 kW.h/day. The electrolysis equipment capability is 2.0 m^3/h of hydrogen. Its electric power consumption is 4.2 kW. It operates 16 hours per day. Its daily electricity demand is 67.2 kW.h. The fuel cell module used in the *small-scale simulated system* has an output power of 6.5 kW. Its hydrogen consumption is 0.325 kg/hr. Three battery packages are used. Together, they can store 54 kWh at night.

- Based on data collected *during autumn*, solar power with a photovoltaic panel area of 298 m^2 can only supply 73.4 out of 2333 kWh/day (3%) of the electricity demand for electrolysis if the energy needed to serve the *island community* is to be supplied. Wind power and the grid should be used as main sources of energy. The capacity of wind power and the grid should be at least 2638 kWh/day (950 MWh/year assuming 360 days of operation/year) to satisfy the energy demand of fuel cell vehicles running on the two routes.

- The results show that PV-based power is not reasonable for the scale of the real system on Chungming Island. As an Island with abundant wind, wind power and the grid should be used as main sources of energy. Hydrogen produced by electrolysis is not economical because of the double conversion of energy.

- Nine wind farms have been built on Chungming Island since 2007, with a total installed capacity of 291 MW. The annual generating capacity is up to 0.6 TWh. The wind speed in the Chungming inland area is approximately 3.5-4.0 m/s. Wind speed around Chungming-Dongtan, Hengsha Island and the Yangtze River Estuary is 5.5-6.0 m/s.

- Chungming Island has been categorized as a Class-3 type area for solar energy. According to the local government, a 1-kW PV system can generate 1100 kWh of electric energy per year in this area. Based on the calculations, the electricity consumption for running fuel cell vehicles in Chungming Island is 2638 kWh/day. Assuming 360 days of operation per year, the total consumption is 950 MWh/year. A 750 kW wind generator set and the PV roof can be used as the energy supply system. This system can meet the fuel cell bus operation demand (950 MWh/year) *and* serve the local community as well.

- Taking 1304 $US/kW as unit cost of wind power generation, 471 $US/kW as unit cost of additional wind power equipment, with a 75-ton tower ($US 1460/ton) and including all other equipment (electrolysis, hydrogen storage equipment, batteries, etc.), the total cost of the system is estimated to be 3.0 Million $US.

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