CONDITIONS IN WHICH A PHOTOVOLTAIC SYSTEM IS MORE VIABLE THAN A LOW-TEMPERATURE SOLAR THERMAL SYSTEM

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ABSTRACT: Photovoltaic (PV) and low-temperature solar thermal (LT-STH) are the most widely used technologies in the building sector. This study determines, depending on the most influential parameters, the conditions in which a PV system is more beneficial than a LT-STH system from an economical, energetic and environmental point of view. The parameter used for economically evaluated both technologies is the levelized cost of energy (LCOE). Moreover the Greenhouse Gas Emissions factor is employed for an environmental evaluation. The main results shown on this study reveal that in most cases PV is economically and environmentally more viable than LT-STH, although it would be necessary to analyze the particular conditions of each site.
Keywords: Economic analysis, viability, CO_2 emissions, zero-energy building.

1 INTRODUCTION

Renewable energies have experienced a noteworthy surge during the last few years [1,2]. Years ago it was rare to see solar collectors or windmills around our cities, but nowadays they have become usual elements [3,4]. With a particular focus in the building sector, it is safe to say that the technologies that have achieved greater growth are PV and LT-STH [5,6].

The function of the PV technology analyzed in this paper is to generate electrical energy for residential buildings. This energy is allocated to conventional uses as lighting, appliance or for the generation of thermal energy. On the other hand it is considered that LT-STH technology exclusively generates thermal energy to obtain hot water through the increase of temperature by the effect of solar radiation. This means that PV technology presents higher exergetic efficiency than LT-STH technology. Against this, LT-STH technology is mainly characterized by higher energetic efficiency than PV technology [7].

From an economic point of view it can be highlighted that PV technology has reduced significantly its costs and new laws in different countries as Spain or Germany have been developed to allow the self-consumption. PV technology also contributes significantly to achieve the European law target about nearly zero-energy building [8,9]. For this reason and because the available free area in buildings is limited, the following question arises: For which technology would it be the use of the free area more economically and environmentally viable? The aim of this study is to provide a useful tool to decide in function of market conditions.

2 CURRENT STATE

To achieve the objective set out above is necessary to establish the relation existing among the most influential parameters. The selected ratios are listed below:

* Investment cost rate: $C_{I\_PV}/C_{I\_LT\text{-}STH}$
* Energetic efficiency rate: $\eta_{PV}/\eta_{LT\text{-}STH}$
* Exergetic efficiency rate: $\eta_{x,PV}/\eta_{x,LT\text{-}STH}$
* Electrical and thermal energy price rate: P_{EE}/P_{THE}
* Environmental conversion factor rate: CF_{EE}/CF_{THE}

The analysis of the current market situation shows that the investment cost of a PV system is between 150€/m^2 and 600€/m^2 depending on their characteristics. In the case of LT-STH the lowest limit of this range is 200€/m^2 and the highest 600€/m^2 [10-12]. Considering this information, the investment cost rate ($C_{I\_PV}/C_{I\_LT\text{-}STH}$) ranges from 0.25 to 3.

As noted earlier another important relationships between PV and LT-STH technologies are the energetic and exergetic efficiencies. According to the current state of technology the energetic efficiency rate ($\eta_{PV}/\eta_{LT\text{-}STH}$) changes from 0.2 to 0.8 while the exergetic efficiency rate ($\eta_{x,PV}/\eta_{x,LT\text{-}STH}$) varies from 2 to 7 [12].

To provide an economic evaluation it is necessary to know the price of energy replaced by solar technologies, in this case electrical energy from the grid and thermal energy obtained by any of the conventional energy sources. The market conditions and the country under analysis affect significantly the value acquired by the ratio P_{EE}/P_{THE}. Average European values indicate that this relationship evolves from 1 to 3 [13].

Finally it is analyzed the relationship between the electrical and thermal environmental conversion factor, CF_{EE}/CF_{THE} that varies from 1 to 4 [14].

3 HYPOTHESES

It is also important to summarize the hypotheses considered to frame the conditions in which this analysis is performed:

* Annual operation and maintenance costs: 1% of investment cost for PV technology and 5% of investment cost for LT-STH technology.
* Replacement costs: 30% of investment cost in year 15 for LT-STH technology, this cost is not considered for PV technology.
* Consumer price index: 3%.
* Energy price index: 1.5%.
* Lifetime: 30 years for both technologies.
* Energetic storage is not considered in this study.

4 METHODOLOGY

As mentioned previously the objective of this study is to provide a useful tool to decide which technology, PV or LT-STH, is more viable. The tool comprises a set of graphs in which the evolution of main economical and environmental parameters can be analyzed in function of rates specified in paragraph 2.

The first part of this analysis is based on the variability of LCOE and savings obtained using each kind of technology. In the second part, from an environmental perspective, it is estimated the impact avoided by the use of each technology.

4.1 Levelized cost of energy

LCOE can be calculated by the following equation in which C_t represents life cycle costs and E_t represents the electrical or thermal energy generated. Furthermore the economical parameters r and s represent the consumer and energy price index respectively [15].

$$LCOE = \left[\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}\right] \Big/ \left[\sum_{t=0}^{n} \frac{E_t}{(1+s)^t}\right]$$

Life cycle costs of this expresion are calculated as the sum of the annual values of investment costs (C_I), operation and maintenance cost ($C_{O\&M}$) and replacement costs (C_R):

$$C_t = C_I + C_{O\&M} + C_R$$

Thermal and electrical energy are obtained using area (A), incident solar radiation (I) and the energetic efficiency of photovoltaic or thermal technology (η_{PV} or $\eta_{LT\text{-}STH}$) as follow:

$$E_E = A \cdot I\,\eta_{PV} \qquad E_{THE} = A \cdot I\,\eta_{LT-STH}$$

The relation between the LCOE of PV and LT-STH technologies is shown below:

$$\frac{LCOE_{PV}}{LCOE_{LT-STH}} = \frac{\left[\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}\right]\Big|_{PV}}{\left[\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}\right]\Big|_{LT-STH}} \cdot \frac{\left[\sum_{t=0}^{n} \frac{E_t}{(1+s)^t}\right]\Big|_{LT-STH}}{\left[\sum_{t=0}^{n} \frac{E_t}{(1+s)^t}\right]\Big|_{PV}}$$

Taking into account the especified hypotheses in third paragraph, the LCOE resulting relationship expressed in terms of energetic efficiency and investment cost of PV and LT-STH technologies is:

$$\frac{LCOE_{PV}}{LCOE_{LT-STH}} = \frac{\left[C_I + 0.196 \cdot C_I\right]\big|_{PV}}{\left[C_I + 0.980 \cdot C_I + 0.193 C_I\right]\big|_{LT-STH}} \cdot \frac{A \cdot I\,\eta_{LT-STH}}{A \cdot I\,\eta_{PV}}$$

The simplification of the expression above is:

$$\frac{LCOE_{PV}}{LCOE_{LT-STH}} = \frac{1.196}{2.173} \cdot \frac{C_I|_{PV}}{C_I|_{LT-STH}} \cdot \frac{\eta_{LT-STH}}{\eta_{PV}}$$

4.2 Savings

Another fundamental issue related to the suitability of installing a PV or a LT-STH system in a building is the saving generated by replacing a conventional source of energy. This saving is obtained as the product of the generated energy and the cost of the conventional replaced energy. It is considered that in the case of a PV system the generated energy replaces the electricity from the grid, while in the case of a LT-STH system the generated energy replace the thermal energy produced from conventional sources as oil or natural gas. The following equation shows this relation:

$$\frac{S|_{PV}}{S|_{LT-STH}} = \frac{P_{EE}}{P_{THE}} \cdot \frac{E_E}{E_{THE}} = \frac{P_{EE}}{P_{THE}} \cdot \frac{A \cdot I\,\eta_{PV}}{A \cdot I\,\eta_{LT-STH}}$$

Analyzing from an energetic point of view this equation results:

$$\frac{S|_{PV}}{S|_{LT-STH}} = \frac{P_{EE}}{P_{THE}} \cdot \frac{\eta_{PV}}{\eta_{LT-STH}}$$

The exergetic efficiencies of a PV and a LT-STH system are shown below:

$$\eta_{x,PV} = \frac{I \cdot A \eta_{PV}}{I \cdot A \left(1 - \frac{298}{5000}\right)}$$

$$\eta_{x,LT-STH} = \frac{I \cdot A\,\eta_{LT-STH}\left(1 - \frac{298}{333}\right)}{I \cdot A \left(1 - \frac{298}{5000}\right)}$$

If the previous savings relationship is analyzed from an exergetic perspective the result is:

$$\frac{S|_{PV}}{S|_{LT-STH}} = \left(1 - \frac{298}{333}\right) \cdot \frac{\eta_{x,PV}}{\eta_{x,LT-STH}} \cdot \frac{P_{EE}}{P_{THE}}$$

4.3 Environmental impact

The relationship of the environmental impact avoided by the use of PV and LT-STH technologies instead of conventional energies is measured in terms of CO_2 emissions avoided ($GHG_{PV}/GHG_{LT\text{-}STH}$):

$$\frac{GHG|_{PV}}{GHG|_{LT-STH}} = \frac{CF_{EE}}{CF_{THE}} \cdot \frac{E_E}{E_{THE}} = \frac{CF_{EE}}{CF_{THE}} \cdot \frac{A \cdot I\,\eta_{PV}}{A \cdot I\,\eta_{LT-STH}}$$

This relationship expressed in terms of the parameters defined in paragraph 2 is:

$$\frac{GHG|_{PV}}{GHG|_{LT-STH}} = \frac{CF_{EE}}{CF_{THE}} \cdot \frac{\eta_{PV}}{\eta_{LT-STH}}$$

5 RESULTS

This paragraph presents the most outstanding results of this study.

5.1 Levelized cost of energy

Figure 1 shows the evolution of the ratio $LCOE_{PV}/LCOE_{LT\text{-}STH}$ depending on the investment costs and the energetic efficiencies relationships. The area of the graph above the $LCOE_{PV}/LCOE_{LT\text{-}STH}$ equal to one indicates that it is more expensive to generate electrical energy with a PV system than thermal energy with a LT-STH system, as the graph shows this is the situation in most cases.

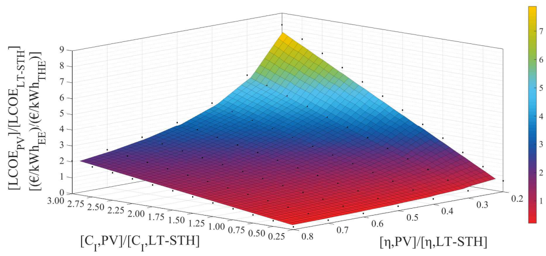

Figure 1: Levelized costs of energy of PV and LT-STH systems

The possibilities of use offered by electrical energy are much greater than the ones offered by low temperature thermal energy. The energy quality is measured by the exergetic variable. All this means that it is necessary to extend this analysis.

5.2 Savings obtained with PV and LT-STH systems

The second graph of this study shows the relationship of the savings generated by replacing the consumption of electrical energy by a PV system and the savings generated by replacing the thermal energy from a conventional source by a LT-STH system depending on prices and energetic efficiency rates.

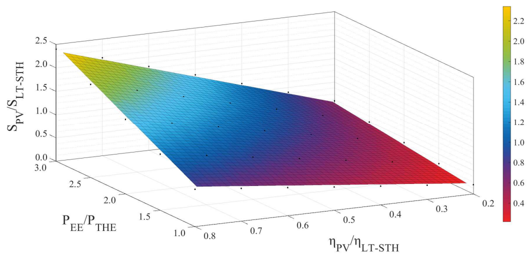

Figure 2: Savings obtained with PV and LT-STH systems depending on prices and energetic efficiency rates.

The surface area between the blue line ($S_{PV}/S_{LT\text{-}STH}$=1) and the yellow line ($S_{PV}/S_{LT\text{-}STH}$=2.5) in Figure 2 indicates the conditions in which the PV system provides greater savings than those generated by the LT-STH system.

Figure 3 shows the evolution of savings of PV and LT-STH technologies ratio depending on prices and exergetic efficiency rates.

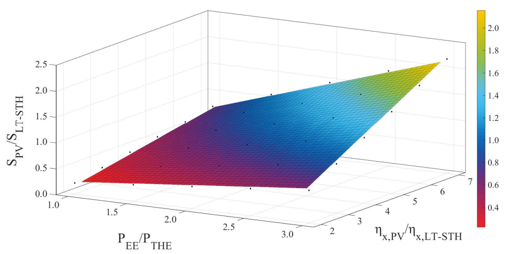

Figure 3: Savings obtained with PV and LT-STH systems depending on prices and exergetic efficiency rates.

The next figure shows the influence of the energetic efficiency ($\eta_{PV}/\eta_{LT\text{-}STH}$), the investment costs ($C_{I\_PV}/C_{I\_LT\text{-}STH}$) and the electrical and thermal energy prices (P_{EE}/P_{THE}) rates in a new parameter defined as savings over initial investment for each technology.

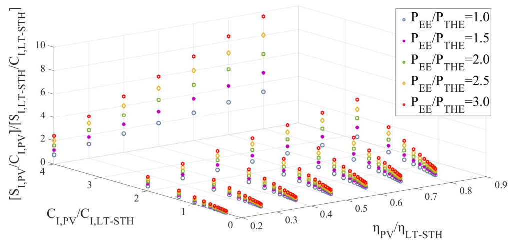

Figure 4: Evolution of savings over initial investment.

5.3 Environmental impact

The fifth and last graph included in this section of results shows the evolution of the $GHG_{PV}/GHG_{LT\text{-}STH}$ ratio depending on the energetic efficiency and the environmental conversion factor rate.

As can be noted from the graph provided when the CF_{EE}/CF_{THE} takes the value 1 the environmental impact avoided with a PV system is lower than the avoided with a LT-STH system. At present and for most countries this factor is usually greater than one, so the opposite extreme is analyzed. When the CF_{EE}/CF_{THE} coefficient takes the value 4 and from an energetic efficiency of 0.3, the environmental impact avoided by using a PV system is higher than the avoided when a LT-STH is employed.

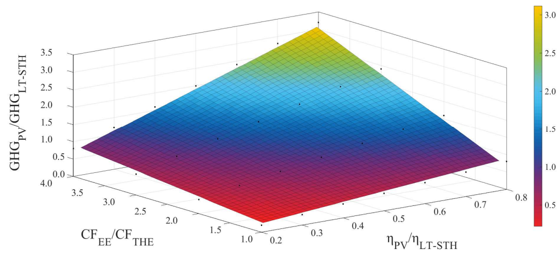

Figure 5: Environmental impact avoided by PV and LT-THS technologies.

5 CONCLUSIONS

As results show, nowadays PV technology is, in most cases, economically and environmentally more viable than LT-STH technology.

The thermal storage linked to LT-STH technology is more economical and reliable than the electrical storage associated to the PV technology, mainly chemical storage batteries. If costs and efficiencies related to energy storage would have been taken into account in this study, LT-STH systems would be more viable than PV systems.

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