ABSTRACT
Industrial halls are characterized with their relatively high roof-to-floor ratio, which facilitates ready deployment of photovoltaic (PV) systems on the rooftop. However, actual performance of such systems might not always match the expected design performance, which is commonly based on rated rather than case-specific conditions.

In order to promote deployment of PV systems, feed-in tariff higher than the price of electricity is available in many countries to subsidize the high capital investment. With the help of energy performance simulation, this paper explores the cost-benefit of the deployment of PV systems of different capacities for a few different application scenarios of industrial halls. The impact of various economic parameters is also investigated.

INTRODUCTION
Photovoltaic (PV) systems were posed as a promising technology to produce renewable energy. In the last decade, global warming, due to emissions from fossil fuels, has become a concern. Today, electricity generation in 2008 from renewable energy sources is estimated at 16.7% in Europe (Eurostat, 2011a), and 18.7% around the globe (IEA, 2010).

The industrial sector is one of the heaviest consumers of energy. In Europe, this sector consumed 24% of the total energy consumption in 2009 (Eurostat, 2011b), while in the United States, the sector consumed 32% in 2009 (LLNL, 2010). Some of the energy from this amount was consumed in the manufacturing processes and for lighting, while much of the rest was spent to provide space conditioning to maintain the building within a reasonable or legally allowable temperature range. Since the manufacturing processes generate large amount of heat as a by-product, buildings in general require cooling to remove the excess heat gain.

Industrial halls are characterized with their relatively high roof-to-floor ratio as compared to other types of buildings of similar total floor area. This makes it quite beneficial to incorporate energy producing components into the building design by taking advantage of the proportionally large rooftop area, which in most cases does not serve any particular purpose. PV systems could be readily deployed and attached to the rooftop with no special requirement on or alteration to the building design. In addition, industrial halls are mainly situated in sparsely populated areas with open fields in which the performance of PV systems is not hampered by shading of surrounding buildings.

However, at the current price level, deployment of PV systems is synonymous with high capital investment, which is not likely to be covered by savings in electricity cost at the current electricity rate. In order to promote wider deployment of PV systems in the hope that wider adoption will lower the cost of deployment in the future, government policies come in different forms of economic incentives to compensate the high investment cost. Out of these, feed-in tariff is the most common form of such incentives (EEG, 2007). The feed-in tariff, administered under different schemes, is the premium rate that the utilities promised to buy back from grid-connected local generation of renewable energy. The premium rate is higher than the electricity rate and is usually guaranteed for a fixed number of years. Therefore, environmental benefits aside, the main attraction or the decision-making factor for the building owners to deploy PV systems is the potential economic benefit that might be gained as a result of savings in the electricity cost or earnings from the feed-in tariff.

With the current design practice, the sizing of PV systems is usually based on rated characteristics of the equipment. For example, watt peak (Wp), the nominal value used for sizing of PV systems, is the nameplate power that a PV module can generate under the Standard Test Conditions (STC) of 1,000 W/m² insolation and 25°C cell temperature. In reality, the insolation peaks at different values according to installation locations and varies hour-by-hour throughout the year. In most cases, sizing of PV systems is based on either the annual average or the worst month average insolation values at the installation location (CEC, 2001); the actual performance of PV systems might not match nor even come close to their designed performance. Moreover, current design practice in evaluating the capability of PV systems in meeting a building’s
The idea, a case study of a typical industrial hall is to be described in the next section. To illustrate process loads with their corresponding heat gains. PV systems are presented, which will be investigated for different tariff, and the annualized cost of the investment will be demonstrated in subsequent sections that for a number of years, which usually reflects the useful life of the system and can be taken as the duration for the life-cycle.

Feed-in tariff schemes

There are different schemes to administer the payout of feed-in tariff. For net feed-in tariff scheme, the electricity generated by the grid-connected PV system is assumed to be first satisfying the power consumption of the building; any surplus electricity will be exported back to the grid at the rate of the published feed-in tariff, which is at a premium to the electricity price. However, in most cases, the generated electricity cannot satisfy the power consumption at the hour, and electricity has to be drawn from the grid at the contract price of the electricity.

Under the gross feed-in tariff scheme, all generated electricity will be purchased at the feed-in tariff, while all consumed electricity will have to be paid at the electricity price. The own consumption scheme is meant to provide incentives to promote use of generated electricity at the local premises rather than exporting back to the grid. Generated electricity consumed locally will be compensated with incentives in additional to the feed-in tariff under the gross feed-in tariff scheme.

Cost-benefit analysis based on energy performance simulation

At the end of the year, the savings in electricity bills and the earnings from any of these feed-in tariff schemes shall exceed that of the annualized capital investment cost to justify, economically, the deployment of PV systems.

As mentioned in the introduction, the current design practice of PV systems usually assumes some constant average performance values. However, the hours in which the power consumption is high might not coincide with the hours in which the solar insolation is peak for maximum power generation. It will be demonstrated in subsequent sections that for either the net feed-in tariff scheme or the own consumption scheme, an hour-by-hour energy performance simulation will be required to perform the cost-benefit analysis.
THE CASE STUDY

Case study building
A case study building, which represents a typical industrial hall, is of rectangular shape with low-pitched gable roof measuring 80m width x 136m depth x 6 - 8m height (6m on the long sides; 8m at the ridge). The building is built with steel cladding on a steel frame with insulation according to ASHRAE standard 90.1 (2004). Infiltration of 0.1 air change per hour is assumed. (ISSO, 2002)

The workers are assumed to perform light work only. For a hot working environment, as in the case of industrial halls, current guidelines (ARAB, 2006) recommend the temperature of the space to be maintained under 30°C during occupied hours to protect workers from heat stress. Heating has to be provided only if the space drops below 18°C during occupied hours. The building and the processes carried out in the building are assumed to operate from 08:00 to 18:00 (the hours reflect one 10-hour work-shift. Consideration of two work-shifts depends on industry, season, economy, and other factors, which are beyond the scope of this paper).

Case study scenarios
The case study building will be investigated for a number of hypothetical scenarios (based on personal communication with industrial partners): processes / equipment consuming 100 W/m² of electricity to represent a high load factory; 50 W/m² to represent a medium load factory; 30 W/m² to represent a low load factory; and 5 W/m² to represent a warehouse. In all scenarios, 50% of the energy drawn is assumed to be released back to the space as heat (Duška et al., 2007). The amount of released heat depends on industries and processes; in general, remaining consumed energy exists as internal energy of the manufactured items and is shipped out of the industrial hall system boundary. In addition, to maintain a lighting level of 500 lux, which is suitable for general work (IES as cited in Cooper, 2006), florescent lighting with power consumption at 13 W/m² is assigned.

Geographical locations
The case study building is investigated for two geographical locations; Düsseldorf in Germany represents a moderate climate, and Palermo in Italy represents a dry subtropical climate with higher solar insolation for most hours. Even though, Düsseldorf and Palermo represent two different climate zones (zones 5 and 4), the prescriptive insulation requirement is the same according to ASHRAE standard 90.1 (2007). The walls and the roofs require a minimum of R-2.3 and R-3.3 respectively.

With the internal heat gain, in practice, only cooling is necessary if the industrial halls are not located in extreme cold climate. To effectively cool the space within the set limit, forced ventilation with exhaust fans is deployed to draw in ambient air, which is controlled by two stages ON-OFF strategy triggered at 30°C and 31°C. At stage 1, 60,000 L/s of ambient air is drawn, and at stage 2, an additional 55,000 L/s is drawn, as in the case for Düsseldorf. The amounts increase to 100,000 L/s and additional 70,000 L/s for stage 1 and 2, as in the case for Palermo. The electricity consumption of the building thus includes those demanded by the processes / equipment and the exhaust fan.

In general, Düsseldorf maintains a lower and flatter insolation profile as compared to that of Palermo. The generally lower temperature of ambient air in Düsseldorf allows lower fan power consumption to cool the space with forced ventilation. Hour-by-hour simulation will determine if this reduction in consumption can compensate for the reduction in electricity generation with the lower insolation.

Power sector of the two countries
In 2007, the EU-wide directive (EU, 2011a) was set such that power from renewable energy sources shall comprise at least 20% of total power generation by 2020 for the European Union as a whole. The targets by 2020 for Germany and Italy are 18% and 17% respectively (and the percentage in 2005 was around 5% for either country) (REN, 2010). Therefore, it is of particular interest for both countries to pursue an energy policy that promotes power generation from renewable energy sources. Grid-connected solar PV system will certainly be one of the options. By year 2009, a total capacity of 9.8 GW was installed in Germany, and 1.1 GW was installed in Italy (REN, 2010). To compensate for the high capital investment, both countries provide feed-in tariff incentives for the installation of PV systems. Table 1 summarizes the rates for systems of different capacities for the two countries.

<table>
<thead>
<tr>
<th>kWh</th>
<th>GERMANY</th>
<th>ITALY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial Electric Rates</td>
<td>0.1233 [1]</td>
<td>0.1327 [7]</td>
</tr>
<tr>
<td></td>
<td>0.0919 [2]</td>
<td>0.1071 [2]</td>
</tr>
<tr>
<td>Feed-in Tariffs</td>
<td>0.2586 [3]</td>
<td>0.355 [5]</td>
</tr>
<tr>
<td></td>
<td>0.2156 [4]</td>
<td>0.351 [7]</td>
</tr>
</tbody>
</table>

[1] consumption < 2,000 MWh/year (EEP, 2011)
[2] consumption < 24,000 MWh/year (EEP, 2011)
[5] generation capacity 20 - 200 kW (Focus, 2011)
[6] generation capacity 200 - 1000 kW (Focus, 2011)
[7] generation capacity 1000 - 5000 kW (Focus, 2011)

Both countries adopted the gross feed-in tariff scheme. There has been debate on the effectiveness in encouraging the development of PV systems between the net and the gross schemes (Zahedi, 2011...
The debate itself is outside the scope of this paper. However, both net and gross schemes will be studied to provide a glimpse on their impact on the cost-benefit from the building owners’ perspective. In Germany, there are also incentives to promote the use of generated electricity at the location of generation. The exact administration of this own consumption scheme is rather complicated, in which the compensation is a function of both the feed-in tariff and the current electricity price. To illustrate the concept behind the scheme, the simplified example (and the corresponding assumptions) as presented in EEG (2010) will be adopted, in which, incentives of 3.6 €/kWh for the first 30% of own consumption and 8 €/kWh for the remaining 70% of own consumption will be applied on top of the gross feed-in tariff scheme for the whole range of installed capacities under investigation (in practice, the incentives are available for systems up to 500 kWp. The limit will not be considered here to facilitate cross comparison among schemes).

**Grid-connected solar PV systems**

The capital investment of PV systems, including the cost of the PV modules (assuming the common monocrystalline type with a rated efficiency of 14%) and BoS cost, is estimated to be €3500 per kWp (Poullikkas, 2009), which is roughly coherent with other recent estimates (Audenaert et al., 2010). For the case study, the capacity of the PV system is investigated in fifteen steps from a minimum of 100 kWp to a maximum of 1.5 MWp, which roughly fills the whole rooftop.

The current discount rate is 2.49% for both Germany and Italy (EU, 2011b). PV modules are usually guaranteed for a lifetime of 20 years to 25 years. Since feed-in tariff is usually fixed for 20 years, the more conservative life-cycle of 20 years is applied in this study.

**Simulation of energy performance**

The building energy performance simulation program TRNSYS is used to perform the energy analysis. TRNSYS is chosen as the simulation environment due to its flexibility and capability in modelling supply and generation side equipment.

The annual sum of the annualized capital investment cost, savings in electricity cost, and earnings from generated electricity is calculated for each of the scenarios and for each of the PV system capacities in both locations.

**RESULTS**

One of the issues of current design practice of estimating PV system performance with average value for input parameters is the possibility of either over or under estimating the performance. That is particularly true if there can be more than one rate for the generated electricity at any hour depending on the situation; for example, the price for own consumption of the electricity is not the same as the price of exporting the electricity, as in the case with both net feed-in tariff scheme and own consumption scheme. For this scheme, the annual total amount of electricity generation is not of much importance to the economics; rather, the amount of surplus generation for each of the hour is of much benefit since it is exporting back to the grid at a higher rate. Figure 1 and Figure 2 demonstrate this point. Figure 1 depicts a PV system deployment for a typical summer day in Palermo, Italy. The figure indicates that the amount of energy generated might not match the amount consumed at each of the hours. In this example, the energy surplus (the positive area bounded by the “Exported Energy” line) is roughly equal to the energy deficit (the negative area bounded by the “Exported Energy” line). In other words, the sum of surplus and deficit is nearly zero for this particular day.

On the other hand, the income (exporting at the feed-in tariff for hours of surplus; negative, if purchasing from the grid at the price of electricity for hours of deficit) is calculated for each of the hours in Figure 2. It is clear that there is a net income for the day (the negative area is more than double of the positive area bounded by the “Income” line). Therefore, analyses that are based on the annual amount of energy do not reflect the actual cost-benefit situations; analyses have to be performed on an hour-by-hour basis to truly reflect the economics.

The situation for the own consumption scheme is more complicated, various possibilities that involve different combinations of electricity price, feed-in tariff, and incentives of own consumption, can happen.
Annual energy related costs

Power consumption and generation for each of the scenarios of the case study building are studied for both locations. The power consumption is comprised of a base power consumption that reflects the electricity usage for all of the processes and equipment, and the additional power consumption of the fan that depends on how much ambient air (at temperature lower than that of indoors) has to be drawn in to remove the released heat of the processes.

In the summer, PV systems receive higher solar insolation. However, power consumption also peaks in the summer, when it is more difficult to maintain the space temperature with ambient air at higher temperature. Therefore, an hour-by-hour matching of power consumption and generation has to be carried out to determine whether (or how much of) the higher output of the PV systems can compensate the higher consumption of the building.

As outlined in Equation (2), the annual energy related cost, \( C \), is the sum of the annualized investment of PV systems and the net energy cost, \( \sum C_E \), which is the annual sum of the hourly cost of electricity minus any possible earnings from feed-in tariff and any incentives (for own consumption scheme).

\[
C = I_A + \sum C_E \quad (2)
\]

Cost-benefit analysis

To provide the decision makers a clearer picture on the economic viability of deploying PV systems, a cost-benefit analysis has been performed.

The energy cost savings per year, is equal to the difference between the electricity bills that would have to pay without PV systems (opportunity cost, \( C_0 \)) and the net energy cost paying (or earnings) with PV systems. And the net benefit, \( B \) is the energy cost savings subtracted by the annualized cost of investment of PV systems. The relationship is illustrated in equation (3):

\[
B = (C_0 - \sum C_E) - I_A \quad \text{that is,} \quad B = C_0 - C \quad (3)
\]

The net annual benefit for Düsseldorf under three different feed-in tariff schemes is presented in Figure 3, 4 and 5. Only positive amounts indicate a net benefit for the building owners. An amount of or close to zero signifies no economic benefit, and the decision making process might depend on other factors, such as an environmental one.

It can be shown that the deployment of PV systems for all four scenarios, in fact, results in no benefit for the case study building in Düsseldorf (within the investigated range of capacity); that is, the added investment cost of PV systems simply increase the annual cost without bringing benefit.

Understandably, the net feed-in tariff scheme (Figure 3), which remunerate at the feed-in tariff only for the surplus electricity, is not as economically attractive as the other two schemes.

![Figure 3 Net annual benefit under the net feed-in tariff scheme of PV systems in Düsseldorf, Germany](image)

It can be observed that there is no difference in benefit among the four scenarios under the gross feed-in tariff scheme (Figure 4). In other words, the benefit is independent of amount of energy consumption, and is a function of energy generation capacity and economic parameters only. It is not necessary to perform an hourly analysis as illustrated in this paper to evaluate the economics for this gross feed-in tariff scheme.

![Figure 4 Net annual benefit under the gross feed-in tariff scheme of PV systems in Düsseldorf, Germany](image)

With additional incentives on top of the gross feed-in tariff scheme, the own consumption scheme (Figure 5) is the most economically attractive one. The addition of the incentives, in which their availability depending on the hourly matching between the generation and consumption, require energy performance simulation to study the economics.

![Figure 5 Net annual benefit under the own consumption scheme of PV systems in Düsseldorf, Germany](image)

The case of Palermo, Italy under the less attractive net feed-in tariff scheme (to demonstrate the least beneficial scheme) is presented in Figure 6. It can be
observed that PV systems of capacity of more than 1,100 kWp for a warehouse are economically viable. The desirable actual size might only be limited by the initial financial resource or the space available for a rooftop installation. Please note that the lower energy consumption of the warehouse allows more surplus electricity generation, and thus brings in higher benefit under the net-feed-in-tariff scheme.

Impact of changes in economic parameters

In order to realize more benefit, the scenarios shall generate more surplus electricity under the net-feed-in-tariff scheme, or shall promote generation that can fulfil the consumption under the own-consumption scheme. In fact, the potential benefit is highly sensitive to a number of input economic parameters. Therefore, an extra study has been carried out to investigate the impact of changes in input economic parameters to the net benefit. The changes are listed in Table 2.

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>CHANGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity Rates</td>
<td>decreased by 30%</td>
</tr>
<tr>
<td></td>
<td>increased by 30%</td>
</tr>
<tr>
<td>Feed-in Tariffs</td>
<td>increased by 30%</td>
</tr>
<tr>
<td>Capital Investment</td>
<td>decreased to €2500 per kWp</td>
</tr>
<tr>
<td>Life-cycle</td>
<td>increased to 25 years</td>
</tr>
<tr>
<td>Discount Rate</td>
<td>decreased by 100 basis points</td>
</tr>
</tbody>
</table>

All of the proposed changes are arbitrary. The purpose is to study the potential benefits that might be brought forth by the changes. A slight drop in energy prices has recently been seen due to the economic downturn; therefore, a case with lowered electricity rate by 30% has also been studied.

Out of the many investigated scenarios under the net feed-in-tariff scheme, only the warehouse at Palermo shows promising prospects for the deployment of PV systems. Figure 7 presents the results of applying the changes of the input economic parameters to this particular scenario.

It can be observed that the increase and the decrease in electricity rate follow exactly the same trend and envelop the base case in the middle. In contrast, with an increase in feed-in tariff, the net benefit for PV systems larger than 400 kWp (in this particular scenario) takes off drastically, since systems of higher capacity can generate more surplus electricity to capitalize the benefit of higher feed-in tariff. Longer life-cycle or lower discount rate basically yield the same impact on net benefit. Out of all of the economic parameters investigated, a reduction in the cost of PV systems makes the most impact over the whole capacity range.

Figure 8 presents the same information by dividing the net annual benefit by the corresponding capacities of the PV systems; therefore, the results will be presented as per kWp of the design capacity. For the warehouse case at Palermo, the benefit (negative if no benefit) stays as a constant for PV systems smaller than 400 kWp, since there is limited surplus electricity generation only during early morning hours.
The warehouse at Düsseldorf is used to demonstrate the impact of changes of input economic parameters under the own consumption scheme; the net annual unit benefit is presented in Figure 9. The results of Figure 5 already indicate that there will be no benefit for the base case (before any changes in economic parameters). Out of the studied changes in economic parameters, only lowering the cost of PV systems bring benefit for the whole range of installed capacities. Please note that it is quite possible to have more than one change in economic parameters at any time. A combination of a lower cost of PV systems and an increase in electricity price, for example, will make the deployment of PV systems more economically viable.

**DISCUSSION**

Under both net feed-in tariff scheme and own consumption scheme, more than one rate can be applied to the generated electricity depending on the balance between generation and consumption. Therefore, the hour-by-hour simulation approach presented in this paper provides a means to perform the economic analysis that is very much depending on the number of hours with surplus electricity or hours with consumption being fulfilled.

By contrast, under the gross feed-in tariff scheme, only one rate, the feed-in tariff, is applied to the generated electricity. As discussed in previous section, no simulation is necessary to assess the economic performance for this scheme.

The implication of generating electricity at one rate can be further demonstrated with Figure 8 (an example of net feed-in tariff scheme). There is no power consumption during early morning hours; therefore, any electricity generation yields pure income, which is directly proportional to the PV system capacity. If the capacity is smaller than 400 kWp, in this particular scenario, PV systems do not generate surplus electricity during the day; that is, for any particular hour, either there is earnings at feed-in tariff (early morning hours) or savings (or payment) at electricity rate (during the day), regardless of PV system capacity. As a result, net unit benefit stays constant (for capacity smaller than 400 kWp). In other words, benefit is constant if the system is operating at one rate. And the fact that the life-cycle cost of PV systems is also directly proportional to the capacity, the implication is two folds:

1. Constant negative value of net unit benefit implies the system is economically not viable regardless of system capacity.
2. The economic viability can be evaluated solely based on unit calculation of economic parameters such as electricity rate, investment cost, discount rate and years of life-cycle.

The above implication can be applied to countries with no feed-in tariff, or countries adopting the gross feed-in tariff scheme.

Based on current high investment cost and relatively low electricity rate, PV systems are only economically viable with an attractive feed-in tariff scheme. It is worthy to note that technological advances will improve the efficiency of PV modules. An increase in efficiency will in fact be reflected as a reduction in capital investment since the unit price (€ per kWp) will decrease. An efficiency increase will open up opportunities to increase the generation capacity for the same roof area or for the same investment. The effect of such will be investigated in the future.

**CONCLUSION**

From the previous discussion and the demonstration of changing the input economic parameters, it can be concluded that those parameters (including the implied changes in cost due to the improvement in efficiency) have a great impact on the economics of the deployment of PV systems. However, the economic parameters are not factors that the building owners can change, but are the result of market forces. Hopefully, with the advent in technology, the cost of PV systems will decrease in the future.

Through the case study, this paper demonstrates that for those countries, which adopt either the net feed-in tariff scheme or the own consumption scheme, an hour-by-hour energy performance simulation is necessary to provide the information to conduct the cost-benefit analysis for decision makers to assess the economic viability of the deployment of PV systems. Moreover, what the building owners can control are the many processes that take place in the building and the design of the building. With more energy efficient processes and better building design, power consumption will decrease. As a result, electricity generation shall satisfy the lowered consumption for more hours such that a smaller-capacity PV system will still be economically viable (or a larger-capacity PV system will yield higher benefit).
This paper demonstrates that energy performance simulation provides a means to assess the economic performance of PV systems.

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