Assessment of Energy and Economic Effectiveness of Photovoltaic Systems Operating in a Dense Urban Context

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Cite as: Cellura, M., Di Gangi, A., Orioli, A Assessment of Energy and Economic Effectiveness of Photovoltaic Systems Operating in a Dense Urban Context, J. sustain. dev. energy water environ. syst., 1(2), pp 109-121, 2013, DOI: http://dx.doi.org/10.13044/j.sdewes.2013.01.0008

ABSTRACT

A methodology that permits testing the level of integration of the photovoltaic technology in urban areas is presented. The percentage of coverage of the electricity demand of grid-connected photovoltaic systems installed on the roofs of buildings were investigated in a district of the city of Palermo (Sicily). After classifying roofs according to their shape, orientation and pitch by means of satellite images provided by Google Earth, the ratio of the productivity of the PV systems and the consumption of electricity of the households was analysed. The results of the energy assessment have been screened considering the economic feasibility of grid-connected photovoltaic systems: the energy produced by the PV systems whose economic analysis showed disadvantageous values of NPV or IRR was rejected. As a result, it can be concluded that the size of the PV system that may be installed corresponding to the number of floors, and the consequent production of electricity, does not recover the costs for installation and maintenance of the system.

KEYWORDS

Grid-connected Photovoltaic Systems, Photovoltaic, Solar Potential, Urban Context, Available Roof Surface, Energy Assessment, Economic Assessment, Energy Cover Factor

INTRODUCTION

The European Union (EU) set a series of climate and energy targets to be met by 2020, known as the "20-20-20" targets. With the Directive 2009/28/EC, the EU stipulated for each Member State the national overall target for the share of energy from renewable sources. For Italy the share of energy from renewable sources in gross final consumption of energy in 2020 would be at least 17%. To achieve the latter target solar energy could play the main role in urban contexts.

The problem involves different aspects that concern not only the energy performance but also economic effects. It means that, according to the actual generation of electricity, the PV systems have to be a feasible economic investment. To attain and test these results it is basic to consider the size of the studied system. Actually, when they refer to a specific PV system analysed such as one-family detached house, every single aspect of the problem can be considered (panels, inverters, orientation, pitch, obstructions, economic analysis) but the data of predictions cannot be used to extrapolate the results of the analysis to a whole city or region [1-3]. On the other hand, when the purpose of the study is to analyse the energy potential of a nation, or even a continent, it is impossible to consider all details of the problem [4-7]. The potential of solar electricity generation was

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assessed for areas whose surface varied from an apartment [8] to a whole city [9] or a continent [10]. To evaluate the collecting roof surfaces, Vardimon [11] considered that, for slanted roofs, 18-24% of the area was available, while flat roofs had an availability ratio of 50-70%. Ordóñez *et al.* [12] estimated availability ratios of 79-98% for pitched roofs and 65-80% for flat roofs, depending on the typology.

Many researchers have investigated the effectiveness of supporting measures for the production of electricity by PV systems. Papadopoulos et al. [13] discussed a quantitative assessment of the feed-in tariff (FIT) introduced in Greece. Campoccia *et al.* [14] compared the supporting measures adopted by France, Germany, Italy and Spain. Dusonchet *et al.* [15, 16] extended the comparison to 17 western and 10 eastern European Union countries.

THE METHODOLOGY

The proposed methodology considers many aspects of the problem including the energy and economic ones. Actually, even if it is important to evaluate the energy cover factor of a PV system, it could happen that the PV system does not harvest economic advantage from the operational phase. The combined analysis of energy and economic aspects is of basic importance for evaluating real outcomes of investments. To reach this result the proposed methodology follows the following steps:

- Architectonic aspects:
  - identification of building roof surfaces (flat and slanted);
  - estimation of number of floors for each building;
  - shape classification of roofs.
- Energy aspects:
  - estimation of the electricity produced by the PV systems as regards to each floor;
  - estimation of the electricity consumed by the homeowners;
  - estimation of the energy cover factor.
- Economic aspects
  - evaluation of costs of the PV systems (investment costs and costs for maintenance, servicing and insurance against damage) and benefits due to the gains for the avoided bill costs, the incentives and the sold electricity;
  - analysis of cash flows;
  - evaluation of the economically effective and ineffective roofs;
  - estimation of the energy cover factor related to the results of the economic analysis;
  - sensitivity analysis for the most significant physical and economic parameters.

THE STUDY-ZONE

The methodology has been applied to the city of Palermo (Sicily) (Fig. 1) and in particular to a district characterized by regular square layout of streets, well-ordered orientation of buildings (117° East of South and 153° West of South) (Fig. 2), and almost constant pitch of slanted roofs (about 25° to the horizontal).

Architectonic aspects

<u>Identification of buildings roof surfaces</u> The maps of Google Earth were used to identify and measure the roofs of the analysed district (Figs.1-2).

Figure 1. The city of Palermo

The district area occupied by buildings measures 109,207 m^2 (Fig.3), i.e. 40% of the whole district's surface and it is subdivided into the following parts:

- slanted roofs 60,145 m^2 (55.07%)
- flat roofs 37,902 m^2 (34.71%)
- terraces 11,017 m^2 (10.09%)
- others 143 m^2 (0.13%)

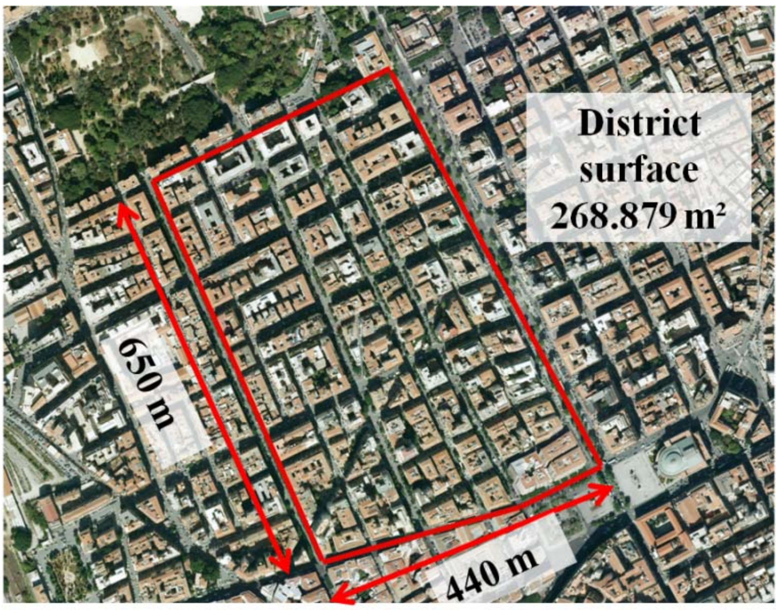


Figure 2. The analysed district

Estimation of number of floors of each building. The amount of roof surface that is available for any co-owner of the building to install a PV system derives from the number of floors of building. The Fig. 3 was determined by using the Street View function (technology featured in Google Maps and Google Earth that provides panoramic views from various positions along many streets in the world).

The majority of roof areas cover buildings of four floors. Moreover most of the slanted roofs belong to buildings of four floors whereas most of the flat floors cover buildings with eight floors. This distribution disagreement is due to the different ages of buildings, and consequently to the different technologies used to build them.

The slanted roofs typically cover old stone buildings traditionally made with massive walls, with a thickness varying from 30 to 60 cm. In these buildings, which were built before Second World War without using reinforced concrete frame, for structural stability, two opposite thick walls cannot be more than 4.5 metres apart; besides, because each room has at least a window, each building has a standard depth of about 9 metres. Buildings contain residential apartments that are regularly made with an entrance hall, a corridor, 5-6 rooms, a kitchen and bathrooms; for each apartment a gross surface of about 150-170 m^2 can be estimated.

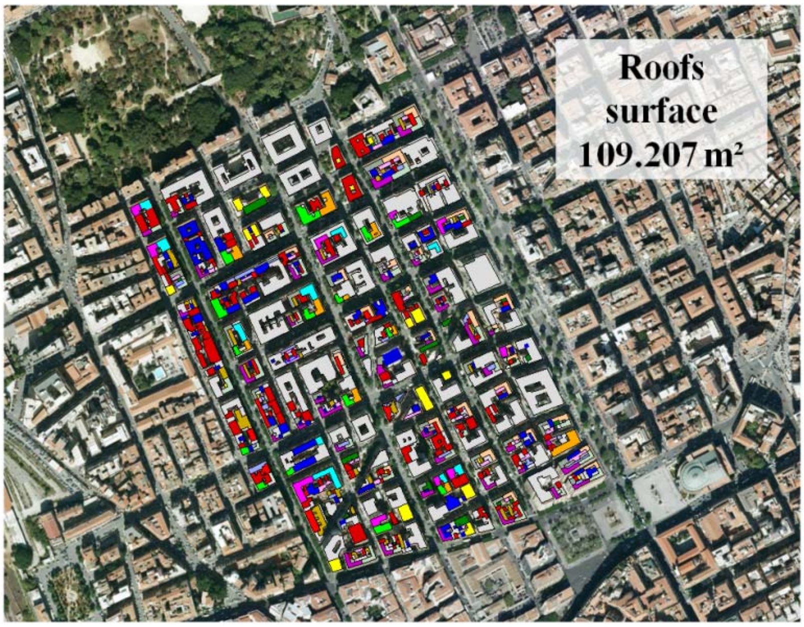


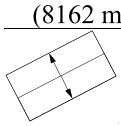
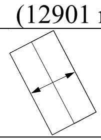
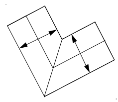
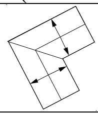
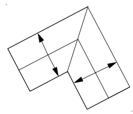
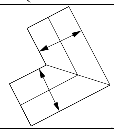
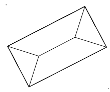
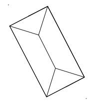
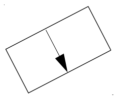
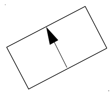
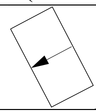
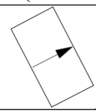
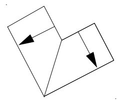
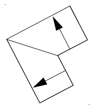
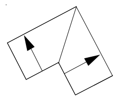
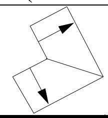
Figure 3. The area of district occupied by buildings

Classification of slanted roofs. With the aim of classifying the roofs in the district it was necessary to study their disposition in the urban context. The roof of many buildings looks like a complex composition of different elementary roof shapes such as gable, hip and skillion.

Some buildings have roofs orthogonally joined; besides, the roofs have different orientations.

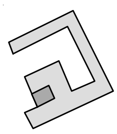
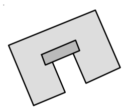
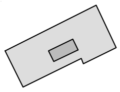
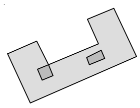
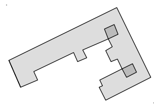
In order to classify the slanted roofs, the 16 types of shapes reported in Table 1 have been identified. The roof of each building was subdivided in parts similar to the roof types of Table 1; all parts were catalogued by assigning the corresponding roof type, the surface area and the identification code of the building. The prevalent roof shapes are the simple gable roofs (T1: 14% - T2: 21%).

Table 1. Classification of roof shapes

T1 (8162 m²)	T2 (12901 m²)	T3 (2690 m²)	T4 (2031 m²)
			
T5 (2144 m²)	T6 (2219 m²)	T7 (1582 m²)	T8 (2880 m²)
			
T9 (2296 m²)	T10 (1683 m²)	T11 (3298 m²)	T12 (2906 m²)
			
T13 (3787 m²)	T14 (3765 m²)	T15 (3618 m²)	T16 (4183 m²)
			

Classification of flat roofs. To classify flat roofs, which have different characteristics in comparison with the slanted roofs, a different criterion was used. Five classes containing almost the same number of buildings were identified. Once the area mean value for each class is evaluated, five regularly shaped buildings, with a roof area close to the class mean values were selected to represent the five groups of buildings.

Table 2. Classification of flat roofs

FR1 265 m²	FR2 387 m²	FR3 482 m²	FR4 717 m²	FR5 1394 m²
				

As it is shown in Fig. 4, most of the slanted roofs belong to buildings of four floors whereas most of the flat roofs cover buildings with eight floors.

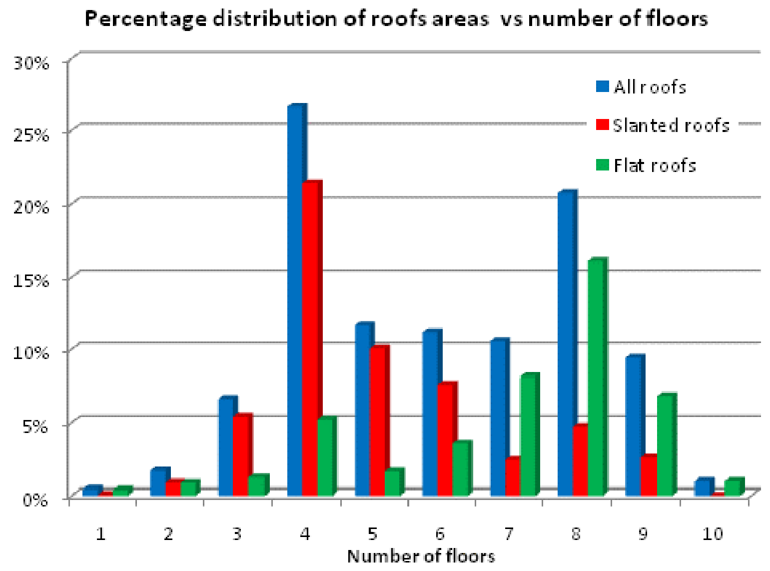


Figure 4. Distribution of roof areas versus number of floors

Energy aspects

Estimation of the electricity produced by the PV systems in slanted roofs as regards to each floor. The electricity generation produced by PV systems of each floor was calculated using the software PVsyst 5.06 [17] which includes monthly data of the global irradiation, temperatures and wind velocity (Meteonorm, versions 4-5).

It was assumed that:

- each type of roof in Table 1 had a standard surface of 162 m^2 and a fixed dimension (width or length) of 9 metres;
- the commercial PV panel used (Kyocera KD210GH-2P) had dimensions 1.50 x 0.99 metres;
- PV panels were considered to be collocated with the same pitch of the roof surface.

In the Tables below some results of the energy estimation are summarized.

Table 3. Electricity produced by slanted roofs

number of floors	Total roof area (m^2)	Electricity produced (kWh)
1	64	5,266.96
2	934	41,300.53
3	5,923	149,476.55
4	23,316	512,594.78
5	10,947	163,643.40
6	8,320	784,56.53
7	2,658	224,70.96
8	5,158	44,347.64
9	2,825	10,223.05
Total	60,145	1,027,780.40

Estimation of the electricity produced by the PV systems in flat roofs as regards to each floor. The electricity produced by flat roofs was estimated considering:

- the panels oriented to the South with a pitch of 30°, which is considered the most efficient for the city of Palermo;
- the shadowing effect due to balustrades, elevator housings and other obstructions.

To compare the flat roofs to the slanted roofs, the PV field sized for the roof area of each selected representative buildings were resized to occupy the area of the standard apartment (162 m^2). The results are shown in Table 4.

Table 4. Electricity produced by flat roofs

number of floors	Total roofs area (m^2)	Electricity produced (kWh)
1	0	0.00
2	0	0.00
3	0	0.00
4	2,319	43,090.88
5	320	3,014.04
6	3,581	45,646.84
7	8,011	89,973.85
8	15,911	165,323.55
9	6,718	55,099.39
10	1,042	7,572.44
Total	37,902	409,721.00

Estimation of the electricity consumed by the homeowners. The electricity consumption of a household was derived by the information officially issued by TERNA [18], which is the major Italian electricity transmission grid operator, and the ISTAT - Italian National Institute of Statistics [19] (Table 5):

Table 5. Energy and statistical figures for Palermo

Electricity consumption in Palermo's province	1475,80 GWh/year
Area of inhabited apartments in Palermo	22,141,320 m^2
Number of inhabitants in Palermo's province	1,244,680
Number of inhabitants in Palermo	686,711

On the basis of the above figures, in the standard apartment of 162 m^2 was calculated that a household of 5.02 people would live and on an average would consume **5957.3 kWh** of electricity every year.

Estimation of the energy cover factor. A criterion to establish the level of integration of PV systems is the evaluation of the PV energy potential by comparing the electricity generated and the energy demand by means of the energy cover factor C_{PV} [20]:

$$C_{PV} = \frac{E_{PV}}{D_{Total}} \cdot 100 \tag{1}$$

in which E_{PV} represents the electricity produced by the PV system and D_{Total} is the electrical energy demand. Taking account of the available areas and the number of floors, the actual PV energy potential of all roofs of the district was computed. As shown in Fig. 5, both slanted and flat roof buildings seem to be adequate to produce enough electricity to meet the "20-20-20" targets. PV systems cover 35.8% of the district electricity demand; the energy production is mainly due to the sloped roofs covering buildings of four floors.

The results shown in Fig. 5 are too optimistic because no shading and technical malfunctioning or unforeseeable solar energy unavailability were considered. Moreover, a problem may exist due to the mismatch when the generated electricity is not consumed immediately. To describe the matter properly, we have to examine two conditions:

1) the PV system is undersized to cover the energy demands D_{Total} and consequently the electricity generated E_{PV} is less than the demand;
2) the PV system is not undersized but the generation does not fully cover the energy demand D_{Total} for lack of contemporaneousness.

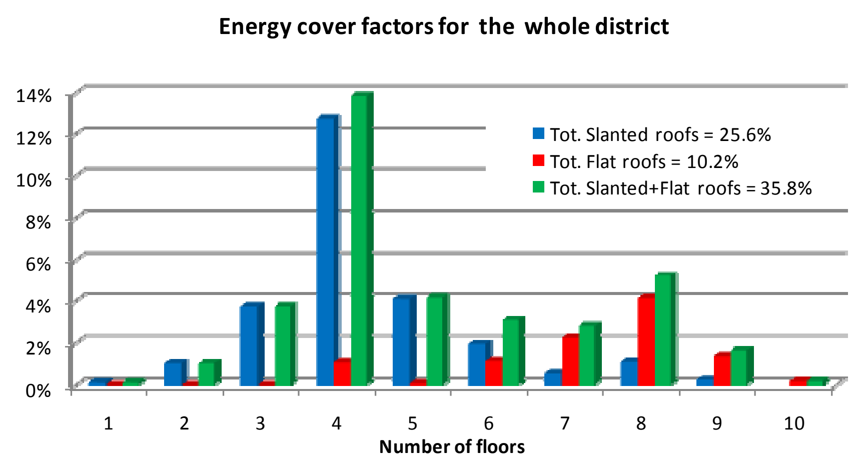


Figure 5. Yearly energy cover factors for the whole district, versus the number of floors.

First of all, both of conditions have been analysed by computing the night energy demand D_{night} which is always covered by the grid. It was assumed that the following appliances were working in the standard apartment [21-24] during the night:

- Lamp 85 W from T_i to 23:00 – from 07.00 to T_f
- Refrigerator: 90 W from T_i to 24:00 – from 00.00 to T_f
- Television + P.C.: 75 W from T_i to 23:00 – from 07.00 to T_f
-

where T_i was assumed one hour before sunset time and T_f one hour after dawn time. It was calculated that D_{night} = 716.5 kWh/year and consequently the day energy demand D_{day} = 5,240.8 kWh/year.

When a significant amount of electricity is generated by a great number of PV systems the surplus of produced energy can be a complex problem for the public grid managers. The surplus also represents an economic disadvantage for the self-producers because the purchase price is generally higher than the selling price. Moreover, as it will be shown by the economic assessment, the disadvantage related to the difference between purchase and selling prices is a reason why the households may decide not to install PV systems on their roofs.

Economic aspects

When the aim of an investment is to install PV systems on building roofs, the main problem is to define a criterion that permits assessing the actual feasibility of the project. The benefits are related to the gain for the avoided bill cost, for incentives and for selling electricity. The disbursements are due to the costs for investments, system devices replacement, maintenance and management, and insurance.

The electricity bills were calculated considering the difference between the bills corresponding to the electricity demand D_{Total} and those referred to the difference between D_{Total} and E_{cons}, which is the energy consumed while the PV systems are producing electricity. The electricity tariffs issued by the AEEG - Italian Authority for electricity and gas for domestic consumers with an electricity capacity of 3 kW were used. For the incentives, the values of FIT given by the decree issued in 2011 by the Ministry for the Economic Development were assumed. For the first four-month period of 2011 incentives varying from 0.402 to 0.333 €/kWh are paid, depending on the rated power of the PV system. For the gain in selling electricity, which was calculated on the basis of the exported PV generation $E_{PV} - E_{cons}$, a mean selling price of 0.102 €/kWh was used. The net gain in selling the exported PV electricity was calculated charging an income tax of 30.22%, which was estimated on the basis of the average income of the inhabitants of Palermo.

The costs of the investment were obtained from the market prices of components, considering the cost for labour and fitter's wages.

All the above factors are connected to the cash flows that permit assessing the effectiveness of installing PV systems on buildings through the evaluation of the net present value (NPV), the internal rate of return (IRR) and the pay-back periods. The cash flows were calculated for 20 years, which is the duration for which incentives are provided in Italy. The economic analysis was performed by considering:

- decline in of the efficiency of the PV panels every year of 1% of the nominal initial value:
- the maintenance and management costs, estimated to be 2% of the investment cost every year;
- the replacement of 1% of the PV panels every year and of all inverters every five years;
- an annual increase of 5.2% in the price of electricity;
- the effect of inflation, assumed equal to 2.1%, as deduced by the data issued by the ISTAT;
- the current value of 4.36% of the weighted average cost of capital.

RESULTS

In order to evaluate the actual values of the energy cover factor C_{PV} of the district, the results obtained from the energy assessment were filtered by using the results of the economic analysis: the energy produced by the PV systems whose economic analysis showed disadvantageous values of NPV or IRR was rejected.

Fig. 6 shows the yearly energy cover factors filtered to take account of the economic assessment; the shading coefficient was set equal to zero. The comparison with Fig. 5 shows the significant reduction of the energy cover factors due to the assessment of the economic convenience of PV installations; the energy cover factor of the district lowers from 35.8% to 24.1%, with a percentage decrement of 32.7%. The PV systems installed on modern buildings with flat roofs cover only 3.4% of the district demand; they passed from 28.5% of the global PV production to only 14.1%. About 50% of the global PV electricity is generated by the PV systems installed on the slanted roofs of buildings with four floors. Because the contribution of the building with a number of floors greater than five is only 3%, one may think that the PV systems on those buildings are not worth installing.

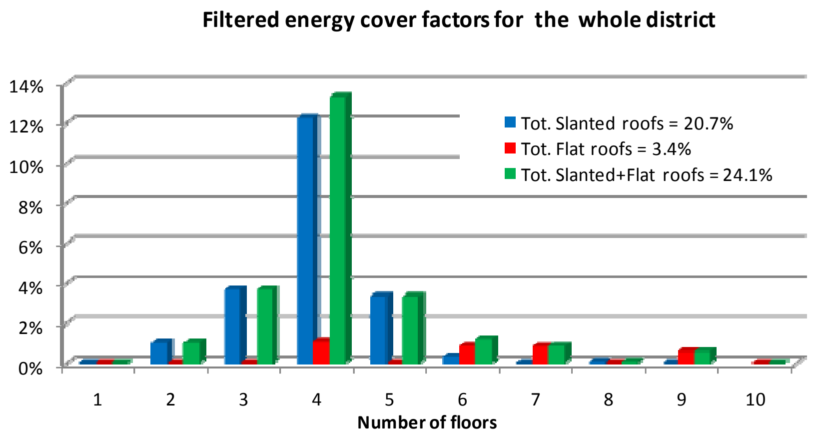


Figure 6. Yearly energy cover factors for the whole district, filtered by the economic assessment, versus the number of floors.

As it is shown in Fig. 7, the reduction of the energy cover factors is even severer if the effects of shading are considered.

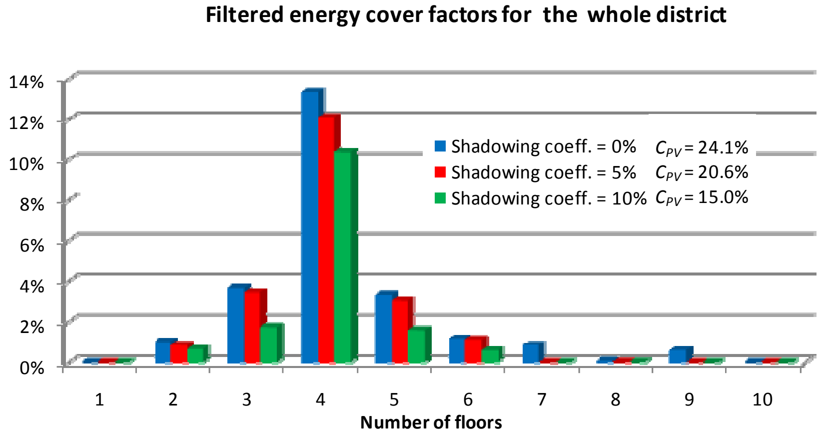


Figure 7. Yearly energy cover factors for the whole district, filtered by the economic assessment, at various values of the shading coefficient versus the number of floors.

Although the shadowing coefficient produces a reduction of the generated PV electricity that is directly proportional to its value, the effect on the cover factor is not quite proportional.

With a reduction of 5% in the electricity generated by the PV systems, the cover factor of the district changes from 24.1% to 20.6%, which is a reduction of 14.5%. The reduction is even greater with higher values of the shading coefficient; a reduction of 10% of the electrical generation due to the shadowing causes a decrement of 37.8 % in the energy cover factor of the district.

CONCLUSION

The evaluation of the real energy and economic effectiveness of the PV systems for reaching ambitious targets of the European Union in the energy field is of paramount importance for addressing decision makers towards different options of financial supports. In the meantime scientists have developed much experience in the above field but still now it misses a simple methodology for assessing the effectiveness of the PV systems in urban contexts, where the complexity of the problem has to cope with the need to simulate PV systems in reliable, fast and effective ways. The shown methodology has the above requested features and permits testing the level of integration of the photovoltaic technology in urban areas. The methodology was applied in a district of the city of Palermo (Italy) and the percentage of coverage of the electricity demand and the economic feasibility of grid-connected photovoltaic systems installed on the roofs of buildings were investigated. The obtained results showed the difficult to size the PV systems in big urban contexts in a proper and effective way, and point out the suitability of the tool for energy planning of the above systems. Considering energy and economic parameters the cover factor decreases from 35.8% to 24.1%. The possibility to identify situations where the economic feasibility of investments is not convenient is an important feature of the method that can help decision makers to select effective alternatives in energy planning procedures. The householder's perspective on PV investment is also related to energy storage and policies regulating self-production. Both aspects need an accurate analysis: due to the load mismatch some amount of PV electricity may be exported to the grid because the electrical demand is temporarily lower than production, whereas a consumption, which is higher than production and/or that does not match the available PV generation, will require to be supplemented by the public grid electricity. The energy self-sufficiency is one of the factors which may determine an economic advantage upon careful analysis of the actual costs for the devices. Similarly, an energy policy that supports the PV electricity consumed, penalizes the energy exported to the grid with a reduced incentive value.

NOMENCLATURE

C_{PV} Energy cover factor [%]
E_{PV} Electricity produced by PV system [kWh]
D_{Total} Electrical energy demand [kWh]
D_{dayl} Day energy demand [kWh]
D_{night} Night energy demand [kWh]

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Paper submitted: 04.03.2013
Paper revised: 15.04.2013
Paper accepted: 17.04.2013