Evaluating the Effectiveness of Photovoltaic Cells for Air Conditioning in Athens, Greece

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ABSTRACT: There is a continuous growth in demand for air conditioning worldwide over the past few years, especially in regions with high summer temperatures. This study represents a comparison of the energy demand for artificial cooling of multi-storey dwellings in Athens with the potential energy supply provided by photovoltaic cells located on the roofs and facades of the buildings. It aims to assess if artificial cooling of a particular building type can be made more environmentally responsible. A brief analysis of climate data prefaces the presentation of the basic data regarding energy requirements of appropriate cooling equipment and the solar energy available at this location. The paper concludes by performing a cost analysis of grid-generated supplied energy compared with the photovoltaic cells installation cost.

Keywords: solar energy, air conditioning, photovoltaic cells, Athens

1. INTRODUCTION

As the population of the cities and the urban densities continuously increase, urban microclimate tends to deteriorate [1, 2]. In addition, people easily accept the use of non-passive comfort methods such as air condition systems. Air conditioning, however, requires a large amount of energy and puts a major demand on the nation's electrical power grid in summer time.

When considering ways to reduce this energy requirement, a question arises: is it possible to restrict electricity consumption by using solar energy in order to provide cool and comfortable conditions in urban dwellings? This question initiated the present research, taking Athens as a test case, with the aim, ideally, of using photovoltaic cells for air conditioning.

The investigation consists of five parts. The first part analyses the climate and the built form of Athens. The second and third parts explain the choice of both a specific air conditioner and two different types of photovoltaic modules. The fourth part develops the calculation method of calculating the cooling energy required and the energy produced by photovoltaic cells, and estimates the application cost for Athens. The last part includes the conclusion to the investigation.

2. CLIMATE AND BUILT FORM OF ATHENS

2.1 Climate

Athens is located in central Greece with latitude and longitude 38.04° and -23.38° respectively. The climate is typically Mediterranean; it is moderate with sunny, dry and hot summers, and mild and damp winters. There is little diurnal temperature variation and medium seasonal variation, while freezing temperatures are uncommon (Fig. 1). Athens is subject to hot and dry winds blowing from the south and dry but cold winds blowing from the north (boras) [3]. This arid Mediterranean region has modest precipitation and receives scant rainfall in winter and minimal rainfall in summer. In addition, the solar radiation is very high, especially in the summer time (Fig. 1).

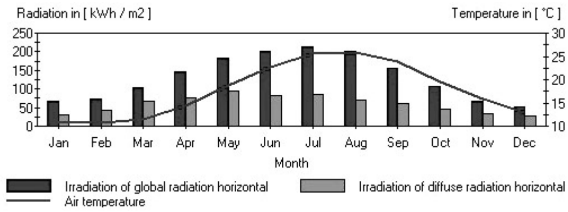

Figure 1: Irradiation of global radiation horizontal, irradiation of diffuse radiation horizontal and air temperature in Athens. [4]

2.2 Built form of Athens

The urban development of Athens presents some peculiarities, because the original city plans of Kleanthis, Schaubert and Klenze were only applied in part, while, without any state control, the city grew in every direction when the population more than doubled during the twentieth century. The most important features of the urban environment are the organic growth, the compact form, the homogeneity, the lack of vegetation and the high density of 926 inhabitants per km^2 [5].

Athens can be separated into three zones. Zone A consists of the city centre, the key characteristics of which are the mixed-use areas with offices, shops, small industries and leisure facilities all together in the same place, and the eight-floor blocks of flats often with penthouses: apartments with a terrace on the roof of the buildings. The only exception is Plaka, the old town of Athens, which maintained the vernacular architecture of two-level houses. Zone B includes the wider centre of Athens with the seven-floor blocks of flats and Zone C is the suburban area with four-storey houses and single dwellings.

To facilitate this survey, the following analysis applies only in Zone B of Athens. It is proposed for it not to be applied in Zone A, because of its historical and morphological qualities along with the limited number of residences, and in Zone C, due to the great number of single houses. The choice of Zone B is a good one because of its homogeneity.

3. AIR CONDITIONING

Mechanical cooling in Athens is considered essential, due to the high temperatures in summer time. The average temperature is higher than that typically considered a comfort temperature (Fig. 2). Cooling can be achieved by natural ventilation only if buildings are designed with cross ventilation but without so the number of overheating hours may be excessive. On the other hand, fans and air conditioners are able to decrease the inside temperature and to re-establish thermal comfort in the buildings. Both of these devices require an enormous amount of electricity. The following investigation examines ways of restricting the electricity consumption of air conditioning.

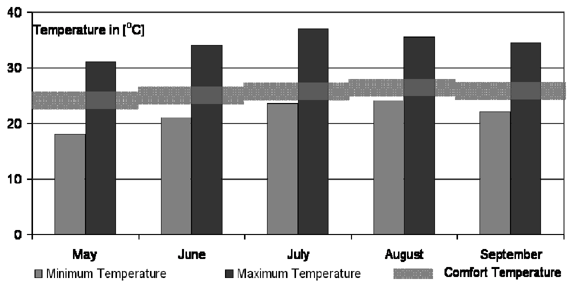

Figure 2: Comparison of minimum, maximum and comfort temperatures in Athens. [4, 6]

The choice of air-conditioner was based on the assumption that every apartment will have only one air-conditioning system in the main room, controlling the climate of an apartment area of 90 m^2 maximum. A single wall-mounted R22 refrigerant system with 3.5 kW cooling capacity was chosen for this study, which offers a cost effective and efficient solution to climate control in a room of 90 m^2.

4. PHOTOVOLTAIC CELLS

Photovoltaic cells (PV) convert sunlight directly into electrical energy. PV systems have many advantages including high reliability, low operating costs, low maintenance, transportable technology and power during blackouts only if there is storage battery. Environmentally, PV cells have the benefit of producing no pollutant emissions and reducing CO_2, NO_x and SO_x emissions by replacing grid-generated electricity with solar energy [7].

PV systems can be incorporated into buildings in various ways. Sloping rooftops are an ideal site, where modules can be mounted using frames. PV systems can also be incorporated into the actual building fabric, for example PV roof tiles are now available which can be fitted as would standard tiles. Moreover, PV can also be incorporated as building facades, canopies and sky lights amongst many other applications.

The most common PVs are monocrystalline silicon, polycrystalline silicon and thin-film silicon, which is used for amorphous silicon (Table 1). The theoretical maximum efficiency is 30%. However, the typical efficiency is lower mostly from 5% to 15% (Table 1).

Table 1: Available PVs and their efficiencies. [8]

Material	Level of Efficiency in % Lab	Level of Efficiency in % Production
Monocrystalline Si	approx. 24	14 to17
Polycrystalline Si	approx. 18	13 to15
Amorphous Si	approx. 13	5 to7

For this survey, two specific types of PV cells were chosen, which are available in Greece; polycrystalline silicon for the flat roof and amorphous silicon (a-Si) for the façade. The aim of using two different types of cells was to compare the efficiency of the two different photovoltaics (Table 2).

Polycrystalline silicon modules come in a variety of sizes and shapes. They have high efficiency, high resistance, but high cost. The modules are usually blue and because of their poor appearance are more suitable for roofs. Amorphous silicon modules are commercially available in smaller scale and lower weight than the previous type of modules. They have low cost, but lower efficiency. They are durable in high temperatures and are more ductile, hence they can easily form complex shapes. They can be found in a variety of colours, i.e. grey, brown, black, etc., and they have a delicate appearance. As a result, they are suitable for elevations.

Table 2: Comparison of the two selected PV modules. [9, 10]

Model Name	PV-MF130EA2LF	HD40
Cell Type	Polycrystalline Silicon	Amorphous Silicon
Dimensions [mm]	1248x803	635x1245
Weight [kg]	12.5	13.2
Thickness [mm]	46.0	7.0
Maximum Power Rating [W]	130	40
Module Efficiency [%]	13.0	5.1

5. METHOD

The calculation method for comparing the energy demand for cooling and the energy produced by photovoltaic cells is composed of four parts. The first part provides the required energy for air conditioning in Zone B of Athens. The second part calculates the energy gain from both types of photovoltaics. The third part compares the two energy results and the last part estimates the application cost.

5.1 Assumptions

Before giving the detailed analysis of the method, it is necessary to mention the most important assumptions of this survey:

- In Zone B there are predominantly seven-storey buildings. On the ground floor there are shops and offices, and on the other floors only apartments. Residential buildings with penthouses are excluded, because the roof area intended for PV applications is dramatically reduced. The roof is available for PV installation apart from the staircase projection, whose shading effects are considered by reducing the original PV system efficiency as it is further explained in Section 5.3.2. The blocks of flats of this zone are separated into three types. Type A is composed of two apartments on every floor, Type B of three and Type C of four apartments (Fig. 3).

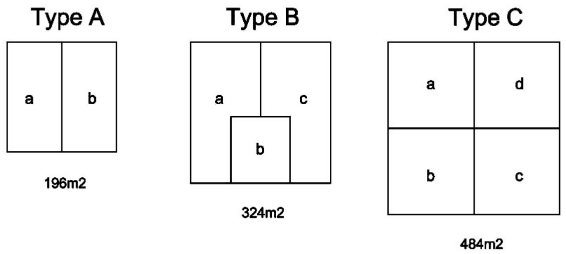

Figure 3: The three building types in Zone B in Athens.

- On the roof, the horizontal tilt angle is only considered and on the façade the vertical due to lower installation cost.
- The following study is analysed in detail only for Type A. The results of the other two types are cited in tables.
- Despite the fact that the correct assumptions require consideration of many factors such as the inside house temperature, the occupants' comfort preference, the working hours, the building orientation, the window size, etc, it is assumed that the diurnal usage hours of air conditioning are 6.5 per summer day. This assumption is accurate even thought the consumption of electrical cooling in August is higher than that in June, since the energy produced by PV cells could be allocated depending on the cooling demand of each summer month.
- It is also assumed that only one cooling system is used in every flat and it is installed in the common room of the apartment.
- The energy calculations is carried out only for the three summer months; June, July and August, when the air conditioning demand is essential.

5.2 Energy demand for air conditioning

The energy demand for cooling in Athens will be calculated for each type in relation to the number of air conditioners required.

More specifically, for Type A, 12 air conditioners are required since there is sixth-storey building with two flats per floor. It is assumed that the air conditioning uses 2/3 of the power (2.3 kW per hour from 3.5 kW), because it does not use energy the whole hour like other domestic appliances. Therefore, for 6.5 hours per day the power demand is 14.95 kWh (2.3kWx6.5h).

Identically for the other two types the total energy demand for cooling in relation to the number of air conditioners per type is presented in Table 3. The required power fluctuates from 179.40 kWh for Type A to 358.80 kWh for Type C.

Table 3: Energy demand for air conditioning.

	Type A	Type B	Type C
No. of Air Conditioners	12	18	24
Energy Demand (kWh) for Air Conditioning	179.40	269.10	358.80

5.3 Energy gain from PV cells

The total energy gain from the application of polycrystalline silicon modules on the flat roof and the amorphous silicon modules on the façade is calculated for June, July and August.

The number of PV modules used for the three building types results from the analysis of roof plans and elevations. On the one hand, the polycrystalline silicon module occupies an area of 1.00 m^2 (1248x 803mm). For Type A of 196 m^2 (14000x14000mm) area per floor, it seems reasonable to assume the use of 196 modules on the roof. On the other hand, the amorphous silicon module occupies an area of 0.79 m^2 (635x1245mm). It is possible the PV modules could be used on the parapet, the balcony front, the roof overhang or in combinations of these. Choosing to use solar modules on the balcony front, we could safely assume the use of 77 south oriented unshaded modules (7 floor parapets x 11 modules).

Consequently, for Type A, 273 PV modules are used in total. Identically, for Type B, we could assume the use of 422 modules; 324 of polycrystalline silicon and 98 of amorphous silicon, and for Type C, 603 modules; 484 of polycrystalline silicon and 119 of amorphous silicon.

5.3.1. Use of polycrystalline silicon modules on the flat roof

The average daily radiation ($kWh/m^2/day$) collected on a flat roof in Athens is 7.72 in June, 7.77 in July and 7.08 in August according to NASA Satellite Data [11], (Table 4). The highest diurnal radiation on horizontal surface is observed in July and the lowest in August.

However, the PV system efficiency is assumed to be 11.7% instead of 13%, reduced by 10% [10], because of losses during the lifetime of PV modules, the peripheral equipment, the wiring, shading effects etc. In particular,

June: 7.72kWh/m^2/dayx11.7%=0.90kWh/m^2/day
July: 7.77kWh/m^2/dayx11.7%=0.91kWh/m^2/day
August: 7.08kWh/m^2/dayx11.7%=0.83kWh/m^2/day

Table 4: Energy produced daily by 196 flat PV modules for June, July and August [kWh].

Type A, Flat Roof	June	July	August
Average Daily Radiation Collected on Flat Roof (kWh/m^2/day)	7.72	7.77	7.08
Average Daily Radiation Delivered (kWh/m^2/day)	0.90	0.91	0.83
kWh Produced Daily by 196 Flat PV Modules	176.40	178.36	162.68

Hence, the average daily radiation delivered by solar modules (kWh/m^2/day) is 0.90 in June, 0.91 in July and 0.83 in August.

The energy produced daily by 196 flat modules for June, July and August in kWh is illustrated in Table 4. Specifically, for Type A configurations, 176.40 kWh is produced in June, 178.36 kWh in July and 162.68 kWh in August.

Finally, the comparison of the average daily radiation collected on a flat roof of 196 m^2 in kWh/m^2 per day with the energy produced by 196 flat modules and the energy demand for cooling per day is very interesting. Generally, the average daily radiation is very high in relation to the energy produced by solar electric systems, because of the low efficiency of the photovoltaics.

5.3.2. Use of amorphous silicon modules on the façade

According to NASA Satellite Data [11], the average daily radiation (kWh/m^2/day) collected on a façade in Athens in June is 2.74, in July 2.90 and in August 3.49, Table 5. The highest diurnal radiation is noticed in August and the lowest in June. It is obvious that the average radiation on vertical surfaces is poorer than on the corresponding radiation on the flat roof.

Table 5: Energy produced daily by 77 PV modules on the elevation of the buildings for June, July and August (kWh).

Type A, Façade	June	July	August
Average Daily Radiation Collected on Façade (kWh/m^2/day)	2.74	2.90	3.49
Average Daily Radiation Delivered (kWh/m^2, day)	0.12	0.13	0.16
kWh Produced by 77 Modules (Daily)	9.24	10.01	12.32

Assuming 4.6% PV system efficiency instead of 5.1% (10% reduction) [10] due to different sun angles and shading effects, the average daily radiation delivered by solar modules (kWh/m^2/day) is reduced to 0.12 in June, 0.13 in July and 0.16 in August. Table 5 shows the energy produced daily in kWh by 77 flat modules for June, July and August.

5.3.3. Total energy gain from both photovoltaics for Type A

The total power production per day for June, July and August (kWh) is:

June: 176.40kWh/day+9.24kWh/day=185.64kWh/day
July: 178.36kWh/day+10.01kWh/day=188.37kWh/day
August: 162.68kWh/day+12.32kWh/day=175.00kWh/day

Comparing the two types of photovoltaic, it is concluded that the energy produced by 77 amorphous silicon modules on the façade is very small in relation to the 196 polycrystalline silicon modules on the flat roof. Despite the fact that a smaller number of amorphous silicon modules are used, the proportion of the bar chart is dramatic. The contribution of the photovoltaic on the façade is slight.

5.3.4. Total energy gain for Type A, B and C

The total energy produced per day in every summer month for the three building types is presented in table 6. The energy produced in July is greater than the energy produced in either June or August. For the Type B configuration, 303.36 kWh/day is produced in June, in July 307.58 kWh/day and in August 284.60 kWh/day and for the Type C configuration; 449.88 kWh/day is produced in June, in July 455.91 kWh/day and in August 420.76 kWh/day.

Table 6: Total energy gain in kWh for Type A, B and C in June, July and August.

	Type A	Type B	Type C
Total kWh Produced per Day in June	185.64	303.36	449.88
Total kWh Produced per Day in July	188.37	307.58	455.91
Total kWh Produced per Day in August	175.00	284.60	420.76

5.4 Comparison

The energy cooling demand for Type A is 179.40 kWh/day, for Type B is 269.10 kWh/day and for Type C is 358.80 kWh/day depending on the number of air conditioners (Table 3).

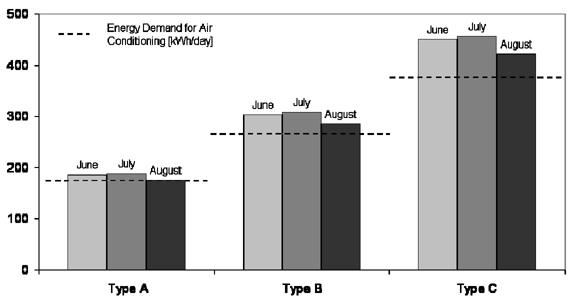

Figure 4: Comparison between the energy gained by the use of PV cells and the energy demand for cooling for the three building types in kWh/day for each summer month.

The energy production from PV cells is described in Table 6 and is illustrated in Figure 4. Comparing the energy gain and the energy demand for every summer month, it can be seen that the amount of energy required for cooling is smaller than the energy produced by PV cells. For Type A with two flats per floor, it is noticed a slight difference (188.37 kWh/day energy gained in July compared with 179.40 kWh/day energy required), while for Type C with four flats per floor, the difference is substantial even in August when the radiation collected on the surface is the lowest (455.91 kWh/day from PV cells compared with 358.80 kWh/day for cooling).

5.5 PV cells application cost and cooling electricity cost

5.5.1. PV cells application cost

Nowadays, solar electric PV systems are more economic in many parts of the world, but are still expensive. The cost of PV systems varies significantly according to the application and the efficiency of the system. Prices are expected to fall over the next decades.

For this investigation, the cost for the assumed life of polycrystalline silicon is € 7,900 per kW and for amorphous silicon € 8,200 per kW including installation and modules cost. The cost is based on the market prices in Greece in 2005 [10]. The high cost of amorphous silicon seems unreasonable. In fact, the installation cost in facades increases the price compared with the price of installation on the flat roof.

Tables 7 and 8 show the total cost for every building type. The cost is estimated according to the rated power and not to power produced per hour, because this is how cost is estimated in trade.

The cost of polycrystalline silicon modules rates from € 201,292 for 196 modules of Type A to €497,068 for 484 modules of Type C, while the cost of amorphous silicon modules rates from € 25,256 for 77 modules of Type A to € 39,032 for 119 modules of Type C.

Table 7: Cost of polycrystalline silicon modules.

Polycrystalline Silicon	Type A	Type B	Type C
PV Modules	196	324	484
Rated Power (W)	130	130	130
kW Produced	25.48	42.12	62.92
Estimated Cost (€ 7,900 per kW)	201292	332748	497068

Table 8: Cost of amorphous silicon modules.

Amorphous Silicon	Type A	Type B	Type C
PV Modules	77	98	119
Rated Power (W)	40	40	40
kW Produced	3.08	3.92	4.76
Estimated Cost (€ 8,200 per kW)	25256	32144	39032

5.5.2. Cooling electricity cost

Table 9 presents the cost of electricity for cooling in Greece for a 25 year period equivalent to the photovoltaics' lifetime [12].

Table 9: Electricity Cost for Cooling.

	Type A	Type B	Type C
Power Demand kWh	179.40	269.10	358.80
Day Electricity Cost in Greece (€ 0.085 per kWh)	15.25	22.87	30.50
92 Summer Days Electricity Cost in € (Greece)	1403.00	2104.04	2806.00
25 Years Electricity Cost in € for Greece	35075	52601	70150

The current daily electricity cost in Greece is €0.085 kW per hour according to the Hellenic Public Power Corporation [13]. The monthly compulsory electricity charge is not counted as it is paid at a flat rate whether or not household appliances/utilities are in use.

More specifically, for 25 years (2300 summer days) the electricity cost for cooling is € 35,075 for Type A, € 52,601 for Type B and € 70,150 for Type C.

5.5.3. Cost comparison

The data on the cost comparison shows that the application cost of photovoltaic systems is dramatically high in relation to the electricity cost required for 25 years especially without subsidies from the Government. Currently, the EU and the Greek Government gives economic incentives in form of public subsidies to investments on PV industries [14]. However, there is not financial aid to individual families to install PV cells on their houses.

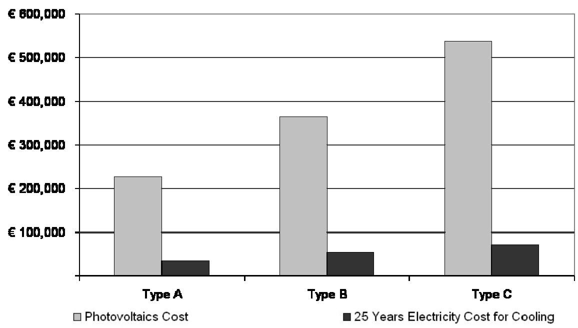

Figure 5: Comparison between the PV module cost and the 25 years electricity cost for cooling in Euros.

Particularly, the electricity cost for air conditioning use in summer time (€ 35,075) is only the 16% of the PV cost (€ 201,292) for Type A with two flats per floor, 15% for Type B with 3 flats per floor and 13.5% for Type C with 4 flats per floor. The following figure illustrates this comparison (Fig. 5).

This difference in cost could be balanced by either increasing the PV cells efficiency or reducing their installation cost. Also, a potential increase of electricity cost in Greece could make the PV modules more attractive. Furthermore, the Greek government could encourage the installation of PV systems on buildings by partly sponsoring the cost such as the UK government has recently decided [15].

6. CONCLUSION

This study has shown that it is possible to reduce energy consumption using solar energy in order to cool dwellings at an urban scale. Photovoltaic cells are able to produce the required energy for cooling assuming that there are between six and seven cooling hours per day. Of course, the starting points should be to reduce the number of cooling days and hours for air conditioning which is definitely the best way to decrease energy consumption and to have environmental benefits.

After analysis and comparison of the two photovoltaic types, it can be concluded that the application of amorphous silicon on façades is not able to produce beneficial or acceptable results. Typically, it is an expensive and low-efficiency choice.

The cost of the photovoltaic system application is still very high and the efficiency is low. Certainly, the prices are expected to fall in the near future. Today, however, solar systems are not cost-effective for this purpose.

ACKNOWLEDGEMENT

The author would like to thank Mrs Polykseni Emmanouilidou for her valuable help in air conditioner queries and HELIODOMI for the helpful information in photovoltaic cells.

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