# Evaluation of photovoltaic energy potential in residential buildings

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**Abstract.** This paper evaluates the potential contribution of grid connected photovoltaic generation to supply electric energy needs of Spanish consumers, and to reduce greenhouse gases emissions. To do this evaluation the structure of generation and demand is analyzed, the solar energy potential of the roof of residential buildings is evaluated, and a case study with data from seven residential customers is done. Then an extrapolation to a national level is made. Also, a simple economical evaluation is done. The results suggests than a massive installation of photovoltaic solar panels in the roof of residential buildings can have a great impact in electric energy generation as well as in Kyoto protocol compliance, with a reasonably fast amortization period.

**Keywords:** Photovoltaic, residential consumption, $CO_2$ emissions, Kyoto protocol.

## 1. Introduction

Electric energy consumption in Spain during 2004 was of 247 409 GWh [1]. 233 551 GWh of them correspond to the peninsular system and 13 858 GWh to the extra peninsular system. In the peninsular system this demand has been supplied by hydroelectric (12 %), nuclear (25 %), coal (31 %), fuel and gas (3 %), combined cycles (12 %) power plants and special regime generation (17 %), as it is shown in Figure 1.

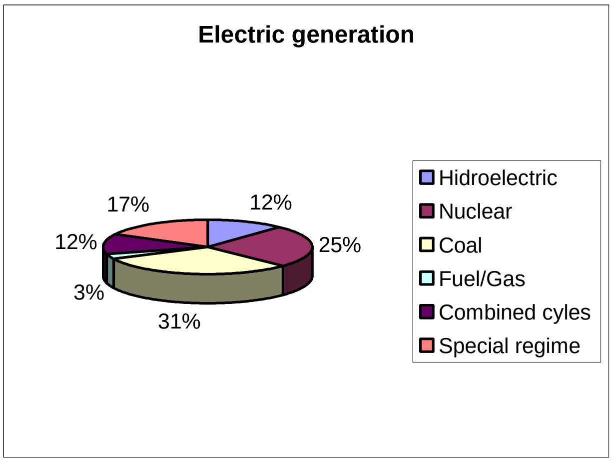


Figure 1 Generation percentage per type

The distribution of supply among consumers, shown in Figure 2 is: 25% for big industrial consumers, 20% for residential customers, 6% for commercial sector, 0.5% for big tourist hotels and 48.5% for the remaining consumer types [2].

As a consequence of this generation, greenhouse effect gases are produced. According to the information given by the Spanish Environmental Ministry [3], during 2001, total greenhouse gases produced were 382 789 $CO_2$ tons, a 15% more than Kyoto protocol allows (in 2008 – 2012 period). 109 860 tons of them (28.7%) correspond to electric generation industries.

Obviously, there is a big interest in any technology that can contribute to reduce emissions without reducing electric energy supply.

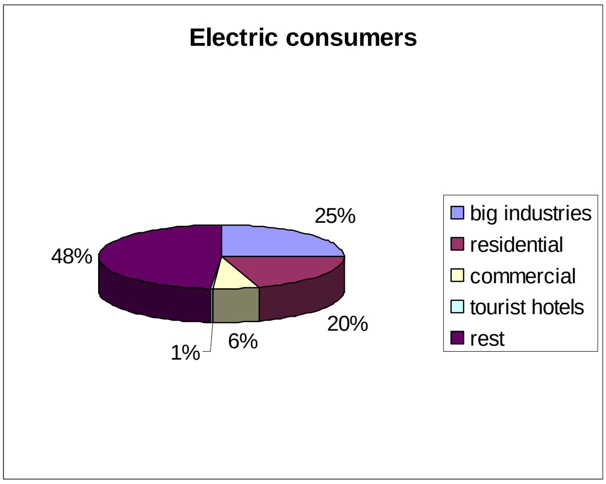


Figure 2 Consumption percentages per type

In this context the roof of residential buildings is a resource worth considering. Photovoltaic solar panels placed on this roof can contribute significantly to supply the electric energy needs of the inhabitants who live in these buildings. Because these buildings are grid connected it is assumed that its potential photovoltaic electric energy generation will be injected into the distribution network.

In order to analyze this possibility, data of actual energy consumption of several residential consumers are gathered.

## 2. Solar Energy Potential

The available solar energy depends on several factors. First of all it is the insolation levels of the zone in consideration. These levels depend on its geographical position (longitude and latitude) and also on its climate characteristics (average cloudiness). Although a theoretical calculus can be done taking into account the geographical parameters of the considered site, the climate influence can only be measured. So, an experimental determination of the insolation levels is necessary. In Table 1 a ten years average of Madrid insolation levels can be found [4].

Table 1 Madrid ten year average insolation levels

| Months | Jan | Feb | Mar | April | May | June | July | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $kW \cdot h/m^2/day$ | 1.93 | 2.75 | 4.09 | 4.83 | 5.85 | 6.52 | 7.11 | 6.30 | 4.91 | 3.07 | 1.97 | 1.59 |

The Madrid annual average is 4.62 $kW \cdot h/m^2/day$ [4].

The second factor that must be taken into account is the efficiency of the photovoltaic panels. This efficiency depends on the considered technology. Nowadays there are two main competing technologies in this sector: crystalline and amorphous silicon technologies. Its main characteristics are shown in Table 2 [5].

Table 2 Comparison of Crystalline and Amorphous Silicon Technologies

| | Crystalline | Amorphous |
|---|---|---|
| Status (1996) | Workhorse of terrestrial and space applications | New, rapidly developing technology |
| Thickness | 200 – 400 µm | 2 µm |
| Raw material cost | High | About 3% of crystalline silicon |
| Conversion efficiency | 16 – 18 % | 8 - 9 % |
| Module Costs (2005) | € 5 – 7 per watt | € 5 - 7 per watt |

Solar panels produce energy in direct current form but the loads need to be supplied with alternating current. So, an inverter is needed. Its efficiency $\eta$ can be estimated circa 85%.

The remaining factor is the surface available but this depends on the building in consideration.

## 3. Photovoltaic potential

The photovoltaic potential depends directly of the available surface *S*. Each consumer that lives in a flat can have a roof surface that is equal to his flat surface divided by the number of floors of its building.

This potential depends also on the insolation level *I* in the zone of the building. As all the flats, whose data are analyzed, are located in Madrid this level is the same and it has the values shown in Table 1.

Other aspect is the efficiency $\eta_s$ of the solar panel itself. This efficiency depends on the technology used. In Table 2 values for the two main technologies are given. Additionally, the efficiency of the inverter $\eta_i$ must be taken into account.

So the energy produced in a month with *d* days can be expressed by:

$$E = S * I * d * \eta_s * \eta_i \quad (1)$$

## 4. Case Study

The annual electric energy needs of six flats and one house are summarized in Ttable 3. In this table data about its surface and number of floors of the building are also given.

Table 3 residential consumer's data

| | Flat 1 | Flat 2 | Flat 3 | Flat 4 | Flat 5 | Flat 6 | House |
|---|---|---|---|---|---|---|---|
| Surface $m^2$ | 130 | 105 | 120 | 80 | 125 | 100 | 200 |
| Floors | 9 | 8 | 9 | 5 | 8 | 5 | 3 |
| Consumption kWh | 3893 | 2695 | 3298 | 3924 | 3222 | 2121 | 2447 |

The energy consumption of these consumers varies between 12 and 49 $kWh/m^2$ by year. In figures 1 to 7 the electric energy generation capabilities and demands of these potential installations are shown.

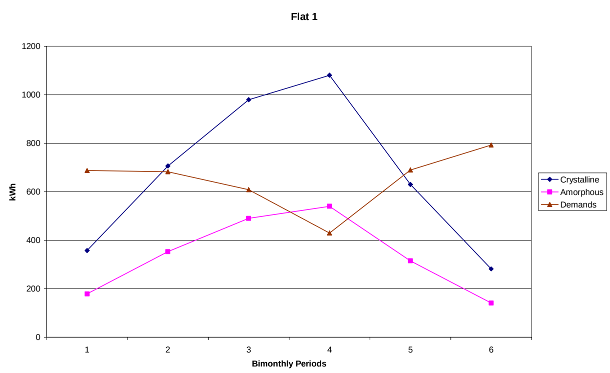


Figure 1 Generation and Demand of flat 1

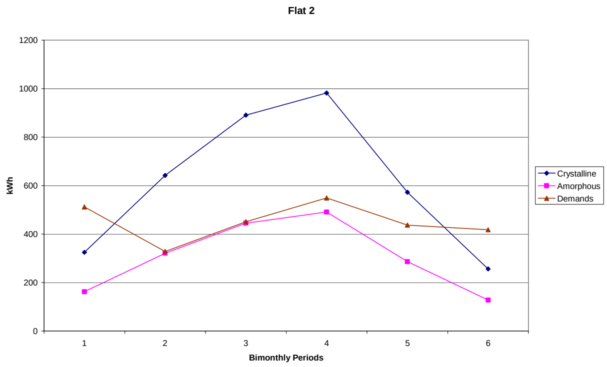


Figure 2 Generation and Demand of flat 2

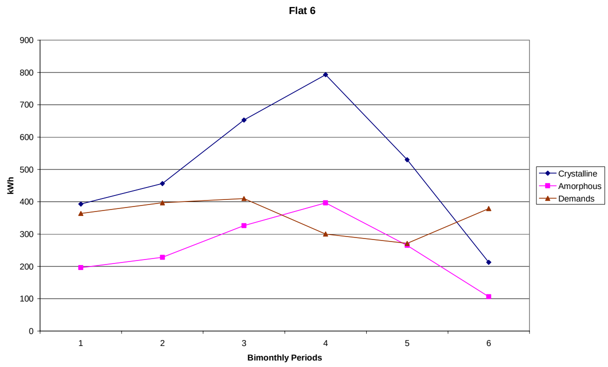


Figure 6 Generation and Demand of flat 6

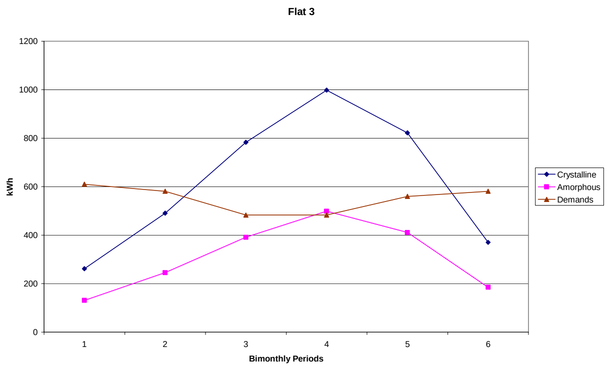


Figure 3 Generation and Demand of flat 3

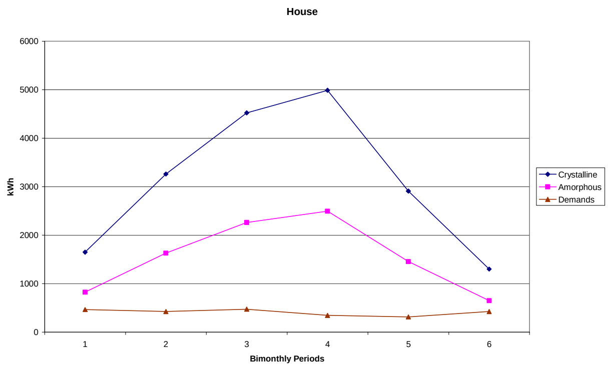


Figure 7 Generation and Demand of house

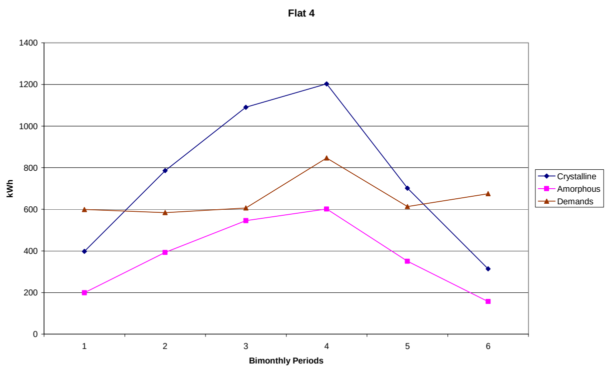


Figure 4 Generation and Demand of flat 4

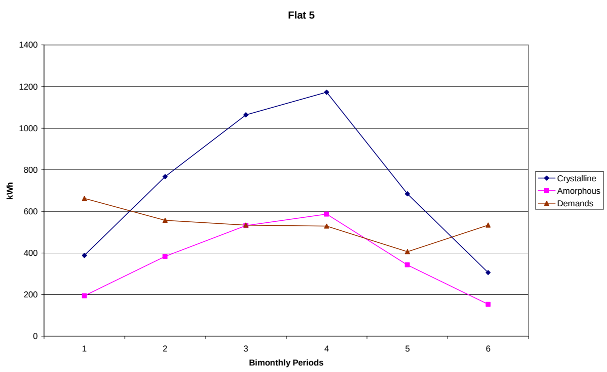


Figure 5 Generation and Demand of flat 5

From these figures it is obvious that the potential electric energy demand coverage is variable among these consumers. The consumer with a house (figure 7) can cover all his energy demand using both technologies all months. In all the remaining cases there is always a bimonthly period in which no technology can cover the needs of the consumers.

In Table 4 an annual summary of generation and demand is shown for all the studied cases. From these table data, it is obvious than the amorphous technology cannot cover the annual demand of any flat. And it is also obvious than the crystalline technology can cover, with excess, the electric energy needs of all the consumers.

Table 4 Annual summaries of generation and demand

| Energy kWh | Flat 1 | Flat 2 | Flat 3 | Flat 4 | Flat 5 | Flat 6 | House |
|---|---|---|---|---|---|---|---|
| Amorphous | 2019 | 1834 | 1863 | 2246 | 2191 | 1519 | 9316 |
| Crystalline | 4037 | 3668 | 3727 | 4491 | 4381 | 3039 | 18633 |
| Demand | 3893 | 2695 | 3298 | 3924 | 3222 | 2121 | 2447 |

The percentage of demand that can be covered by both technologies is shown in table 5.

Table 5 Percentage of annual demand covered

| % | Flat 1 | Flat 2 | Flat 3 | Flat 4 | Flat 5 | Flat 6 | House |
|---|---|---|---|---|---|---|---|
| Amorphous | 52% | 68% | 56% | 57% | 68% | 72% | 381% |
| Crystalline | 104% | 136% | 113% | 114% | 136% | 143% | 761% |

Due to the similar cost per watt of both technologies it is better to install the technology with higher efficiency. So, using crystalline technology the electric energy needs of these residential consumers can be completely supplied.

## 5. National average

In order to estimate the possible contribution of photovoltaic electric generation to a national level it is neccessary to analyze the representativity of these seven residential customers. In [2] the residential customers are classified according to the following criteria:

- Age
- Size
- Working wife
- Climatic zone
- City size

All the customers are in the same age range (from 35 to 65 years old), same size (from 2 to 4 persons), same climatic zone and city size. Only in flat 3 the wife does not work, so its electric energy needs are 20% less than the others [2]. According to INE data [7], husband and wife work only in the 25,30% of all spanish homes. So the average percentage of annual residential demand that can be covered by photovoltaic electric energy generation is circa 116% for consumers that live in flats.

As it is obvious from Table 5 the buildings with greater potential are one family houses. According to INE data [7] in Spain there are 6 885 843 one family houses, and there are 14 187 169 homes. So, an 48,5% of all families live in houses. Taking into account this proportion the average percentage of annual residential demand that can be covered by photovoltaic electric energy generation is 429%.

So, in 2004, residential customers consumption was of 49 482 GWh. A 429% of this energy is 212 278 GWh. This is enough energy to substitute all fossil fuel plants, so total $CO_2$ emissions of the electric energy sector (109 860 tons in 2003) could be avoided. So the $CO_2$ emissions of 2003 would be 272 929 tons, a 18% less than Kyoto protocol allows instead of a 15% more.

## 6. Costs

The price of a kW·h of photovoltaic origin is of 0,22 € if the installation has more than 5 kW of installed power capacity. As 1 kW of installed capacity requires 7,3 $m^2$ of horizontal surface, it can generate 7,3*4,62*365,25 = 12 310 kW·h per year. This means an income of 2 708 € per year. The installation cost of 1 kW solar plant is around 12 000 €. So there are needed 5 years to amortize the investment with an interest rate less than 4,17%.

## 7. Conclusions

The calculus made shows that by installing photovoltaic solar arrays in the roofs of residential buildings it is possible to supply four times its total electric energy demand. In 2004 this demand was of 49 482 GWh. Depending on the energy source that this generation could replace, $CO_2$ emissions up to 109 860 tons can be saved. This means reducing to zero total greenhouse effect gas emissions of the energy generation sector in 2004. This measure by itself allows compliance of Kyoto protocol in 2004 with an 18% margin. So it seems a very attractive proposal to help in the compliance of Kyoto protocol.

Additionally, the investment made can be fully amortized in five years provided that the payment conditions for photovoltaic electric energy generation are maintained.

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