Rooftop photovoltaic (PV) systems: a cost–benefit analysis study of industrial halls

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Abstract

Rooftop photovoltaic (PV) systems can be readily deployed on industrial halls with a relatively large rooftop area. The feed-in tariff above the base price of electricity is offered in many countries to subsidize the high initial investment of PV systems. To fully capitalize the benefit of the feed-in tariff, the investigation of the actual performance of PV systems under case-specific conditions is very important. With building energy simulation, this paper explores the cost–benefit of implementing PV systems of different capacities for a few different cases of industrial halls. The impact of various economic parameters is also investigated.

Keywords: industrial halls; photovoltaic; PV systems; cost–benefit analysis; energy performance simulation

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1 INTRODUCTION

The industrial sector is one of the heaviest consumers of energy, which, in 2009, consumed 24% of the total energy consumption in Europe [1], and 32% of that in the USA [2]. Other than the energy consumed for the manufacturing processes and lighting, the remaining amount was spent to provide space conditioning. Cooling demands most of the energy since the manufacturing processes generate a large amount of heat as a by-product. To fulfill such a large energy demand, it is desirable to draw the energy from renewable sources due to the concern over global warming that is possibly linked to emissions from the combustion of fossil fuels. Electricity generation in 2008 from renewable energy sources was estimated to be 16.7% in Europe [3] and 18.7% worldwide [4].

Industrial halls, which are mainly single floor structures, maintained a relatively high roof-to-floor ratio when compared with other types of buildings of similar total floor area. The proportionally large rooftop area that does not serve any particular purpose, in most cases, can be used to deploy energy-generating components such as photovoltaic (PV) systems without much alteration to the building design. Moreover, most industrial halls are situated in areas that are quite open, and thus the performance of PV systems is not hampered by shading of surrounding buildings.

However, a wider adoption of PV systems for industrial halls is discouraged by the high initial capital investment cost, which is unlikely to be covered by the saving in electricity cost. It becomes a dilemma since wider adoption is believed to be a driving force in lowering the cost of PV systems. 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 [5]. The feed-in tariff, administered under different schemes, is the premium rate at which the utilities promised to buy back power from the 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, apart from the environmental benefits, 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 (W_P), the nominal value used for the sizing of PV systems, is the nameplate power that a PV module can generate under the standard test conditions (STC) of 1000 W/m^2 insolation, 25°C cell temperature and an air mass

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of 1.5. In reality, the insolation peaks at different values according to installation locations and varies hour-by-hour throughout the year. In most cases, the sizing of PV systems is based on either the annual average or the worst month average insolation values at the installation location [6]; the actual performance of PV systems might not match nor even come close to their designed performance. Moreover, the current design practice in evaluating the capability of PV systems in meeting a building's power consumption is to assume the same daily consumption load profile for the whole year or to adopt an annual total consumption [6].

Little of the literature studying the performance of PV systems actually conducts an hourly assessment on matching the generation to the demand profile. With noted exception, researchers from University of Strathclyde studied how to optimally match the renewable energy systems to a reduced energy demand. Born *et al.* [7] described in detail the decision support tool that facilitates the matching of generation and demand.

However, there is a lack of literature that evaluates the economics of PV systems based on hourly analysis. To fill the gap, this paper will assess the economic performance of PV systems based on computational simulation of both the power generation capability of the PV system and the power consumption of the industrial hall building. A notable portion of the power consumption, that is the cooling load of the building, is greatly affected by the weather/solar insolation of the location. This is particularly problematic for industrial halls with high heat gain from the power-intensive manufacturing processes since most conventional means of heat removal (forced ventilation, cooling tower, etc.) are highly sensitive to the time-varying ambient environment.

A complete cost–benefit analysis that considers the savings in electricity cost, the earnings from feed-in tariff and the annualized cost of the investment will be performed on different feed-in tariff schemes that are to be described in the next section. To illustrate the idea, a case study of a typical industrial hall is presented, which will be investigated for different process loads with their corresponding heat gains. PV systems for a range of capacities will be studied. This paper presents some of the results of an ongoing project 'Sustainable Energy Producing Steel Frame Industrial Halls', which also studies other operation energy-related aspects of industrial halls.

2 COST–BENEFIT ANALYSIS OF ROOF-TOP PV SYSTEMS

2.1 Annualized life-cycle cost of PV systems

The three components of the life-cycle cost of PV systems are capital investment cost, maintenance cost and deconstruction cost. The cost of deconstruction can be considered as the net sum of dismantling and disposing the systems, and the potential worth of the recyclable aluminum frames. The net deconstruction cost, which is estimated to be <2% of the capital investment, can be safely neglected [8]. The cost of maintenance involves that of cleaning and other minor costs, which comprises <2% of the total life-cycle cost and is also neglected [9]. The capital investment of the PV systems is usually calculated as the sum of the cost of the PV modules and the balance-of-system (BoS) cost that includes all other upfront costs—the cost of the mounting structure, wiring, inverter and the cost of installation. Contrasted with a simple payback calculation, the annualized life-cycle cost provides a finer estimate of the actual cost, in which financial parameters are also taken into consideration. Therefore, the annualized life-cycle cost is adopted in this paper. The annualized cost of the investment I_A can be calculated with a real discount rate r, for the number of years of the life cycle n, based on the initial capital investment I, using the following equation:

$$I_A = \frac{I}{[((1+r)^n - 1)/(r \cdot (1+r)^n)]} \quad (1)$$

The discount rate is assumed to be 100 basis points over the reference rate [10]. In most countries, the feed-in tariff for the investment in PV systems is fixed for a number of years, which usually reflects the useful life of the system and can be taken as the duration of the life cycle.

2.2 Feed-in tariff schemes

There are different schemes to administer the payout of feed-in tariff. For a *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.

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 contract price.

The *own consumption* scheme is meant to provide incentives to promote the use of generated electricity at the local premises rather than exporting it back to the grid. Generated electricity consumed locally will be compensated with incentives in addition to the feed-in tariff under the *gross feed-in tariff* scheme.

2.3 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 will 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 during which the power consumption is high might not coincide with the hours during which the solar insolation is at a peak for maximum power generation. Moreover, in the summer, it is more difficult to maintain the space temperature with the ambient air (for example, with a forced ventilation system) at a higher temperature, which results in higher energy consumption; even though solar insolation can also be high at the same time. 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 PV-related cost C is the sum of the annualized investment of PV systems and the net energy cost ΣC_E, which is the annual sum of the hourly cost of electricity minus any possible earnings from the feed-in tariff and any incentives (for *own consumption* scheme).

$$C = I_A + \Sigma C_E \qquad (2)$$

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 be paid without PV systems (opportunity cost, C_O) and the net energy cost to be paid (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 the following equation:

$$B = (C_O - \Sigma C_E) - I_A \quad \text{that is,} \quad B = C_O - C \qquad (3)$$

3 THE CASE STUDY

3.1 Case-study building

A case-study building, which represents a typical industrial hall, is of rectangular shape with a low-pitched gable roof measuring 80 m width × 136 m depth × 6 − 8 m height (6 m on the long sides; 8 m at the ridge). The building is built with steel cladding on a steel frame with insulation according to ref. [11]. The infiltration of 0.1 air change per hour is assumed [12].

The workers are assumed to perform light work only. For a hot working environment, as in the case of industrial halls, the current guidelines [13] recommend the temperature of the space to be maintained <30°C during occupied hours to protect workers from heat stress. Heating has to be provided only if the space temperature drops <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-h work shift. Consideration of two work shifts depends on industry, season, economy and other factors, which are beyond the scope of this paper).

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/m^2 of electricity to represent a high load factory; 50 W/m^2 to represent a medium load factory; 30 W/m^2 to represent a low load factory and 5 W/m^2 to represent a warehouse. In addition, to maintain a lighting level of 500 lx, which is suitable for general work [14], florescent lighting with power consumption at 13 W/m^2 is assigned.

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 the ambient air, which is controlled by two stages ON–OFF strategy triggered at 30°C and 31°C, respectively. 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 and 70 000 L/s for stages 1 and 2, respectively, as in the case for Palermo. The electricity consumption of the building thus includes the electricity demands of the processes/equipment and the exhaust fan.

3.2 Location depending factors

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 the American Society of Heating, Refrigerating and Air-Conditioning Engineers standard 90.1 [11]. The walls and the roofs require a minimum of R_{SI}-2.3 and R_{SI}-3.3, respectively (R_{SI} has a unit of m^2 K/W).

In general, Düsseldorf maintains a lower and flatter insolation profile when compared with that of Palermo. The generally lower temperature of the 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.

3.3 Power sector and feed-in tariff of the two countries

In 2007, the European Union (EU) wide directive [15] was set such that the power from renewable energy sources shall comprise at least 20% of the total power generation by 2020 for the EU 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) [16]. Therefore, it is of particular interest for both countries to pursue an energy policy that promotes power generation from renewable energy sources. The grid-connected solar PV system will certainly be one of the options. By 2009, a total capacity of 9.8 GW was installed in Germany and 1.1 GW was installed in Italy [16]. 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 1. *Industrial electricity rates and feed-in tariffs for PV system deployment of different capacities in 2011.*

€/kW h	Germany	Italy
Industrial electricity rates	0.1233[a]	0.1327[a]
	0.0919[b]	0.1071[b]
Feed-in tariffs	0.2586[c]	0.358[e]
	0.2156[d]	0.355[f]
		0.351[g]

[a]Consumption <2000 MW h/year [22].
[b]Consumption <24 000 MW h/year [22].
[c]Generation capacity <1 MW_P [18].
[d]Generation capacity >1 MW_P [18].
[e]Generation capacity 20–200 kW_P [23].
[f]Generation capacity 200–1000 kW_P [23].
[g]Generation capacity 1000–5000 kW_P [23].

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 [17]. The debate itself is outside the scope of this paper. However, both *net* and *gross* schemes will be studied to provide a glimpse of 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 the guideline [18] 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 kW_P. The limit will not be considered here to facilitate cross-comparison among schemes).

3.4 PV systems and building energy simulation

The capital investment of grid-connected PV systems, including the cost of the PV modules (assuming the common monocrystalline type with a rated efficiency of 14%) and the BoS cost, is estimated to be €3500/kW_P [19], which is roughly coherent with other recent estimates [20]. For the case study, the capacity of the PV system is investigated in 15 steps from a minimum of 100 kW_P to a maximum of 1.5 MW_P, which roughly fills the whole rooftop.

The current discount rate is 2.49% for both Germany and Italy [21]. PV modules are usually guaranteed for a lifetime of 20–25 years. Since the feed-in tariff is usually fixed for 20 years, the more conservative life cycle of 20 years is applied in this study.

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 modeling supply- and generation-side equipment. For example, when modeling a PV array, Type 194 is deployed. The model voltage and current are set at 21.6 V and 6.5 A, respectively, at the maximum power point at STC.

4 RESULTS

4.1 Implication of different feed-in tariff schemes

One of the issues of the current design practice of estimating PV system performance with the average value for input parameters is the possibility of either over- or underestimating 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 the *net feed-in tariff* scheme and the *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 hour is of much benefit since it is exporting power back to the grid at a higher rate. Figures 1 and 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

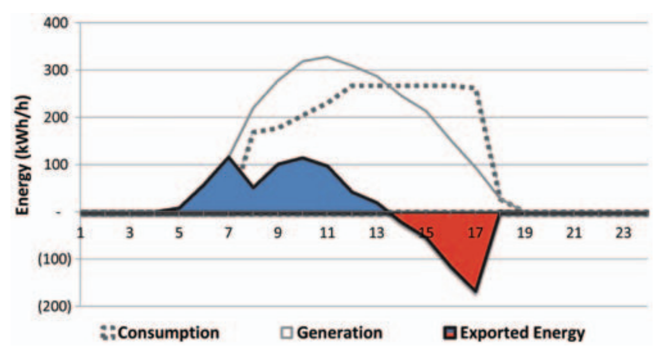

Figure 1. *Energy consumption and generation profile for a typical summer day in Palermo, Italy.*

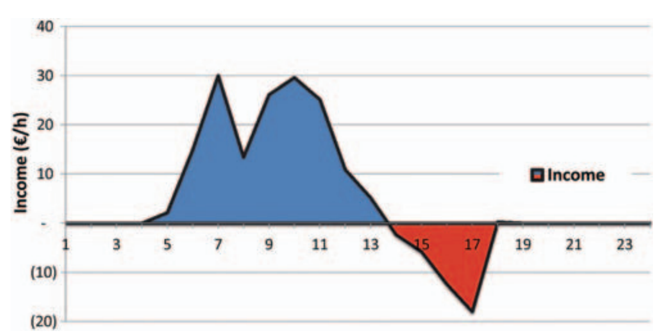

Figure 2. *Income as a result of exporting surplus electricity (negative, if purchasing from the grid) for the same day of Figure 1.*

match the amount consumed at each hour. 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 the surplus and the deficit is nearly zero for this particular day.

On the other hand, the income (exporting at the feed-in tariff for the hours of surplus; negative, if purchasing from the grid at the price of electricity for the 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 positive area is more than double of the negative 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 possible scenarios that involve different combinations of electricity price, feed-in tariff and incentives of own consumption can occur and will be considered in this paper.

4.2 Cost–benefit of different scenarios under different FIT schemes

The net annual benefit for Düsseldorf under three different feed-in tariff schemes is presented in Figures 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 gains remuneration at the feed-in tariff only for the surplus electricity, is not as economically attractive as the other two schemes.

It can be observed that there is no difference in benefit among the four scenarios under the *gross feed-in tariff* scheme

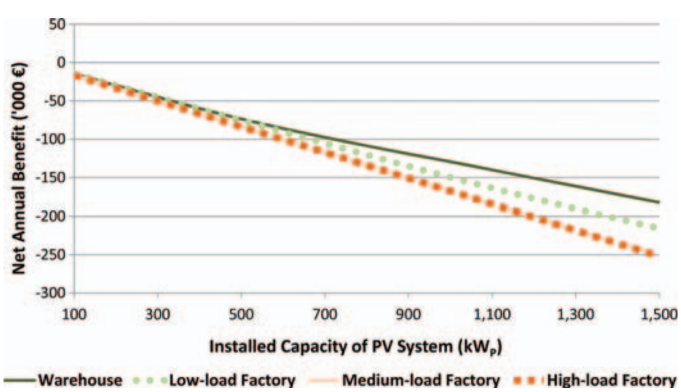

Figure 3. *Net annual benefit under the net feed-in tariff scheme of PV systems in Düsseldorf, Germany.*

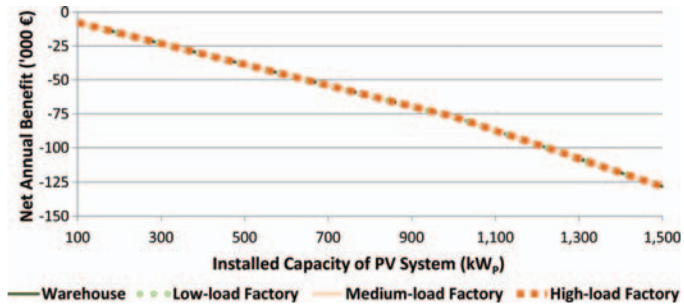

Figure 4. *Net annual benefit under the gross feed-in tariff scheme of PV systems in Düsseldorf, Germany.*

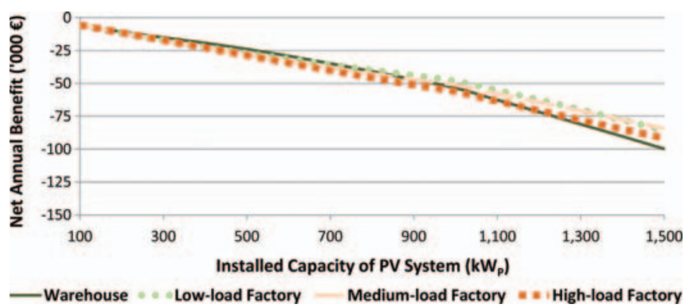

Figure 5. *Net annual benefit under the own consumption scheme of PV systems in Düsseldorf, Germany.*

(Figure 4). In other words, the benefit is independent of the amount of energy consumption, and is a function of the 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 the *gross feed-in tariff* scheme.

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

The case of Palermo, Italy under the less attractive *net feed-in tariff* scheme (so as to demonstrate the least beneficial scheme) is presented in Figure 6. It can be observed that PV systems of capacity of $>1100\,kW_P$ 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.

4.3 Impact of changes in economic parameters

To realize more benefit, the scenarios shall generate more surplus electricity under the *net feed-in tariff* scheme, or shall promote generation that can fulfill the consumption under the

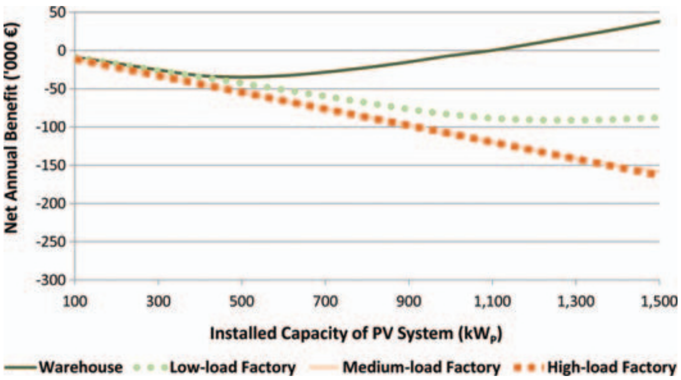

Figure 6. *Net annual benefit under the net feed-in tariff scheme of PV systems in Palermo, Italy.*

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 on the net benefit. The changes are listed in Table 2.

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 a 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 the electricity rate follow exactly the same trend and envelop the base case in the middle. In contrast, with an increase in the feed-in tariff, the net benefit for PV systems >400 kW_P (as in this particular scenario) takes off drastically, since systems of higher capacity can generate more surplus electricity to capitalize on the benefit of a higher feed-in tariff. Longer life cycle or a lower discount rate basically yields the same impact on the 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 kW_P of the design capacity. For the warehouse case at Palermo, the benefit (negative if no benefit) stays as a constant for PV systems <400 kW_P, since there is limited surplus electricity generation 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 brings 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.

Table 2. *Proposed changes to input economic parameters to study the impact of the net benefit.*

Parameters	Changes
Electricity rates	Decreased by 30%
	Increased by 30%
Feed-in tariffs	Increased by 30%
Capital investment	Decreased to €2500/kW_P
Life cycle	Increased to 25 years
Discount rate	Decreased by 100 basis points

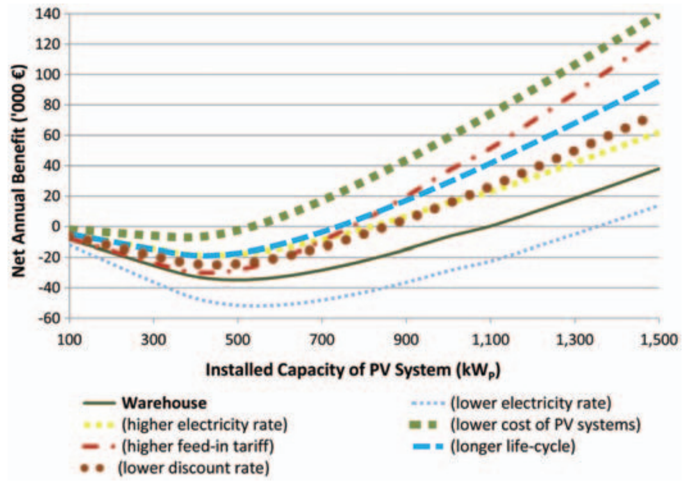

Figure 7. *Net annual benefit of PV systems with changes in input economic parameters for a warehouse in Palermo under the net feed-in tariff scheme, Italy.*

5 DISCUSSION

Under both the *net feed-in tariff* scheme and the *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 dependent on the number of hours with surplus electricity or hours with consumption being fulfilled.

In contrast, under the *gross feed-in tariff* scheme, only one rate, the feed-in tariff, is applied to the generated electricity. As

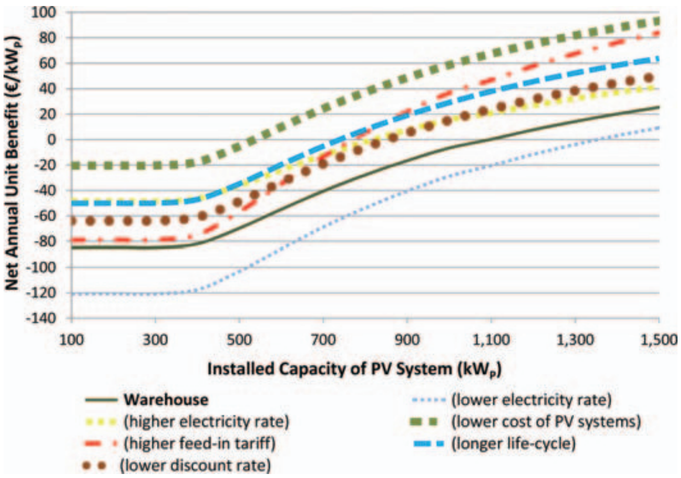

Figure 8. *Net annual unit (per kW_P) benefit of PV systems with changes in input economic parameters for a warehouse in Palermo under the net feed-in tariff scheme, Italy.*

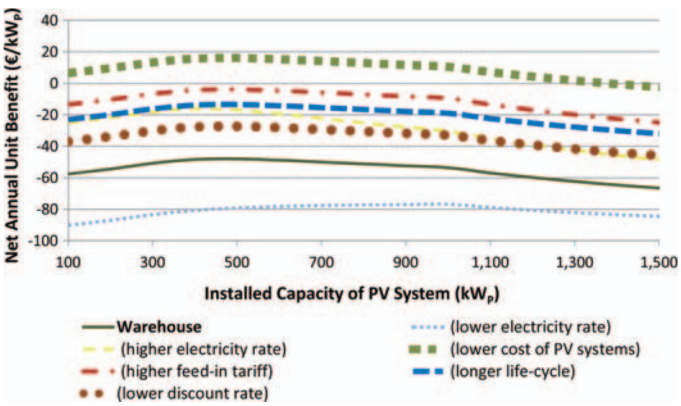

Figure 9. *Net annual unit (per kW_P) benefit of PV systems with changes in input economic parameters for a warehouse in Düsseldorf under the own consumption scheme, Germany.*

discussed in the previous section, no simulation is necessary to assess the economic performance of this scheme.

The implication of generating electricity at one rate can be further demonstrated with Figure 8 (an example of the *net feed-in tariff* scheme). There is no power consumption during early morning due to the assumed operating hours; therefore, any electricity generation yields pure income, which is directly proportional to the PV system capacity. If the capacity is $<400\ kW_P$ in this particular scenario, PV systems do not generate surplus electricity during the day; that is, for any particular hour, either there are earnings at the feed-in tariff (early morning hours) or savings (or payment) at the electricity rate (during the day), regardless of the PV system capacity. As a result, the net unit benefit stays constant (for capacity $<400\ kW_P$). In other words, the benefit is constant if the system is operating at one rate. And from the fact that the life-cycle cost of PV systems is also directly proportional to the capacity, the implication is 2-fold:

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

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

Based on the 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 the capital investment since the unit price (€/kW_P) 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 effects of this will be investigated in the future.

6 CONCLUSION

From the previous discussion and a 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 of newer technology, the cost of PV systems will decrease in the future.

Through a 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 can 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 a higher benefit).

This paper demonstrates that energy performance simulation provides a means to assess the economic performance of PV systems.

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