A SIMULATION-BASED ANALYSIS OF PHOTOVOLTAIC SYSTEM ADOPTION FOR RESIDENTIAL BUILDINGS IN ASIAN COUNTRIES

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ABSTRACT
In this study, a linear simulation model is developed for aiding the adoption of PV system in an economic way. The objective is to minimize annual energy cost including investment cost, maintenance cost, utility electricity cost, subtracting the revenue from selling the excess electricity. As an illustrative example, residential buildings in three Asian countries are selected as the end-use energy consumers for analysis. By using the developed simulation model, optimum sizes of the PV systems for residential buildings located in selected three countries are determined. In addition, sensitivities of some economic and policy conditions on PV system adoption are analyzed.

INTRODUCTION
Energy consumption in Asia has been growing rapidly over the past few decades. Especially, as the improvement of people's living quality and the acceleration of urbanization process, there is a dramatic increase in building energy consumption in this region. It was reported that the building sector accounted for approximately one third of the region's total energy consumption, and the value was projected to increase to an even higher value in the coming future (Yang et al., 2007). The enormous energy consumption and fossil fuel based energy structure have resulted in not only extensive emissions of local air pollutants (SO₂, NOx, etc.), but also great press on the global environmental issues (CO₂ emissions). If it is not solved in a good and efficient manner, not only will human society be beyond the goal of sustainable development, but it will also make a serious impact on the living environment and quality of human society. In this regard, the searching for a substitute for fossil energy sources has increased the interest in photovoltaic (PV) system as a long-term, inexhaustible, environmentally friendly and reliable energy technology. PV system has been proved to be an effective option in helping countries to meet their CO₂ reduction and renewable energy generation targets (Oliver and Jackson, 2001). In the process of introducing a PV system, one of the most important questions faced by potential customers is that of economic feasibility. In order to introduce the PV system in a rational way, it is of vital importance to employ a simulation model which can evaluate various economic aspects in a comprehensive way.

In this study, a linear simulation model is developed for aiding the adoption of PV system in an economic way. The objective is to minimize the annual energy cost of a given customer, including PV investment cost, maintenance cost, utility electricity cost, subtracting the revenue from selling the excess electricity. It requires the detailed structures and rates of electricity tariff, hourly irradiation data of the local site, hourly end-use load data for the customer, government policy (e.g. subsidies, etc) to the adoption of PV system, and PV system cost and performance data. The model, in turn, determines the economically optimal PV installation, as well as system performance statistics. On the other hand, if specific scale of PV system has been selected by the customer, the model can evaluate the economical, energetic and environmental effects according to customer’s selection.

As is known to all, individual homeowners are the most common buyers in the PV market. Therefore, in this study, as an illustrative example, residential buildings are selected as the end-use energy consumers to adopt the PV system. On the other hand, the economic performance of a PV system may be greatly dependent on the electricity tariff rates and local climate conditions. In this study, the focus is paid to three main Asian countries, namely, Japan, China and Thailand. Firstly, the current status of PV adoption and corresponding economic (tariff rates, etc.) and policy (subsidies, etc.) conditions in the selected three countries are reviewed. Then, foundational concept and mathematical equations of the simulation model for economically optimal PV adoption are introduced. Following which, various kinds of information (solar radiation, etc.) for numerical study are introduced and the simulation results are discussed in a detailed way. Finally, a conclusion of the study is deduced.

CURRENT CONDITIONS RELATED TO PV SYSTEM ADOPTION

Current status of PV system adoption
Japan has been one of the most successful PV industry and mature markets in the world. As shown in Figure 1, by the year 2008, total installed PV
capacity reached about 2.14 GW, which was about 16% of global PV capacity. Before 2004, Japan was the world largest PV adopter driven by the subsidies which were abolished in 2005. Since then, some European countries (Germany and Spain) had paid much attention to the adoption of PV system by introducing the feed-in tariffs (FIT: offering long-term contracts to renewable energy producers, typically based on the cost of generation of each different technology), and overtook Japan in the world PV market. In Japan, individual homeowners are the most common PV buyers, comprising nearly 90% of the market. Recently, in order to develop a sustainable low-carbon society, more active policies have been proposed by the government, such as the reissue of subsidies, as well as the increase of electricity buy-back price. It is expected that total PV capacity will increase to as large as 50 GW by the year 2020 (NEDO, 2004).

On the other hand, compared with the situation in Japan, PV adoptions in both China and Thailand are marginal. By the year 2008, total PV capacity in China was about 97.6 MW, which is far below that of Japan. Among all the applications, about 43% is for remote areas power supply, 40% is for communication and industrial applications. Building integrated PV system (BIPV), which takes up the dominant share in the PV market of developed countries, is mainly adopted in some demonstrative buildings. This, on one hand, leads to the dependence of Chinese PV cell industry, which is the world third largest producer, on the foreign market; on the other hand, results in large environmental load due to PV cell production, rather than reducing emissions though the application of PV system (Ren et al., 2009).

As to Thailand, the situation is similar to China. By the year 2008, total PV capacity in Thailand was about 32.2 MW, most of which was for remote area application. Recently, in order to cope with the continuing global warming, the Thai government has set national strategic policies on energy to focus more on power generation from renewable energy. Consequently, it is expected that the solar energy industry will dramatically expand and Thailand will be able to generate 250 MW of power from solar energy by the year 2011 to meet the increasing demand for energy.

**Electricity tariff structures and tariff rates**

In Japan, the electric utility service is provided by ten regional power companies. As to China, the situation is more complex. Generally, national electricity consumption is served by two companies, namely, Southern China Grid and State Grid which is further divided into five sub-grids. In addition, each sub-grid is composed of some province level companies. The situation is quite simple in Thailand due to its relatively small area. A single electric utility takes the role of whole power supply around the country. Although there may be some difference among the tariffs of various companies in a single country, the variation is marginal. Figure 2 and Figure 3 show the general electricity tariff structure in the three countries. Generally, residence, commerce and industry are always treated in a separate way. In addition, a normal rate and a time of use (TOU: electricity price that varies based on time of day and day of week) (or time of day, TOD: electricity price based on the time of day) rate are the main tariff structures in Japan, China and Thailand.
types in all three countries. However, according to the figures, some difference in the tariff structure can be concluded as follows:

1. As to the components of electricity tariff, China has the simplest one which is only composed of energy charge (calculated based on total power consumption) and demand charge (calculated based on the monthly peak electricity load, sometimes is neglected). In Thailand, a service charge is added to some applications. Japan has the most complicated tariff components. Besides the normal energy charge, the fuel cost adjustment amount which is calculated on the basis of average fuel prices is included. In addition, in order to promote the adoption of photovoltaic system, a solar surcharge which is proportional to the power consumption is expected to be introduced next year.

2. In a TOU or TOD tariff, the tariff rate may fluctuate according to the season and time period in Japan and China. However, in Thailand, due to the single season around the whole year, the tariff is only adjusted to the time period.

3. The division of time period is also different in three countries as shown in Fig. 3. In Japan, the on-peak period is mainly some hours at noon. However, in China, some morning and evening hours are also considered as the on-peak hours.

The comparison of electricity tariff rate is a hard work due to: on the one hand, different tariff structures may be introduced in various countries as discussed above; on the other hand, currency exchange rates are always fluctuating. In the following, the average unit rates based on statistical data are compared for the examined three countries. As shown in Figure 4, different from other two countries, the residential tariff rate is lower than the commercial and industrial one in China. Furthermore, Japan has a relatively high tariff rate than both China and Thailand.

In addition, it should be indicated that in order to promote the introduction of PV system, the power out of PV system is allowed to be sold back to the grid with a relatively high price (48 Yen/kWh) in Japan. However, this policy is currently not available in China and Thailand.

Policies for PV system adoption

In Japan, besides the subsidies which were discontinued in 2005, electricity buy-back price was increased to about twice of the previous value. However, this price is only available for the excess electricity from the PV system. In other words, the PV installer is not allowed to purchase and sell electricity simultaneously.

In China, the government issued the “Method of Financial subsidies for BIPV application” in March 2009 to boost the BIPV application in China. It is the first country policy for the promotion of BIPV adoption in China. According to the method, the capacity of a single project should be not less than 50 kW. Thus, it is much more suitable for public and commercial buildings, rather than the residential buildings. However, if is integrated into a cluster, the method can be also considered for the PV introduction in residential buildings. Currently, the subsidies are set to be about 0.3 $/W for the initial cost, and is priority for the public buildings, including school, hospital, government office, etc.

As to Thailand, in 2006, the government enacted a FIT that provided an adder paid on top of utility avoided costs, differentiated by technology type and generator size, and guaranteed for 7–10 years. Solar receives the highest, about 0.03 $/kWh.

DESCRIPTION OF THE SIMULATION MODEL

This model attempts to solve the optimal sizing problem of PV system utilizing the method of mathematical programming. The annual total cost is minimized from the viewpoint of long-term cost benefit analysis. The calculation of annual total cost includes the calculation of both capital cost and operation and maintenance (O&M) cost. The annual capital cost is calculated as the discount of the initial investment cost and the annual O&M cost is calculated as the interest of the capital cost. The model can be implemented for various planning horizons, and the results can be used to plan the optimal size of the PV system.
economics. As constraints of the evaluation model, it mainly considers the performance characteristic of PV system and the energy balance relationships of each energy flow to satisfy the load demands. Design variables of the model are composed of two parts, namely the PV capacity of the sizing problem and the variables expressing the operational strategies (electricity selling or for on-site use).

The algorithm of optimization procedure is shown in Figure 5. Initial values are given to the PV system at the beginning and the annual capital cost is evaluated. For a specific capacity with each searching step, the operational strategy is assessed and the annual energy charge is evaluated by the comprehensive relationships of load demands, PV system performance characteristics and energy balance of the whole system. Optimal values of PV capacities are searched so as to minimize the annual total cost. When the optimal criterion is satisfied, the optimal sizing of PV array taking in consideration of annual operational strategy can be determined. In addition, given a specific PV capacity, the economic and environmental characteristics of the whole energy system can be evaluated. Furthermore, the sensitivity analysis can be easily executed to understand the influence factors relating to the economic adoption of PV system.

Objective function
The objective function of the model is to minimize the annual energy cost of the given customer, as described in Eq. (1).

\[
\min \{ C_{\text{tot}} = C_{\text{sys}} + C_{\text{mai}} + C_{\text{pur}} - C_{\text{sal}} \} \tag{1}
\]

Where \( C_{\text{sys}} \) is the system investment cost (excluding subsidies), \( C_{\text{mai}} \) is the cost for maintenance of the system, \( C_{\text{pur}} \) is the cost for buying electricity power from the spot market, \( C_{\text{sal}} \) is the income from selling electricity back into the grid.

Main constraints
A balance of supply and demand has to be achieved for the electricity power at each point in time, as illustrated by Eq. (2).

\[
E_{\text{sel}}(d,h) + E_{\text{pur}}(d,h) \geq E_{\text{sal}}(d,h) \tag{2}
\]

where, \( E_{\text{sel}} \) is the power generation of on-site consumption, \( E_{\text{pur}} \) indicates the electricity purchased from the grid, and \( E_{\text{sal}} \) is the customer load. \( d \) and \( h \) indicate day and hour, respectively.

The electricity generation constraint can be defined as Eq. (3). The power output of a PV system depends on the irradiance on the PV cells, the efficiency and effective area of PV cells. Furthermore, the PV system can not generate exceeding its rated capacity.

\[
E_{\text{sel}}(d,h) + E_{\text{sal}}(d,h) \leq \min\{R(d,h) \cdot A \cdot \eta, A \cdot P_{\text{rat}}\} \tag{3}
\]

where, \( E_{\text{sal}} \) indicate the power sold back to the grid. \( R \) is the solar irradiation, \( A \) is the area of PV cells, \( \eta \) is the efficiency of PV system, and \( P_{\text{rat}} \) is the rated capacity of the PV cells.

In addition, additional constraint may be necessary to prevent the purchase and sales of electricity out of PV system at the same time.

\[
E_{\text{sel}}(d,h) = 0 \quad \text{if} \quad E_{\text{sel}}(d,h) + E_{\text{sal}}(d,h) < E_{\text{sal}}(d,h) \tag{4}
\]

NUMERICAL STUDY
An illustration of the model usage is presented below. It is a two-floor residential building with a total floor area of 150 m². Due to the climate conditions are fluctuated in different cities within a country, a major city within each of selected three countries has been selected for analysis. In detail, Kitakyushu is selected for Japan, Shanghai for China, and Bangkok for Thailand. The latitudes of the three cities are 33° 50' 0" N, 31° 0' 18" N and 13° 45' 8" N.

Load assessment
Customer load is one of the most important criteria determining the scale of the PV system. In this study, the all-electric system with PV adoption is assumed for the residential building. The average summer and winter electricity demands are given by hours, just as shown in Figure 6 and Figure 7, respectively. According to the figures, the following conclusions can be deduced:

Firstly, winter has a relatively high electricity load than that of summer, in both Japan and China.
However, in Thailand, summer and winter has similar load profile due to its high temperature with some fluctuation through the whole year.

Secondly, Japan has the largest electricity consumption in both summer and winter, followed by Thailand. On the contrary, China enjoys the least electricity load in selected three countries.

Finally, the daily load curves have similar trend, which peaks around 17:00-23:00, in all three countries, because of the characteristics of the residential building.

Climate data
The power generation out of the PV system is mainly depended on the solar radiation. Figure 8 shows the monthly mean daily global solar radiation in the three cities within the selected countries. It can be found that Thailand has relatively high irradiation throughout the whole year, followed by Japan and China. In addition, both Japan and China have the peak solar irradiation during the summer period, while Thailand peaks during spring and autumn.

Electricity tariff rates
Electricity tariff is one of the main economic conditions affecting the adoption of PV system. If the tariff rate is relatively low, customers may prefer to purchase the electricity from utilities rather than generate on-site. In this study, electricity tariffs for residential buildings in selected three cities are investigated from local electric utilities. As shown in Table 1, Japan has a relatively high tariff rates than other two countries for both Flat and TOU tariffs. As to the buy-back price, although a high price (more than two times of the tariff rate) is available in Japan, it is only available for the residual power after own consumption. On the other hand, a FIT is employed in Thailand with a relatively low price. In China, according to current electrical standard, power out of PV system is not allowed to be sold back to the grid.

RESULTS AND DISCUSSIONS
In the following, firstly, while assuming a 4 kW PV system is installed for the residential buildings located in selected three countries, the economic and environmental performances of the PV systems are calculated and compared. As the base scenario, a conventional system which satisfies all the electrical requirements by local utilities, is also assumed. In addition, by using the developed simulation model, sensitivities of government subsidies, electricity tariffs as well as feed-in tariff on the adoption of PV system are analyzed.

Comparison of system performance
Figure 9 shows the comparison of economic performance. Generally, annual total cost of the residential PV system in Japan is about two times of that in other two countries. Due to its relatively high tariff rate, utility grid electricity cost is very high in Japan; while it is very low in China and Thailand. On the other hand, compared with the conventional system, annual cost reduction ratios are not ideal in all three countries. It is about 3.9% in Japan and the cost is even about three times higher than conventional system in both China and Thailand. Therefore, it can be concluded that it is not feasible to introduce residential PV system in China and Thailand from the economic viewpoint currently.

Figure 10 shows the environmental performance of

### Table 1

<table>
<thead>
<tr>
<th>Tariff type</th>
<th>Japan</th>
<th>China</th>
<th>Thailand</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLAT ($/kWh)</td>
<td>0.2</td>
<td>0.09</td>
<td>0.05</td>
</tr>
<tr>
<td>On-peak ($/kWh)</td>
<td>0.33</td>
<td>0.09</td>
<td>0.10</td>
</tr>
<tr>
<td>Mid-peak ($/kWh)</td>
<td>0.25</td>
<td>0.09</td>
<td>0.01</td>
</tr>
<tr>
<td>Off-peak ($/kWh)</td>
<td>0.10</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Buy-back ($/kWh)</td>
<td>0.59</td>
<td>0.00</td>
<td>0.03</td>
</tr>
</tbody>
</table>
the PV systems installed in three countries. Generally, because of the relatively large energy consumption, Japan has the largest CO₂ emissions than other two countries for the residential buildings with the same floor area. On the other hand, the introduction of PV system results in satisfied environmental merits. As shown in the figure, the system in Thailand has the largest CO₂ emissions reduction ratio, followed by China and Japan.

**Sensitivity of subsidies**

Government subsidies are expected to promote the introduction of PV systems. Figure 11 shows the reduction ratios of annual cost under government subsidies in three countries. Without government subsidies, reduction ratio of annual cost in Japan is about 1%, but in China and Thailand, it is -308% and -366% respectively. When the subsidies in China and Thailand are increased to as high as 80% and 90% respectively, the value begins to become positive. Therefore, it is still hard to introduce PV system with even large subsidies for China and Thailand, which have relatively low tariff rates.

**Effect of electricity tariff structure and tariff rate**

While assuming a subsidies ratio of 50%, Figures 12 shows the reduction ratios of annual cost for three countries with both Flat and TOU tariffs. Different from the situation in China, the employment of TOU tariff results in better economic performance than the Flat tariff in Japan and Thailand. This is mainly because although a TOU tariff is introduced in China, its peak tariff rate is the same as the flat one. In addition, because the electricity tariff rates are too low in China and Thailand, even the tariff rates increase to two times of current value, the reduction ratios always keep a negative value.

**Feasibility of feed-in tariff**

Figures 13 shows the reduction ratios of annual costs when feed-in tariff rate increases based on 50% government subsidies and 150% tariff rate. In Japan, along with the increase of feed-in tariff rate from 0 dollar to 0.2 dollars, reduction ratio of annual cost is above 26.3% but grows slowly. However, at first, reduction ratio of annual cost is below 0 in Thailand and China, but, as the feed-in tariff rate increased, when the value reach to about 0.1 dollars and 0.16 dollars respectively, reduction ratios of the two countries increase over Japan. In Thailand, when feed-in tariff rate increases to 0.14 dollars, reduction ratio of annual cost is 100% and becomes steadied.

**CONCLUSION**

In this study, a linear simulation model is developed for aiding the adoption of PV system from the economic viewpoint with an objective to minimize the annual energy cost of a given customer including PV investment cost, maintenance cost, utility electricity cost, subtracting the revenue from selling the excess electricity. By using the simulation model, PV system adoption for residential buildings in Japan, China and Thailand has been analyzed and compared. According to simulation results, we can get the following conclusions:

1. Currently, it is not feasible to introduce residential PV system in China and Thailand from the economic viewpoint. On the other hand, the economic merit of PV adoption in Japanese residential buildings is marginal, with a cost reduction ratio of about 3.9%.

2. Unless the relatively high subsidies are issued, residential PV system does not show any economic merits in China and Thailand.
A TOU tariff may promote the introduction of PV system in Japan and Thailand; while the situation is contrary in China.

A compound of various policies including subsidies, tariff innovation and feed-in tariff is expected to make the PV system be economic feasible in both three countries.

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