# 가정의 전기 수요를 고려한 태양전지-연료전지 하이브리드 에너지시스템의 경제성 평가

논 문
59P-1-20

# Economical Feasibility Evaluation of Solar-Fuel Cells in Hybrid Energy System for Domestic Electricity Demands

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**Abstract** - The solar cells and fuel cells power are being encouraged to reduce the environmental pollution and combat the global warming. And the electric generation hybrid system is usually more reliable and less costly than the systems that use a single source of energy. HOMER provides a platform to design and simulate the power system and then to choose the optimization results. Based on the electricity demand conditions during a year, this paper simulates with the HOMER and performs the monthly average electrical production and the most feasible economical case includes the net present costs and the annualized costs of the hybrid system components.

**Key Words** : Solar Cell, Fuel Cell, HOMER Micropower Optimization Model, Residential Appliances

## 1. Introduction

Excessive atmospheric pollution growth is an extremely serious problem in the contemporary world. Solar energy and fuel cell energy are important parts of renewable energy which are considered as the most promising new energy technology in the world today. Experts predict that by mid-21st century, solar energy will be an important way to generate electricity and occupies a certain proportion in the world energy consumption structure [1]. However, the single solar power generation may cause insufficient power supply in certain time of a year. Besides, the insufficient supply of electricity often results in excessive battery discharge and affects the battery life seriously.

A PEMFC (polymer electrolyte membrane fuel cell) for residential use has been considered to be suitable for small scale distributed power, which involves a PEMFC stack with a hydrogen generation system to provide electricity to residential loads. High efficiency, low noise, and low emission of air pollutants should be the major benefits obtained from the use of PEMFC system [2]. So, the paper presents a hybrid system consists of solar cell energy and PEMFC energy to supply power to domestic electricity demands to ensure a balanced power supply throughout a year.

The HOMER Micropower Optimization Model is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) to assist in the design of micropower systems and to facilitate the comparison of power generation technologies across a wide range of applications [3].

The object of the study is the domestic electricity demands which havesome base loads occur throughout the day and night and some majority loads occur in day or in night. Based on the data of the loads demand and power supply, utilizing the HOMER, a simulation about supply demand relationship can be done and from the simulation results, the optimization results can be presented.

## 2. Hybrid System

Generally, a hybrid energy system consists of several energy sources and relative components. When designing a hybrid system, both the sizing of the elements and the most adequate control strategy must be obtained. In this paper, the hybrid system includes solar cells, fuel cell, electrolyzer, hydrogen tank, converter and surrette S460 battery. Table 1 shows the technical data of hybrid system components. It shows that the PV array size is from 0.800 [kW] to 8.000 [kW], FC size is from 1.00 [kW] to 3.00 [kW], S460 battery number is from 1 to 6, converter size is from 1.00 [kW] to 4.00 [kW], electrolyzer size is from 1.00 [kW] to 3.00 [kW], hydrogen tank size is from 0.10 [kg] to 0.50 [kg].

Fig. 1 shows the proposed scheme as implemented in the HOMER simulation tool. Because the fuel cell is supplied directly with hydrogen in this system. It needs the electrolyzer to generate hydrogen and hydrogen tank to store the hydrogen.

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Table 1 The technical data of hybrid system components.

| PV Array (kW) | FC (kW) | S460 (Quantity) | Converter (kW) | Electrolyzer (kW) | H2 Tank (kg) |
|---|---|---|---|---|---|
| 0.800 | 1.00 | 1 | 1.00 | 1.00 | 0.10 |
| 1.000 | 2.00 | 2 | 2.00 | 2.00 | 0.20 |
| 2.000 | 3.00 | 3 | 3.00 | 3.00 | 0.30 |
| 3.000 | | 4 | 4.00 | | 0.40 |
| 4.000 | | 5 | | | 0.50 |
| 5.000 | | 6 | | | |
| 6.000 | | | | | |
| 7.000 | | | | | |
| 8.000 | | | | | |

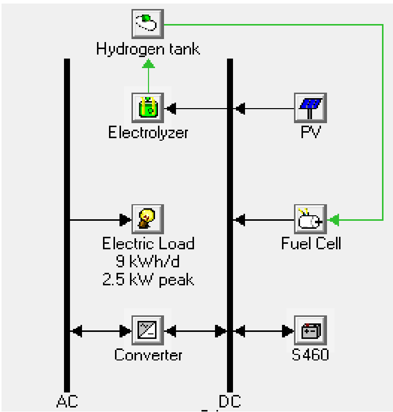



Fig. 1 HOMER implementation of the hybrid energy system.

## 2.1 Load

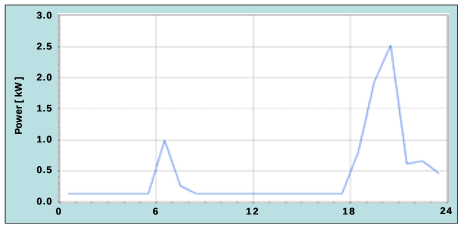
The hybrid system consists of solar cell and fuel cell supply power to domestic electricity demands which have some base loads occur throughout the day time and night time and some majority loads occur in day time or in nighttime. Table 2 shows the power demand of various domestic electricity demands which consist of TV, refrigerator, vacuum cleaner, washing machine, electric iron, electric cooker, microwave oven, smoke exhauster, electric fan, air-condition, audio, hand phone chargers, computer, monitor, printer, scanner, hair drier and lamps. The total daily load averages 9 [kWh/day], with a peak load of 2.5 [kW].

Fig. 2 presents the hourly load of the domestic electricity demands for weekday and weekend in July. Fig. 2 (a) presents that the domestic electricity demands are much during 6:00 to 8:00 in the morning and 18:00 to 24:00 at night on weekday. During day time, the only domestic electricity demand is the refrigerator and during 20:00 to 21:00, the loads demand reaches the peak. Fig. 2 (b) presents that the domestic electricity demands are much from 8:00 in the morning to 24:00 at night at the weekend.

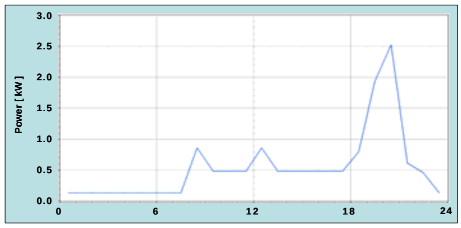
The loads data belong to the January to December, as shown in Fig. 3. Between June to August, three energy peaks are observed namely at night around 20:00 to 22:00. Almost the same energy consumption pattern is observed during January to May and during September to December.

Table 2 The power demand of various domestic electricity demands.

| Domestic Appliance | Power Demand [W] |
|---|---|
| TV | 120 |
| Refrigerator | 128 |
| vacuum cleaner | 600 |
| washing machine | 130 |
| electric iron | 600 |
| electric cooker | 500 |
| microwave oven | 1250 |
| Smoke Exhauster | 200 |
| electric fan | 55 |
| air-condition | 1300 |
| audio | 40 |
| hand phone charger | 6*4=24 |
| computer | 70 |
| monitor | 100 |
| printer | 430 |
| scanner | 50 |
| hair drier | 1000 |
| lamps | 133 |




(a) A weekday of July.




(b) A weekend of July.

Fig. 2 Hourly load of the system for a weekday and a weekend of July.

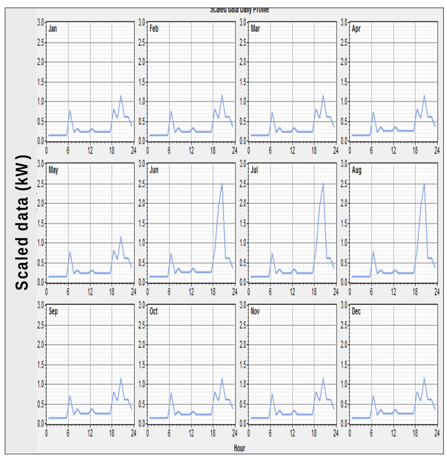



Fig. 3 Monthly average load profile (January to December).

In probability theory, a probability density function (pdf)–often referred to as a probability distribution function–or density, of a random variable is a function that describes the density of probability at each point in the sample space. The probability of a random variable falling within a given set is given by the integral of its density over the set [8]. If F is the cumulative distribution function of x, then it can get the following:

$$F(x)=\int_{\infty}^{x} f(t)dt \qquad (1)$$

The PDF of loads, namely, the percent frequency of occurrence of a certain load is shown in Fig. 4. Almost 58 [%] of time the load requirement is found to be between 0.1 [kW] to 0.2 [kW] and 14 [%] of time to be between 0.4 [kW] to 0.5 [kW]. The power demand is found to be around 2.5 [kW] for only almost 2 [%] of the time.

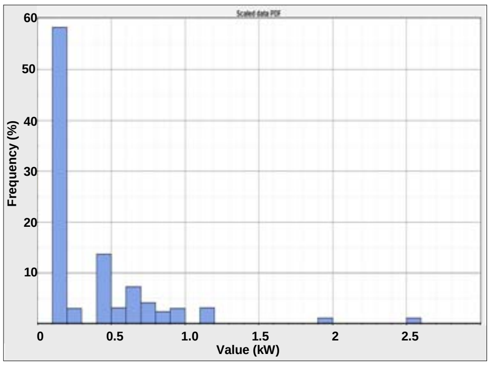



Fig. 4 Electrical load frequency variation for domestic electricity demands.

## 2.2 Renewable resources

### 2.2.1 Solar energy resource

The Kwangju radiation monthly data are obtained from New & Renewable Energy Resource Map Data Center. Fig. 5 illustrates the radiation and clearness index profile over a one-year period in Kwangju. During August, the solar radiation is more than other times of the year.

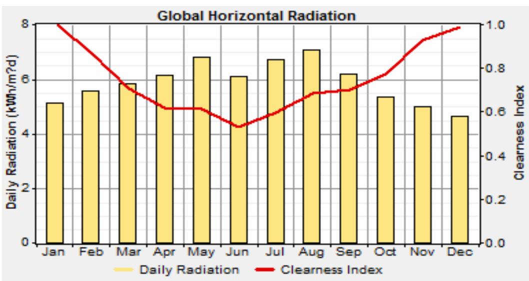
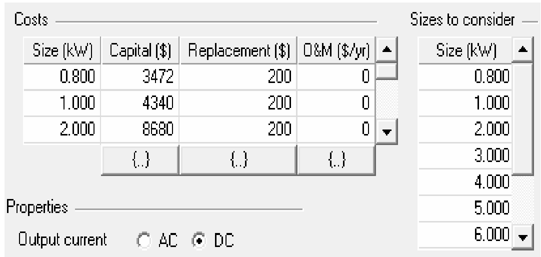



Fig. 5 Solar Radiation profile for Kwangju [9].

Four sensitivity variables (solar cell size, solar cell capital, solar cell replacement as well as operation and maintenance cost) are considered of solar cell. Fig. 6 shows the size and cost data of the four sensitivity variables of solar cell.



Costs

| Size (kW) | Capital ($) | Replacement ($) | O&M ($/yr) |
|---|---|---|---|
| 0.800 | 3472 | 200 | 0 |
| 1.000 | 4340 | 200 | 0 |
| 2.000 | 8680 | 200 | 0 |
| | {..} | {..} | {..} |

Sizes to consider

| Size (kW) |
|---|
| 0.800 |
| 1.000 |
| 2.000 |
| 3.000 |
| 4.000 |
| 5.000 |
| 6.000 |

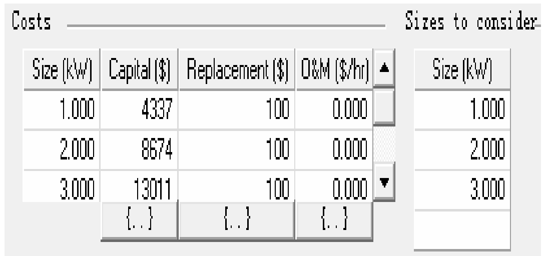
Properties

Output current ○ AC ● DC

Fig. 6 Solar cell size and cost consideration [10].

### 2.2.2 Fuel cell

Four sensitivity variables (fuel cell size, fuel cell capital, fuel cell replacement as well as operation and maintenance cost) are considered of fuel cell. Fig. 7 shows the size and cost data of the four sensitivity variables of fuel cell.



Costs

| Size (kW) | Capital ($) | Replacement ($) | O&M ($/hr) |
|---|---|---|---|
| 1.000 | 4337 | 100 | 0.000 |
| 2.000 | 8674 | 100 | 0.000 |
| 3.000 | 13011 | 100 | 0.000 |
| | {..} | {..} | {..} |

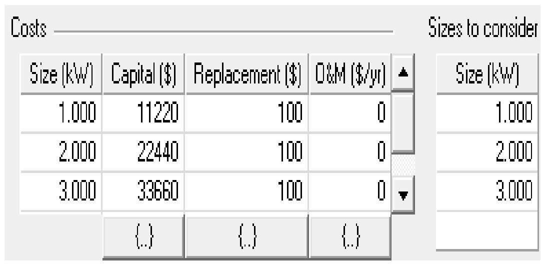
Sizes to consider

| Size (kW) |
|---|
| 1.000 |
| 2.000 |
| 3.000 |

Fig. 7 Fuel cell size and cost consideration [11].

### 2.2.3 Electrolyzer

Four sensitivity variables (electrolyzer size, electrolyzer capital, electrolyzer replacement as well as operation and maintenance cost) are considered of electrolyzer. Fig. 8 shows the size and cost data of the four sensitivity variables of electrolyzer.



Costs

| Size (kW) | Capital ($) | Replacement ($) | O&M ($/yr) |
|---|---|---|---|
| 1.000 | 11220 | 100 | 0 |
| 2.000 | 22440 | 100 | 0 |
| 3.000 | 33660 | 100 | 0 |
| | {..} | {..} | {..} |

Sizes to consider

| Size (kW) |
|---|
| 1.000 |
| 2.000 |
| 3.000 |

Fig. 8 Electrolyzer size and cost consideration [11].

### 2.2.4 Hydrogen tank

Four sensitivity variables (hydrogen tank size, hydrogen tank capital, hydrogen tank replacement as well as operation and maintenance cost) are considered of hydrogen tank. Fig. 10 shows the size and cost data of the four sensitivity variables of hydrogen tank.

Costs — Sizes to consider

| Size (kg) | Capital ($) | Replacement ($) | O&M ($/yr) | Size (kg) |
|---|---|---|---|---|
| 0.100 | 66 | 66 | 0 | 0.100 |
| 0.200 | 132 | 132 | 0 | 0.200 |
| 0.300 | 198 | 198 | 0 | 0.300 |
| | {..} | {..} | {..} | 0.400 |
| | | | | 0.500 |

Fig. 9 Hydrogen tank size and cost consideration [11].

### 2.3 Economical evaluation

The evaluation of the cost of the produced energy by the hybrid system is made by using the life-cycle costing (LCC). The LCC evaluation needs that all costs and benefits, present and future, are brought back to net present cost (NPC). The NPC includes all costs and revenues that occur within the project lifetime. And the NPC has two types of the single net present cost which is paid in one lump sum and the annualized cost which is paid in annual payment.

HOMER uses the following equation to calculate the total net present cost:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{2}$$

where $C_{ann,tot}$ is the total annualized cost, $i$ is the annual real interest rate (the discount rate), $R_{proj}$ is the project lifetime, and $R_{proj}$ is the capital recovery factor, given by the equation

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{3}$$

where $i$ is the annual real interest rate and $N$ is the number of years.

HOMER uses the following equation to calculate the levelized cost of energy (COE):

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}} \tag{4}$$

where $E_{prim}$ and $E_{def}$ are the total amounts of primary and deferrable load, respectively, that the system serves per year, and $E_{grid,sales}$ is the amount of energy sold to the grid per year [5, 10].

## 3. Results and Discussion

A total of 3,888times simulations have been done in this paper. In HOMER software, the optimized results are presented categorically for a particular set of sensitivity parameters. The optimization results are presented in Fig. 10. The most feasible economical case is the COE (Cost of Electricity) of 1.684 [$/kWh]. This is merely due to the small size of PV and $H_2$ tank and more quantity of battery than other cases. Here, the rated power of PV module is assumed as 6.0 [kW] and the rated power of FC is assumed as 1 [kW]. The assumed battery quantity is 6, the rated power of converter is assumed as 4 [kW], the rated power of electrolyzer is assumed as 3 [kW] and the size of the $H_2$ tank is 0.4 [kg].

| PV (kW) | FC (kW) | S460 | Conv. (kW) | Elec. (kW) | H2 Tank (kg) | Initial Capital | Operating Cost ($... | Total NPC | COE ($/kWh) |
|---|---|---|---|---|---|---|---|---|---|
| 6.0 | 1 | 6 | 4 | 3 | 0.4 | $ 70,401 | 30 | $ 70,786 | 1.684 |
| 6.0 | 1 | 6 | 4 | 3 | 0.5 | $ 70,467 | 34 | $ 70,904 | 1.685 |
| 7.0 | 1 | 5 | 4 | 3 | 0.4 | $ 74,391 | 30 | $ 74,769 | 1.778 |
| 6.0 | 2 | 5 | 4 | 3 | 0.5 | $ 74,454 | 33 | $ 74,875 | 1.785 |
| 7.0 | 1 | 5 | 4 | 3 | 0.5 | $ 74,457 | 33 | $ 74,885 | 1.779 |
| 7.0 | 1 | 6 | 4 | 3 | 0.4 | $ 74,741 | 30 | $ 75,127 | 1.784 |
| 6.0 | 2 | 6 | 4 | 3 | 0.5 | $ 74,804 | 34 | $ 75,236 | 1.789 |
| 7.0 | 1 | 6 | 4 | 3 | 0.5 | $ 74,807 | 34 | $ 75,245 | 1.786 |
| 7.0 | 2 | 4 | 4 | 3 | 0.5 | $ 78,444 | 32 | $ 78,857 | 1.878 |
| 8.0 | 1 | 5 | 4 | 3 | 0.4 | $ 78,731 | 29 | $ 79,107 | 1.879 |
| 6.0 | 3 | 5 | 4 | 3 | 0.5 | $ 78,791 | 33 | $ 79,210 | 1.888 |
| 7.0 | 2 | 5 | 4 | 3 | 0.5 | $ 78,794 | 33 | $ 79,218 | 1.883 |
| 8.0 | 1 | 5 | 4 | 3 | 0.5 | $ 78,797 | 33 | $ 79,224 | 1.881 |
| 8.0 | 1 | 6 | 4 | 3 | 0.4 | $ 79,081 | 30 | $ 79,468 | 1.886 |
| 6.0 | 3 | 6 | 4 | 3 | 0.5 | $ 79,141 | 34 | $ 79,570 | 1.892 |
| 7.0 | 2 | 6 | 4 | 3 | 0.5 | $ 79,144 | 34 | $ 79,578 | 1.889 |
| 8.0 | 1 | 6 | 4 | 3 | 0.5 | $ 79,147 | 34 | $ 79,585 | 1.887 |
| 8.0 | 2 | 3 | 4 | 3 | 0.5 | $ 82,434 | 32 | $ 82,842 | 1.973 |
| 7.0 | 3 | 4 | 4 | 3 | 0.5 | $ 82,781 | 32 | $ 83,192 | 1.981 |
| 8.0 | 2 | 4 | 4 | 3 | 0.5 | $ 82,784 | 32 | $ 83,198 | 1.977 |
| 7.0 | 3 | 5 | 4 | 3 | 0.5 | $ 83,131 | 33 | $ 83,552 | 1.986 |
| 8.0 | 2 | 5 | 4 | 3 | 0.5 | $ 83,134 | 33 | $ 83,559 | 1.984 |

Fig. 10 The optimization results of the hybrid system.

Although the COE of 1.684 [$/kWh] is much more than the cost of conventional energy generation, the emission of the hybrid system are clean. In addition, along with the technology development of solar cell and fuel cell, the cost of the solar cell and fuel cell will decrease in the future.

As seen from Fig. 11, the Net Present Costs of PV, FC, surrette S460, converter, electrolyzer and $H_2$ tank are 26,040 [$], 4,337 [$], 2,100 [$], 4,000 [$], 33,660 [$], 264 [$] respectively. From Fig. 6 and Fig. 7, the costs per watt of solar cell module and fuel cell stack are almost same. However, as the electrolyzer cost is much higher than the other components, if increase the capacity of the fuel cell, the capacity of auxiliary equipments of fuel cell such as the electrolyzer should be increased to match the capacity of fuel cell stack. So in the optimal case, the higher capacity of solar cell than the fuel cell caused the higher NPC of solar cell than the fuel cell.

In addition, from Fig. 12, the annualized costs of PV, FC, surrette S460, converter, electrolyzer and $H_2$ tank are 2,377 [$],

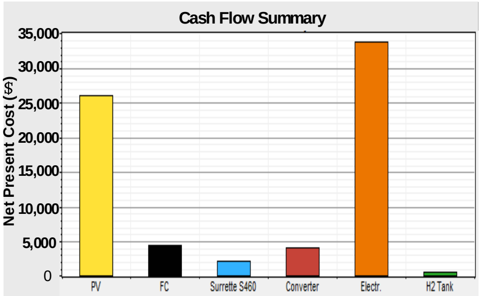



Fig. 11 The Net Present Costs of components.

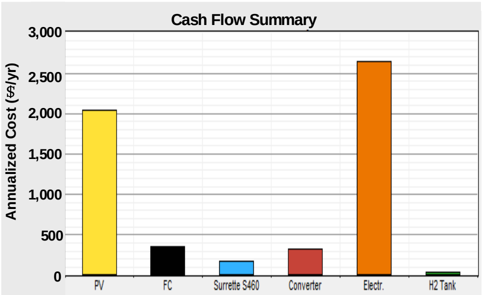



Fig. 12 The annualized costs per year of components.

2,738 [$], 110 [$], 63 [$], 2,347 [$], 430 [$] respectively. Because the lifetime of solar cell and fuel cell are almost same, the situations of annualized cost are similar with the NPC.

The energy yield from different components of the solar cell and fuel cell hybrid system is shown in Fig. 13. Of the total energy requirement of all domestic electricity demands, the solar cell produced 10,810 [kWh/yr] (87% of the total energy served) while the fuel cell produced 13% of the energy i.e. 1,649 [kWh/yr]. Considering economically, and the PV price is less than the total cost of FC and auxiliary equipments, the PV plays more important role than the FC.

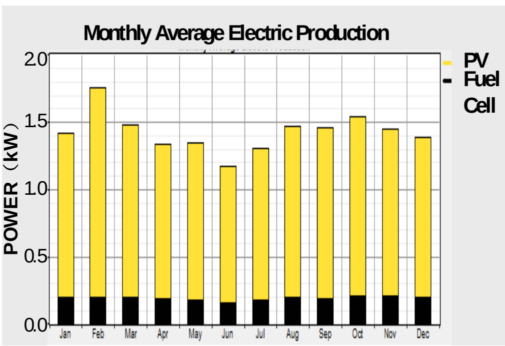



Fig. 13 The monthly average electrical production.

## 4. Conclusions

The paper performed the economical feasibility evaluation of hybrid energy system includes the solar cell energy and fuel cell energy to meet the different domestic electricity demands conditions throughout a year. The solar energy resource varies with geographical and climatic conditions, in addition, the high cost of the auxiliary equipments of fuel cell. So the accurate energy source calculation and the design of the components sizes in the hybrid power generation systems to match the different domestic electricity demands conditions are the key to get the optimal economical feasibility evaluation.

In the hybrid system, the electrolyzer utilizes the power to generate the hydrogen and supply the hydrogen to the fuel cell. The batteries saved the energy generated by the solar cells during daytime and supply to the domestic electricity demands at night or rainy day.

A total of 3,888 times simulations have been done using the hybrid system design tool HOMER in this paper. The most feasible economical case is the COE of 1.684 [$/kWh]. Furthermore, in the most feasible economical case, it showed the Net Present Costs and the annualized costs of hybrid system components. Besides, because of the high cost of auxiliary equipments of fuel cell, the main effect of the fuel cell is just supplying power to the domestic electricity demands to compensate the solar cells energy when the rainy day or the time of high domestic electricity demands. Of the total energy requirement of all domestic electricity demands, the solar cell produced 87% of the total energy served while the fuel cell produced 13% of the energy.


### Acknowledgement

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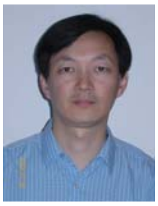

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