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PV Domestic Hot Water System

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Abstract

In this paper, we investigate the technical and economical feasibility of a Photovoltaic Domestic Hot Water System (PV DHWS) consisting in a direct coupling of the energy produced by PV panels and the heating elements (electrical) of a hot water tank.

First, a prototype of PV DHWS was built and experiments were carried out at our outdoor test facilities in order to demonstrate the validity of the concept, evaluate the performances and identify ways of improvements. Then, a numerical model of PV DHWS was developed in *Modelica* / Dymola and validated using collected experimental data. System performances were simulated under various configurations and compared to the performances of solar thermal hot water systems. Finally, based on both experimental and numerical results, a first economic assessment of PV DHWS was done.

The results presented in this paper show that from a technical and economical point of view, PV DHWS could potentially be a cost effective alternative to conventional solar thermal systems.

Key-words: photovoltaic, solar domestic hot water system

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1. Introduction

1.1. Context

Photovoltaic Market: during the last 5 years a large decrease of PV system prices have been observed on the PV market (see Fig. 1a). This evolution has been combined with a steady decrease of feed-in tariffs in Europe. However, the storage of local PV production remains a major issue considering that PV production and building consumptions are not always in phase. As Electro--chemical storage (battery) can be expensive, thermal storage appears as an easier solution to implement.

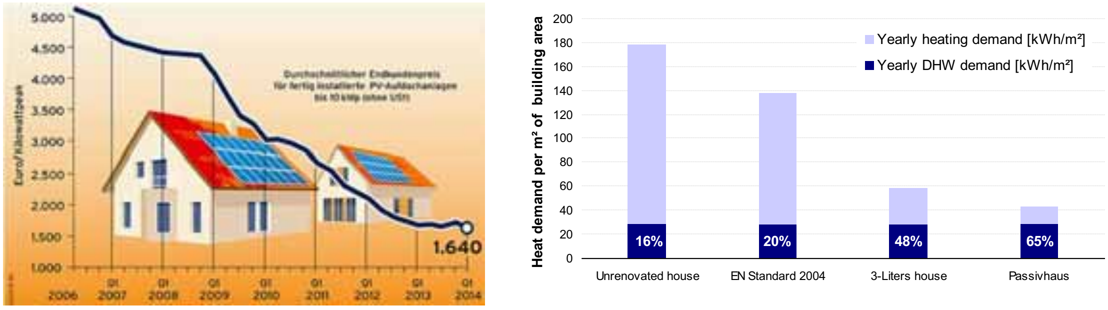

Figure 1. a) PV system price (2006 – 2014) - : source BSW-Solar, 2014. b) Residential building energy demand

Energy in residential buildings. The Fig. 1b shows that the energy needed for space heating decreases with the level of insulation of the building while the energy needed to provide hot water remains almost constant. Thus, the better the buildings are insulated, the higher the share of energy needed to provide hot water gets.

Based on both trends observed on Fig. 1, the coupling between PV systems and local thermal systems such as hot water systems could be an interesting synergy.

1.2. Concept

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In this context, a coupling between PV production and local thermal systems can be an interesting solution to convert produced energy into heating (or cooling) and store it locally more easily, as for instance in the case of a PV Domestic Hot Water System (PV DHWS).

Figure 2 : Concept of a PV Domestic Hot Water System

As presented in Fig. 2, a PV DHWS consists in a direct coupling between a PV system and an electric hot water system. The main advantage of such a system is to provide hot water to a building from renewable sources by storing intermittent solar energy as heat.

In this paper, we investigate the technical and economical feasibility of a PV Domestic Hot Water System (PV DHWS) based on a direct coupling (DC) between PV production and the heating element of an electric hot water tank.

2. Experimental investigations

In order to demonstrate the feasibility of a direct coupling between the energy production of a PV system and a hot water tank using DC current, a prototype of PV DHWS was designed and installed at our outdoor test facilities in southern Paris (see Fig. 3)

2.1. Experimental set-up

For this prototype, 2.2 kWp of PV panels (mono-Si) tilted at 30° and facing south were installed, linked to a MPP tracker and then connected to a 300L water tank with a resistive element of 3 kW (Set point temperature at 63°C). The idea was to use the resistive element that is already present in conventional electric hot water tanks, using DC power generated by photovoltaic panels or AC power when the PV energy is not sufficient to provide hot water needs. The hot water consumption of a 4-person household was then emulated (100L of hot water at 60 °C per day) and the whole PV DHWS was monitored in order to demonstrate the validity of the concept.

Figure 3 : Experimental set-up to evaluate the concept of PV DHWS

2.2. Results

Experimental sequences were conducted from March to June 2014. The monitoring consists in measuring meteorological parameters (solar irradiation, temperature), photovoltaic panels parameters (power, energy, and temperature), water withdrawal parameters (water flow rate, temperature) and Domestic Hot Water tank parameters (power and energy of the heater, temperatures…).

A specific test bench is used to simulate the hot water consumption of a 4 people household according to the European draft standard *prEn50440 Efficiency of domestic electrical storage heaters and testing methods*. The M324 water heater load profile is applied according to a 24 hour drawing schedule with a 21,042 MJ load.

The Figure 4 illustrates how the PV-DHWS operated during the test period.

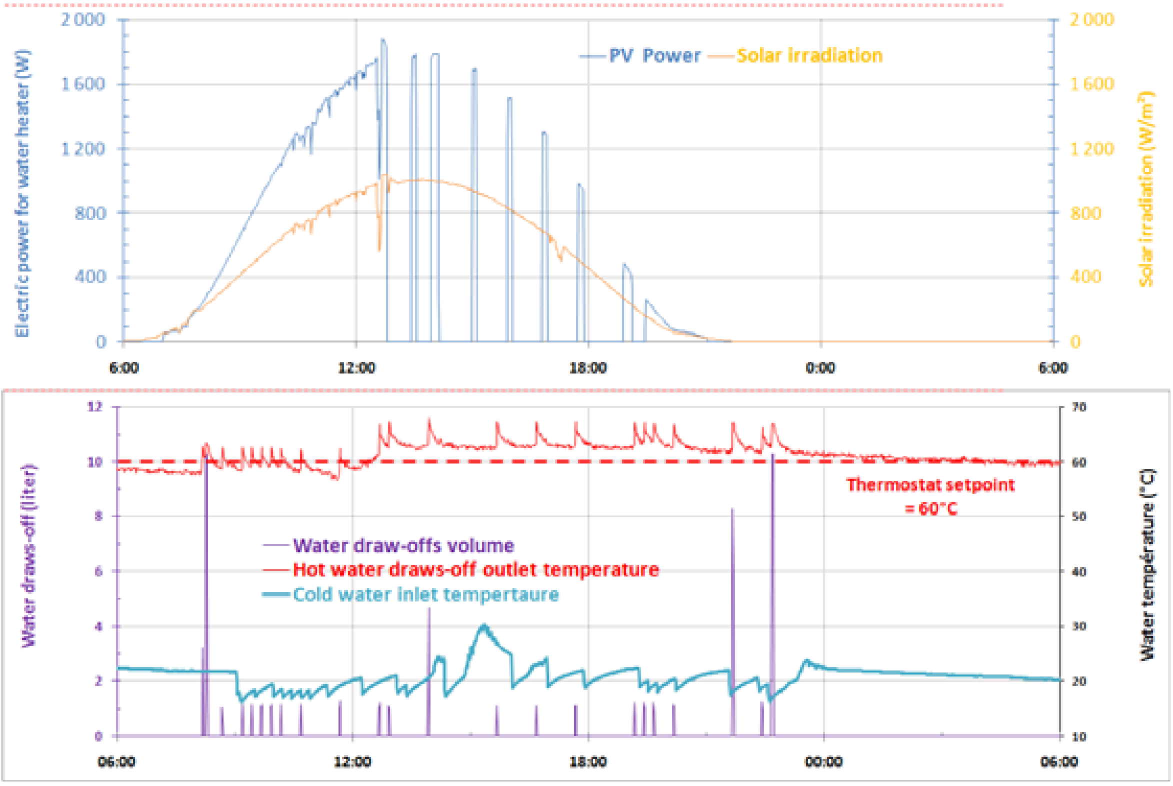

Figure 4 : PVDHWS electric power, water withdrawal and tank temperature

In the morning the PV electricity production increases proportionally with the solar radiation and heats the DHW water tank. When the water thermostat reaches the set point of 60°C, the electrical PV production is disconnected. It results in Solar Losses due to this disconnection (see definition below)).

$$\textbf{\textit{Solar Losses}}\ (\%) = \mathbf{1} - (\ \textbf{\textit{PV energy really injected in the DHW tank}}\ [\textbf{\textit{MJ}}] / \textbf{\textit{PV energy that could be potentially produced}}\ [\textbf{\textit{MJ}}])$$

When water withdrawal occurs, cold water fills the missing volume. The water's temperature decreases in the tank and an extra electrical heater can be needed.

In order to evaluate the performance of a solar hot water system, the estimation of the solar fraction can be a useful indicator. The Solar Fraction is defined as the ratio of solar energy that covers the water heater's needs in order to heat the water up to 60°C.

$$\textbf{\textit{Solar Fraction}}\ (\%) = \textbf{\textit{Solar energy produced by the PV panels}}[\textbf{\textit{MJ}}]\ /\ (\textbf{\textit{Water heater energy}}[\textbf{\textit{MJ}}] + \textbf{\textit{Thermal losses of the tank}}[\textbf{\textit{MJ}}])$$

For example, in Fig. 5, the daily solar fractions during the test period along with the corresponding solar irradiation are presented. The spring test period (from April to June) was rather sunny and the mean Solar

Fraction over this duration was about 81% with a maximal ratio of 86%.

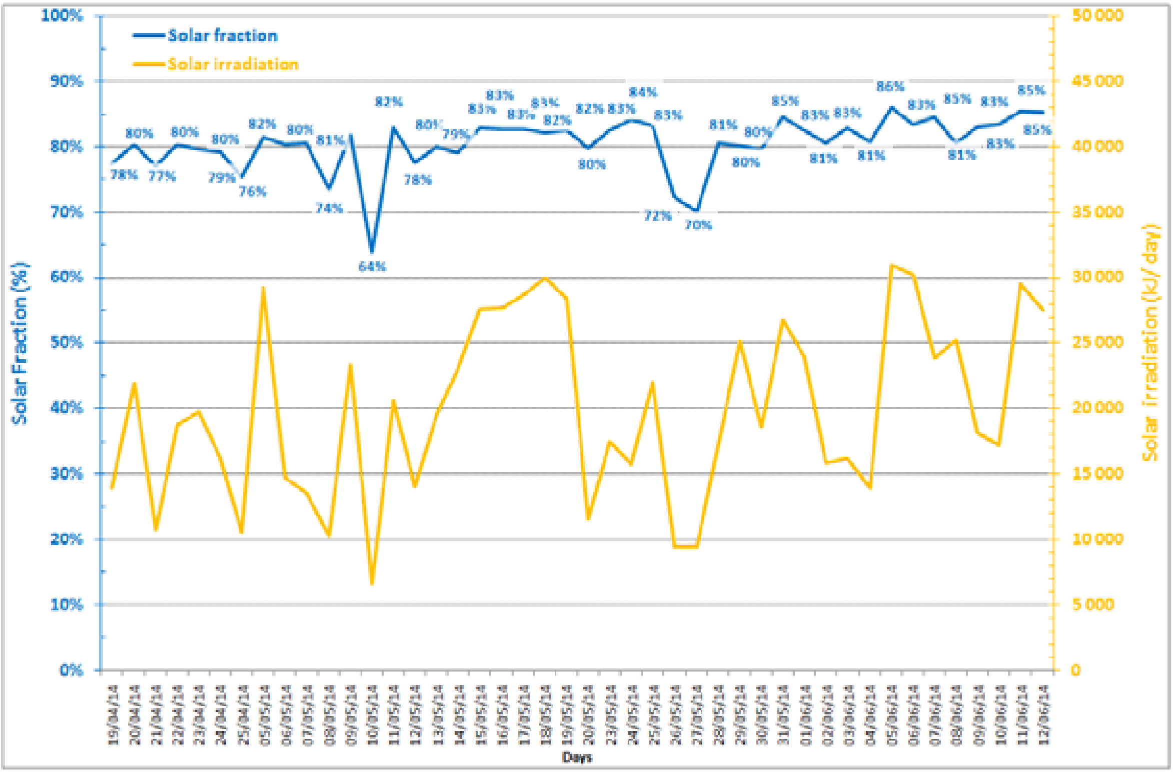

Figure 5: Solar fraction measured from April to June 2014

In order to predict the performances of PV DHWS more accurately, as well as the share of the PV production that is unused, and more specifically in order to evaluate the yield of the system and to compare it with solar thermal domestic hot water systems, a numerical model was required. This model was developed under *Modelica*/ *Dymola* and is presented in the following part.

3. Modeling and simulation

3.1. Development of a numerical model

Dymola is a commercial modeling and simulation environment developed by *Dassault Systems* and specialized in the resolution of dynamic and complex multi-physics systems for use within various applications such as automotive or robotics. As this environment uses the open *Modelica*® modeling language, besides standard libraries (e.g. *Modelica*), users are able to create their own model libraries for their specific simulation needs. In that way, *EnerBAT*, a department of *EDFLab* (*R&D*), has developed its own library - *BuildSysPro*[1] - dedicated to dynamic simulation for buildings and related energy systems. This library was used for this study. The matrix system obtained was solved using the *CVODE-variable orde*r solver with a variable time step.

Parallel to the experiments, a numerical model of PV DHWS developed under *Modelica / Dymola* was validated using monitored data from the test described in the previous part, and was then used to extrapolate the behavior of this system according to various parameters (weather data, regulation, installed PV power, hot water consumption …).

Figure 6 describes the principle of PV-DHWS modeling under *Modelica / Dymola*. It consists in an assembly of elementary models of PV panels and a Domestic Hot Water Tank connected to boundary conditions: meteorology, indoor temperature, cold water temperature… As results, any calculated parameters of the elementary models are reachable at any time of the numerical simulation - mainly temperatures and energy

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[1] *Plessis, G., Kaemmerlen, Lindsay, A., BuildSysPro: a Modelica library for modelling buildings and energy systems. Proceedings of the International Modelica Conference 2014.*

balance (power, production, consumption).

Specifically, modeling allows the extrapolation of the calculation to other meteorology data (other locations and time periods) in order to obtain a yearly yield assessment and to compare the system's performances with those of a solar thermal domestic hot water system.

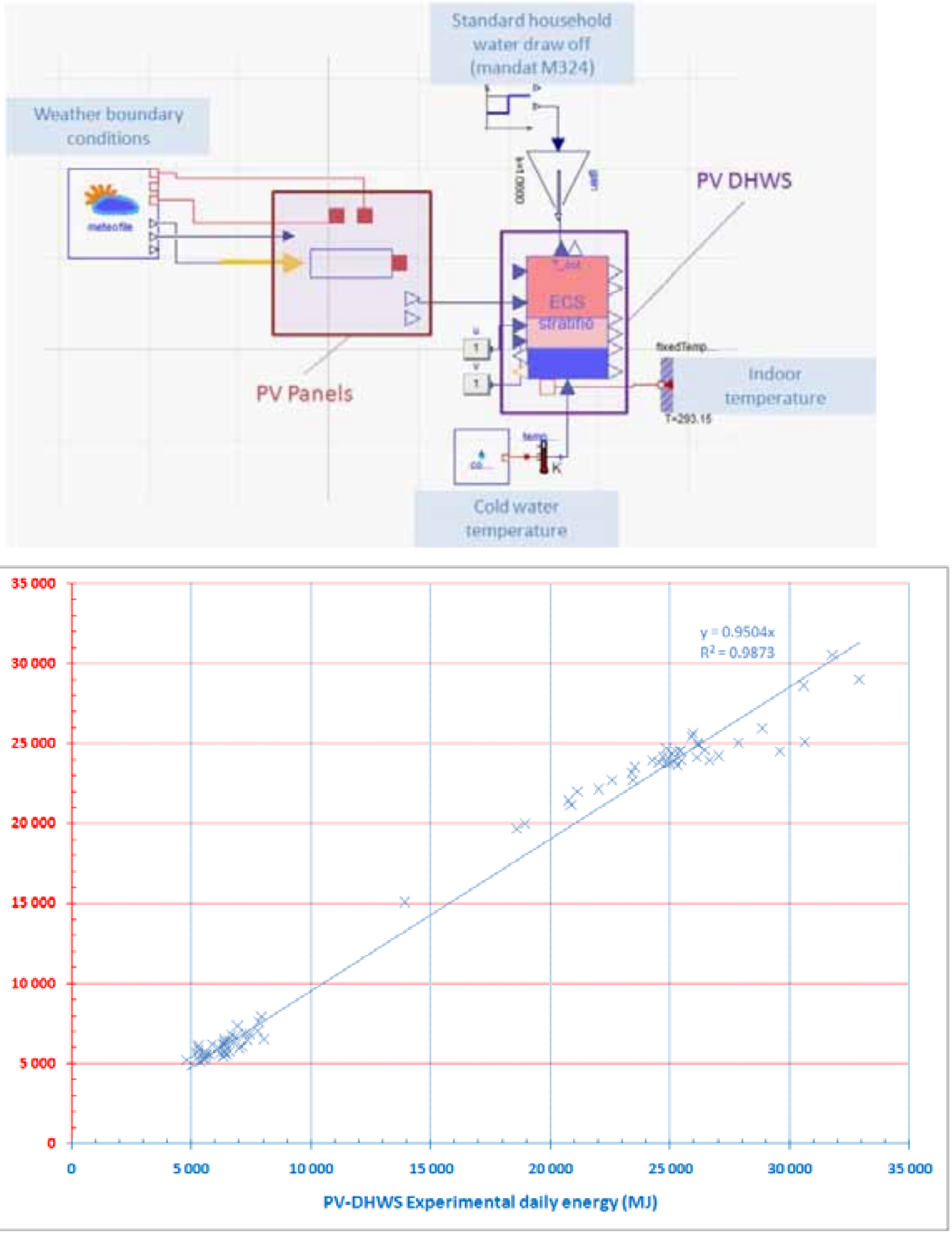

Figure 6: PV-DHWS modeling under *Modelica* / *Dymola*. Model description (top) and experimental validation (bottom)

The PV-DHWS model was validated using experimental data. The measured daily electrical energies for heating the hot water in the tank were compared to the numerical energies calculated with the boundary conditions (weather, cold water temperature, hot water usage profile). The model is calibrated by adjusting the most uncertain measured parameters, such as temperatures in the tank, in order to fit with the daily energy balance (PV-DHWS electric water heater). Figure 6 shows that the validation of the modeling can be considered as relevant.

3.2. Yield simulations

Based on the numerical model, the annual performance of the prototype installed at our test facility was simulated using measured weather data. For the current system, results of the simulation show that the solar fraction of such a system could reach 69% for a corresponding solar loss ratio of 34% (see distribution along the year in Fig. 7).

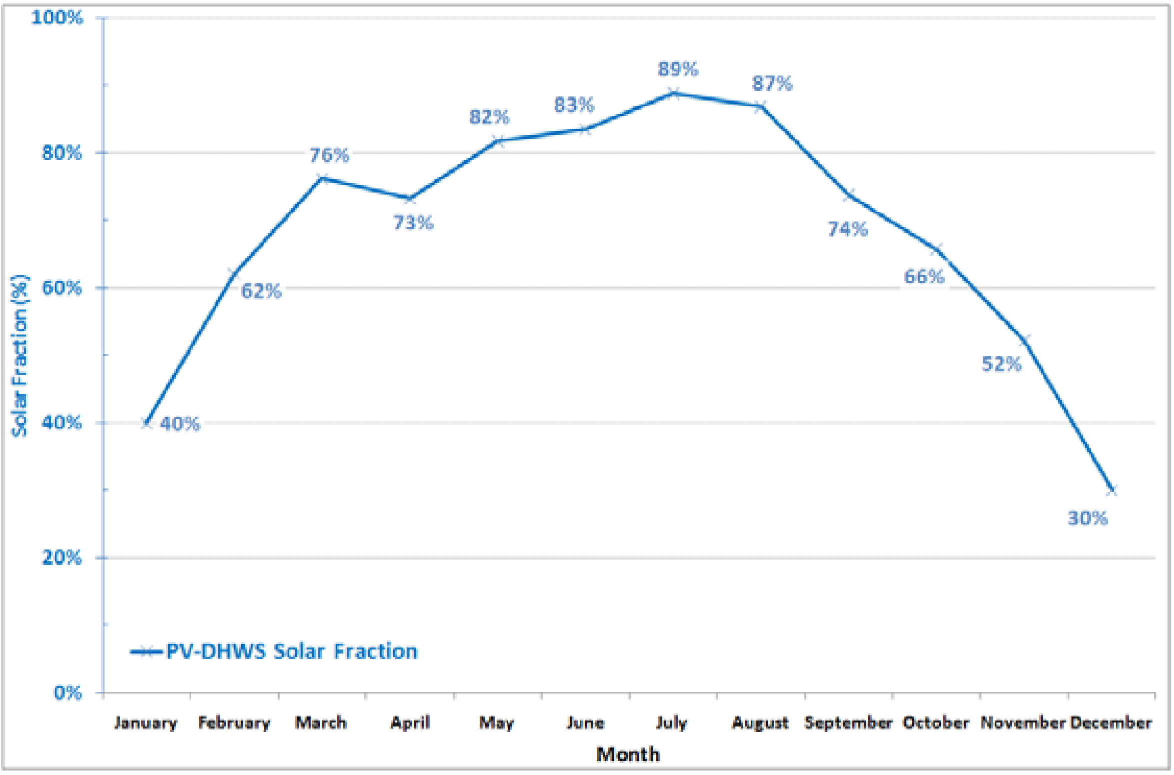

Figure 7: Solar fraction over a year – ***EDFLAB Les Renardières***

Then, a conventional Solar Thermal Hot Water System (ST-DHWS) was simulated using the same weather data. For the ST-DHWS, the collector (glazed and selective coated) surface was 4m², the water tank had a volume of 300l and the water consumption was the water withdrawal schedule M324 at 60°C. The simulation was performed using an existing *EDF Dymola* model (from the *BuildSysPro EDFLab* Library). For the design mentioned above, the results of the simulations show that the solar fraction of the ST-DHWS was about 63%. To simplify the comparison between PV- and ST-DHWS, a parametric analysis was done on PV-DHWS design to determine the required amount of PV panels able to reach an equivalent solar fraction of 63%.

In Figure 8, both the annual solar fraction and the PV loss ratio of PV-DHWS are plotted as a function of installed PV power. The result indicates that to obtain the same solar fraction, the size of an equivalent PV-DHWS must be of 1650 watt peak i.e. approximately 12m² of c-Si PV panels. For this system design, the PV losses are estimated to be around 12%.

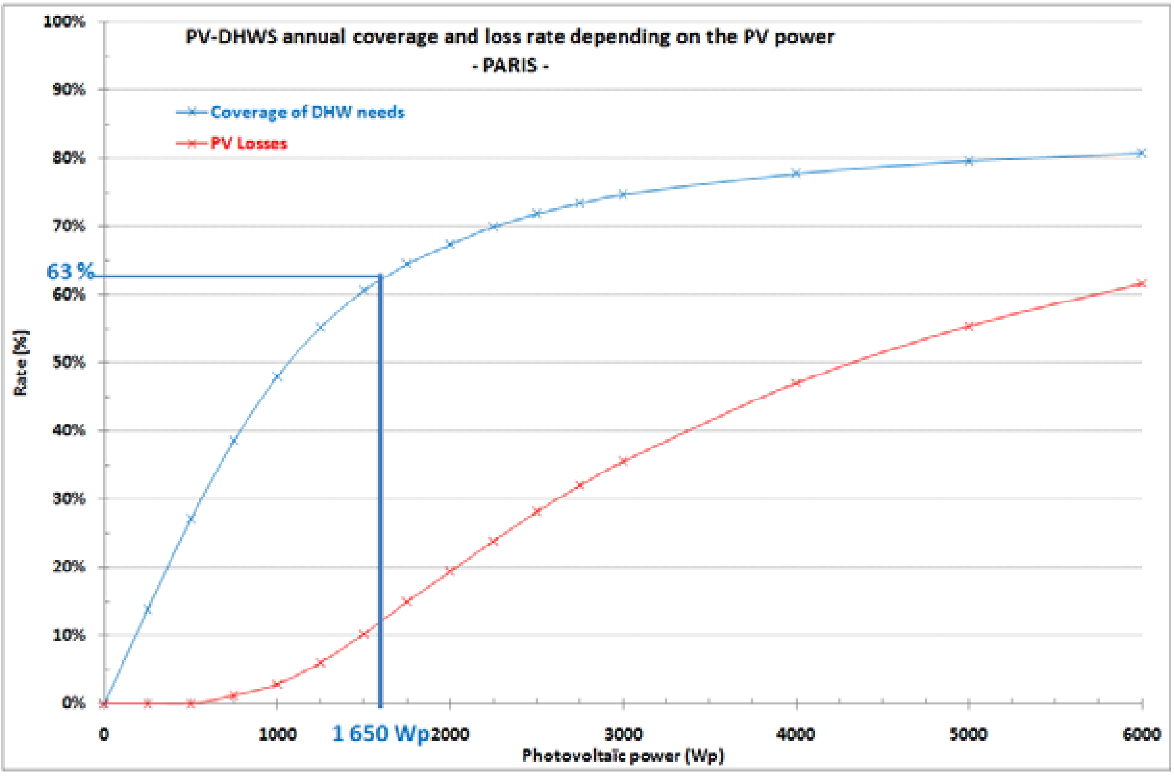

Figure 8 : Yield of a DHWS as a function of installed PV power

Finally, in Figure 9, the monthly distribution of the Solar Fraction for a Solar Thermal DHWS and a PV DHWS located in Paris and with the same annual fraction of 63% is presented. For equivalent performances, a PV DHWS requires a larger collecting surface (12 m² for PV, 4 m² for ST) but seems to have less seasonality in the performances:

- Winter: the PV efficiency increases while the temperature of the PV cells decreases with the outdoor temperature. The Solar Thermal losses increase while the outdoor temperature decreases.

- Summer: the PV efficiency decreases while the temperature of the PV cells increases with the outdoor temperature and the solar irradiation. The Solar Thermal efficiency increases while the solar irradiation and the outdoor temperature increases.

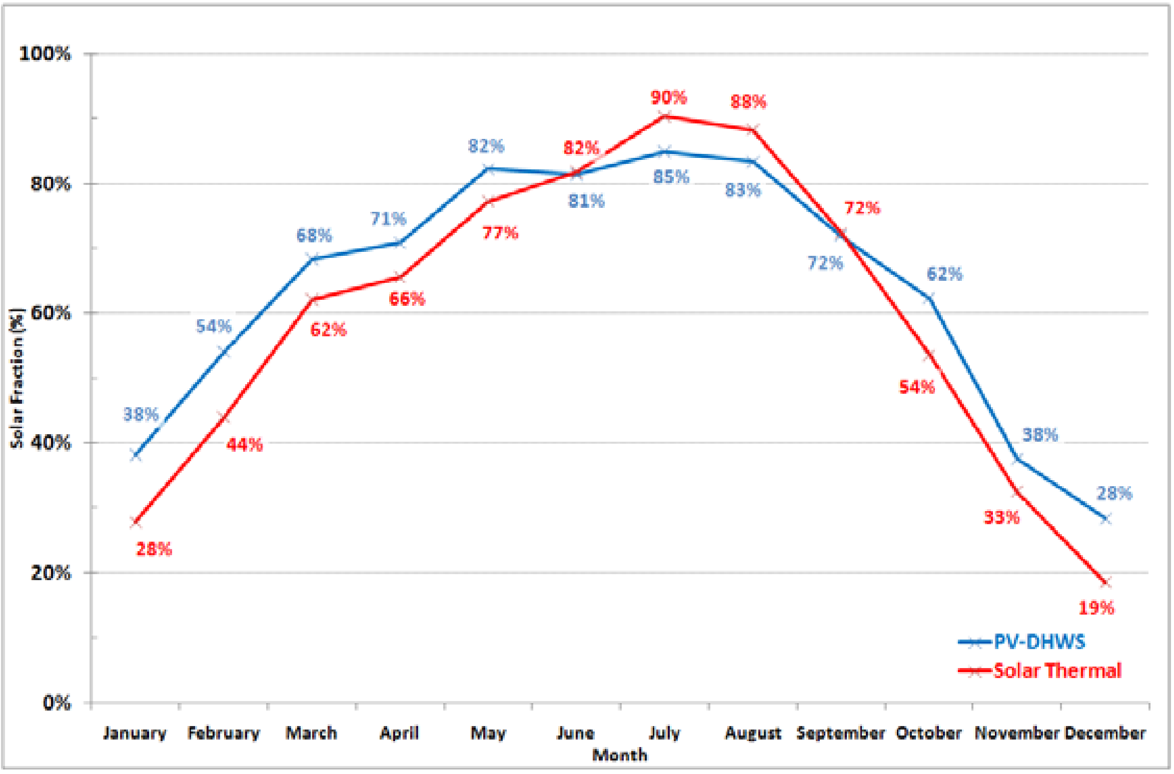

Figure 9 : Monthly distribution of solar fraction for ST-DHWS and PV-DHWS

Based on the numerical and experimental results presented in this part, a first economic assessment of PV-DHWS was done and is presented in next part.

4. Economical assessment of PV-DHWS

Based on internal sources, Figure 10 gives the distribution of the installation cost of a conventional PV system (< 3 kWp) in France:

- PV modules are around one third of the total investment costs,
- BOS & installation are around one third of the total investment costs,
- Soft costs & grid connection costs are around one third of the total investment costs.

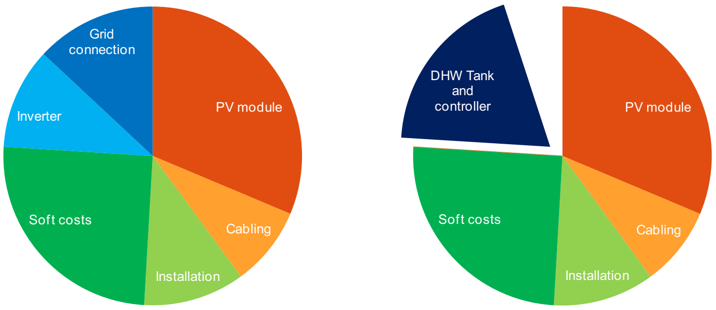

Figure 10 : Cost distribution of a conventional PV system of 3 kWc in France (left) and for a PV-DHWS (right)

For a PV-DHWS, no grid connection and no inverter are required, reducing the total investment cost by around 25%. However, additional costs for the hot water tank and its controller must be considered.

The total investment cost for a 1.65 kWp PV-DHWS is difficult to estimate because the system is still a prototype (i.e. not industrialized). Costs must be estimated more precisely according to variety of options: PV technology, module performances, installation mode, electronic components used... However, based on current market prices of PV, for an equivalent solar fraction, a PV-DHWS could be competitive compared to a conventional solar thermal hot water system.[1].

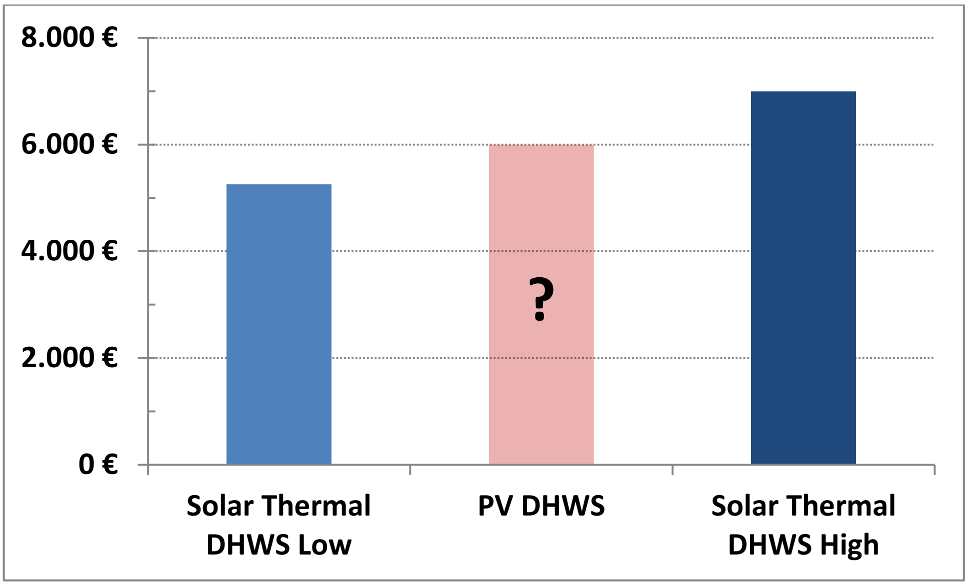

Figure 11 : Cost expectations between ST-DHWS and PV-DHWS

5. Conclusion

Based on simulations, performances of various hot water systems were estimated and the related costs (investment, operation, maintenance) were evaluated.

Numerical and experimental investigations regarding the coupling between PV systems and local thermal systems (DHWS) have shown:

- The technical feasibility of the concept is proven
- High solar fraction can be reached but a part of the PV production is not usable. There is a compromise to find between the thermal performances and the part of the PV production that is not used (overheating strategy to be improved).

The comparison between PV - DHWS and a conventional solar thermal DHWS emphasizes that :

- Equivalent performances require a larger collecting surface (12 m² for PV, 4 m² for Solar Thermal)
- Less seasonality in the performances
- Probably less maintenance

This new concept could be economically competitive compared to a conventional Solar Thermal DHWS.

From a thermodynamic point of view, solar thermal makes more sense for DHWS, but the lower prices of PV could encourage the development of less efficient but possibly cheaper solutions based on photovoltaic technology.

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[1] Solar Thermal DHWS prices are based on *Strategic Research Priorities for Solar Thermal Technology - European Technology Platform on Renewable Heating and Cooling*