Parametric Study and Long-term Prediction of the Production of a Solar Water Heaters Installation

Julien Gambade[1*], *Hervé* Noël[1], *Patrick* Glouannec[1] and *Anthony* Magueresse[1]

[1] Univ. Bretagne Sud, UMR CNRS 6027, IRDL, F-56100 Lorient, France France

Abstract. In order to increase the contribution of solar thermal energy in moderately exposed locations, it is necessary to study solar installations and optimise their design. A parametric analysis was carried out on a solar installation in a European climate, consisting of 16 water-in-glass evacuated tube collectors connected to their storage unit. The purpose of the installation is to prepare large quantities of hot water at 85°C twice a day to prepare feed for a calf rearing farm. The arrangement of half of the collectors in series and half in parallel makes this solar installation suitable for this application. The orientation and the inclination were studied for four different European cities to determine their effects on the energy supplied. The results show that location and orientation have a great impact, especially in the cities with higher solar irradiance. Having solar water heaters facing south with a 45° tilt angle allow the solar installation to maximise its production for three locations. Studying the ratio of the energy supply to the energy demand is an interesting way to show the performance of the solar installation. The developed dynamic numerical model will help design the solar energy production in challenging weather conditions where the reduction of fossil energy consumption can be optimised.

1. Introduction

Reducing fossil fuel consumption became a global priority. The agricultural sector is one area where renewable energy can be a viable alternative, particularly in the production of hot water [1]. Among the many applications, calf rearing farms have a significant daily demand for hot water. In order to prepare the feed for the calves, the livestock farms need water at the required temperature of 85°C.

Solar collectors can provide, or at least, contribute to this level of temperature. However, the type of collectors and their arrangement must be properly chosen. Solar collectors have to contribute as much as possible to the large amount of hot water required twice a day. This study focuses on the contribution of a solar installation composed of "Water-in-glass" evacuated tubes collectors. They consist of several single-ended evacuated tubes directly connected to a horizontal cylindrical storage tank. Each evacuated tube consists of two concentric glass vacuum tubes joined at one end to form an annular vacuum area. In addition, the outer glass surface of the inner glass tube is coated with a selective surface absorber. The inner tube absorbs most of the sunlight transmitted through the outer tube, heating the water in the evacuated tube. Due to the density effect of the water temperature difference, the hot water rises to the top of the storage tank and the cold water descends to the bottom of the tank. Experimental investigations have been carried out on the solar water heaters for domestic applications [2] and for a similar solar installation [3]. Sokhansefat et al. conducted a thermoeconomic analysis between an evacuated tubes and a flat-plate collector in cold climatic conditions [4]. Results showed the first system has better results and is less affected by the weather.

In the present work, the solar installation model and its experimental validation using in-situ measurements are presented. A parametric study is carried out to determine the thermal performance of the specific arrangement with four different locations. The impact of the orientation is also considered as well as the tilt angle whose effect has been investigated for individual solar water heater for domestic application [5].

2. Material and methods

2.1. Solar installation

The solar installation modelled is located in France (latitude 48.2 and longitude 0.50). To provide hot water at the required temperature of 85°C for a veal calf farm, 16 "Water-in-glass" evacuated tubes collectors are divided into two arrays. The first row consists of solar water heaters in series, while in the second row they are arranged in parallel. The collectors in series are always full and pre-heat the cold water while the tanks of the collectors in parallel are used to store energy and are partially emptied at each withdrawal.

* Corresponding author: julien.gambade@univ-ubs.fr

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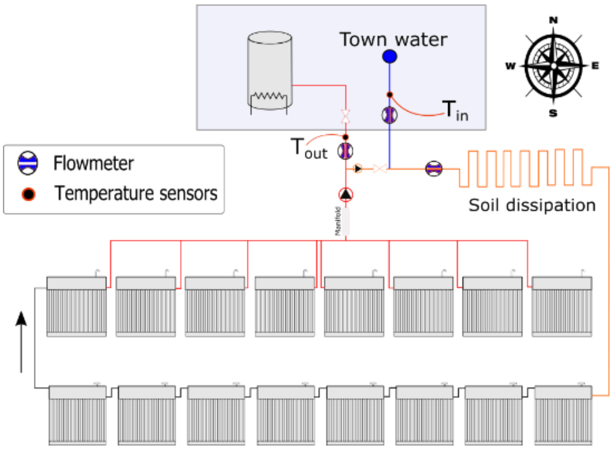


Fig. 1. Solar installation instrumentation

A ground dissipation system was set up in order to improve the energetic performance of the installation and to limit the risk of material degradation due to high level of temperature. It consists of a circuit of serpentine pipes buried in sand. Circulation through this dissipation device is triggered in the event of overheating in the parallel solar water heaters. This system aims to extend the life of the installation and to store the "excess energy" in the soil. The inlet water is introduced during the filling phases circulates in the coil and is thus heated thanks to the accumulated energy.

The contribution of the solar system to the daily requirement is estimated with the flow meter located at the outlet and the temperature sensors. The calculation of the daily energy supplied by the solar collectors Q_{sup} is estimated as:

$$Q_{sup} = \int_0^{24h} \dot{m}_{out}.c_p.(T_{out} - T_{in})dt \qquad (1)$$

Meanwhile the daily energy required Q_{req} is calculated according to the equation (2):

$$Q_{req} = \int_0^{24h} \dot{m}_{out}.c_p.(85 - T_{in})dt \qquad (2)$$

The share of energy consumed by the farm that is produced by the solar installation, also known as the *Coverage ratio*, is obtained by dividing Q_{sup} by Q_{req}.

2.2. Numerical model

The individual solar collector model is based on previous work by Budihardjo et al [6]. The model parameters were adapted to correspond to the collectors studied. The 16 solar collectors and the hydraulic connection are modelled to correspond to the reference solar installation (
Fig. 2). The radiation processor calculates the positon of the sun and the tilted irradiation received on collectors' plane. The heat dissipation in the ground is modelled by the type 997 "Horizontal Ground Heat Exchanger" from the TESS library [7]. The thermal conductivities of the pipe materials and the soil must be specified. The soil temperature is calculated as a function of depth and season using the Kusuda correlation [8]. The model takes into account the length and the shape of the buried circuit, and calculates the exchange coefficients between the fluid and the soil.

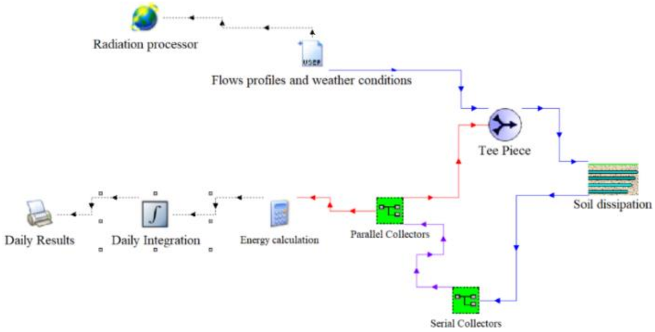


Fig. 2. TRNSYS schematic of the simulated solar installation

The solar installation model was validated using in-situ measurement during 11 days in September (Fig. 3). The energy supplied Q_{sup} was estimated with a relative error of 0.9% and a daily error averaged at 4.0%.

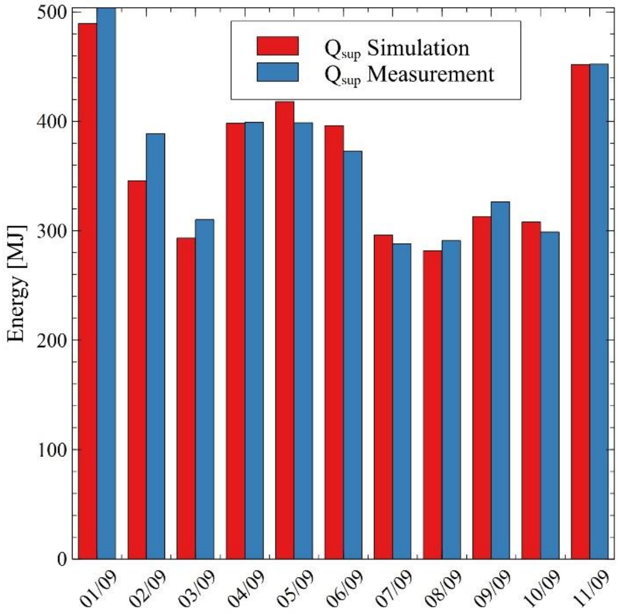


Fig. 3. Numerical model validation

The simulation took place from the 29th of June until the 21st of December 2022. It therefore represents summer and early winter meteorological conditions that occurred during the 2022 breeding cycle. The daily volumes of hot water consumed are plotted in Fig. 4:

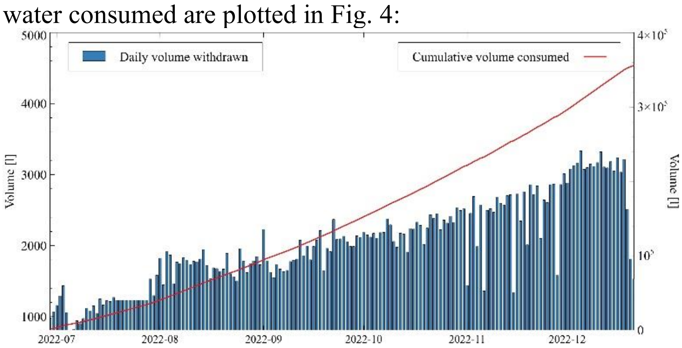


Fig. 4. Amount of hot water required by the veal calf farm

The flow rate used for the simulations is the one measured on the reference solar installation. The daily volume increases during the period due to the larger amount of meal required to feed the calves.

2.3. Parametric study

This study has been carried out with different locations, orientations and tilt angles. Four European cities are considered: Saint-Georges-du-Rosay (the reference solar installation), Herselt in Belgium and Sligo in Ireland and Marseille. The first three sites were chosen to represent the North-West European climate within the scope of the project, and Marseille and its Mediterranean climate as a comparison.

The temperatures and the global horizontal irradiance associated to the four different weather conditions are obtained using the Solcast API [9] every 5 minutes to match the simulation time step. Representative values are presented in Fig. 5:

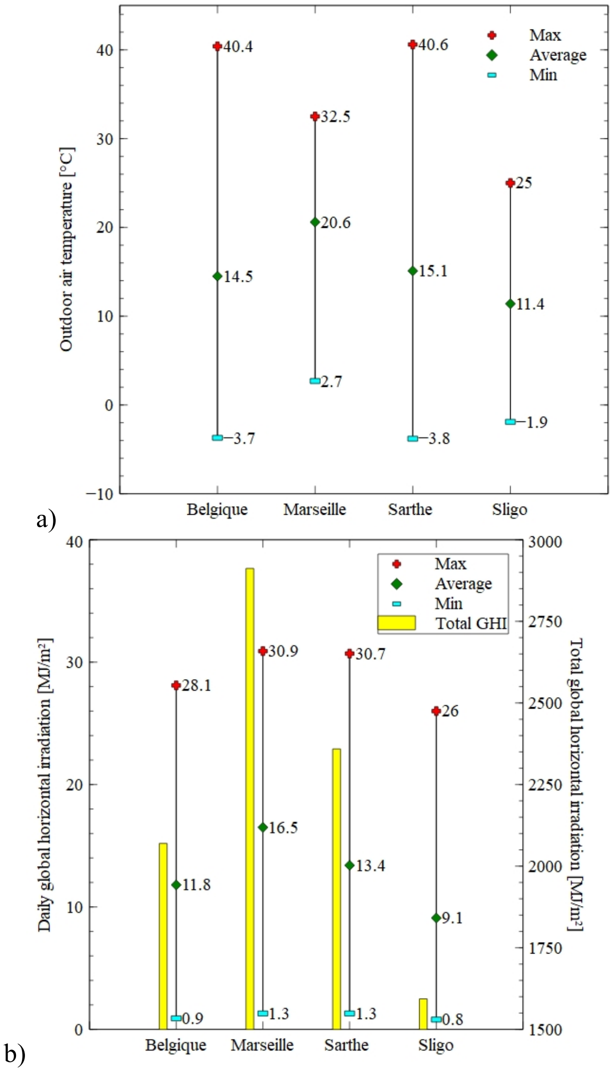


Fig. 5. Weather conditions: a) Ambient temperature and b) Global horizontal Irradiance.

The four different locations are representative of the European climate however, although Marseille can be classified as having a Mediterranean climate. The average outdoor air temperature and the daily global irradiation are higher than in other cities and the total amount of radiation received is more significant. The three other north-western European cities have less favourable weather conditions. Sligo in Ireland has the least solar radiation and the lowest average ambient temperature.

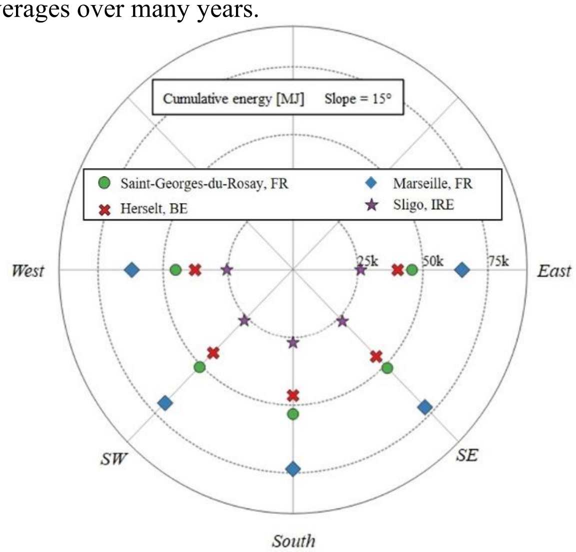
3. Results and discussion

3.1. Cumulative energy supplied

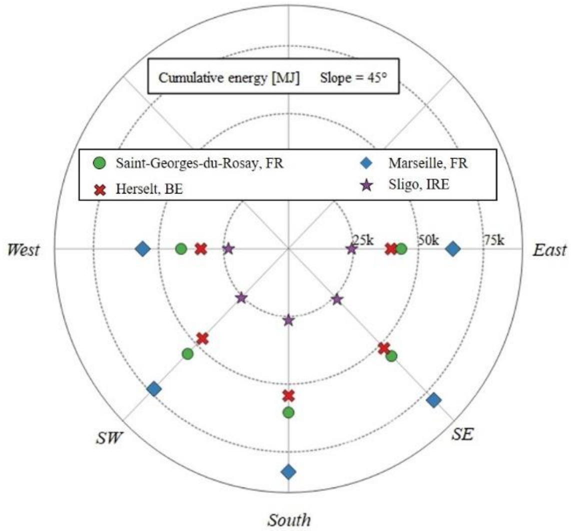
The total energies delivered by the solar installation are shown in Fig. 6. As expected, the contribution of the solar installation differs according to the locations. In the most insolated cities, the solar installation can produce hotter water.

Due to the low cumulative energy, there is no significant effect of orientation in Sligo unlike in Marseille where the east orientation has a decrease of 14%,34% and 37% compared to the optimal south orientation at an inclination of 15°,45° and 75° respectively.

Unsurprisingly, south-facing collectors allow solar systems to deliver the most energy. In addition, simulations in French and Belgian cities with a 45° inclination show the highest cumulative energy. However, the maximum energy delivered in Sligo is obtained with a 15° inclination with a 2% difference with the simulation with a 45° tilt angle. The 15° angle is more suitable in summer when the sun is at his higher position in the sky. This result is questionable. It may be explained by the very low beam irradiance in Sligo over the period, especially in winter, so that diffuse irradiance is mostly available. It should be noted that the weather files are specific to this period and are not representative of averages over many years.



a)



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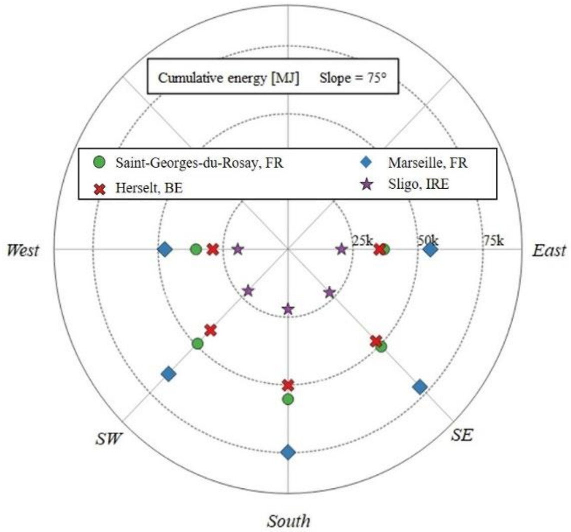
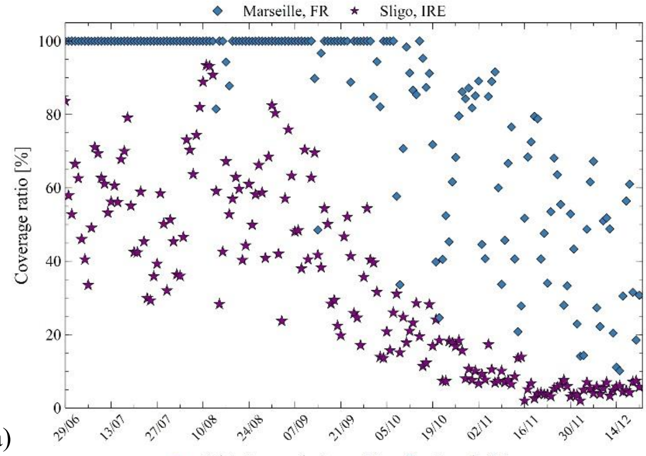


c)

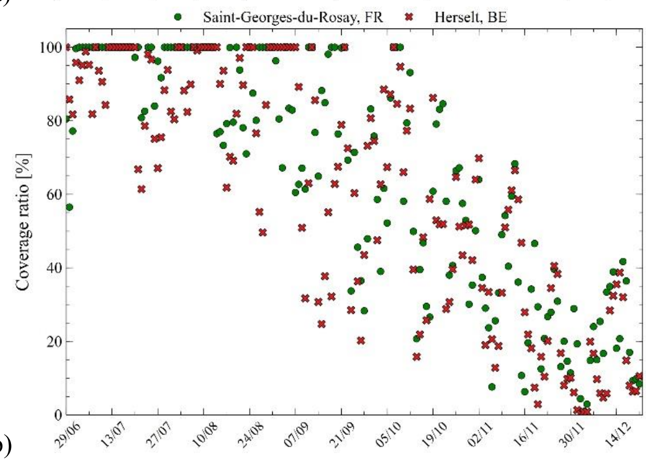
Fig. 6. Cumulative energies supplied with a tilt angle of a) 15° b) 45° and c) 75°

3.2. Coverage ratios

The best results from each site are selected in order to study the share of energy supplied to the energy required (Fig. 7). The simulation with the highest cumulative energy also results in the highest average coverage ratio for the four cities. The energy yield of the system decreases with the deterioration of the weather conditions, while the demand increases. With a value of 80.3%, the solar installation in Marseille has the highest average coverage while it equals to 33.6% in Sligo. The coverage ratios in the other two locations are close to 61.2% and 65.6% for the Belgian and the French cities respectively.



a)



b)

Fig. 7. Coverage ratios obtained with the optimal simulations in Marseille and Sligo (a) and Saint-Georges-du-Rosay and Herselt (b)

The effects of varying the orientation and tilt angle are presented on Table 1. Results show that the effects are lower on the coverage ratio. In summer, the solar installation in Saint-Georges-du-Rosay has a tendency to produce hot water at a higher temperature than required, so the energy supplied exceeds the energy required. Excess energy is reused thanks to the dissipation system and helps to preheat water the following days. Studying the coverage ratio allows to ensure that the solar installation is able to provide the daily energy required.

Table 1. Variation of the energy supplied and the coverage ratio (Saint-Georges-du-Rosay)

Orientation	Slope	Cumulative energy *(Relative change)*	Coverage ratio *(Relative change)*
South	45°	60425 MJ	65.6 %
West	45°	41312 MJ *(-32 %)*	50.4 % *(-23 %)*
East	45°	43350 MJ *(-28 %)*	51.6 % *(-21 %)*
South	15°	53255 MJ *(-12 %)*	59.9 % *(-9 %)*
South	75°	55240 MJ *(-9 %)*	61.3 % *(-7 %)*

4. Conclusion

A parametric study was carried out on a model of a solar installation consist-ing of an arrangement of water in glass" collectors. The aim was to evaluate its contribution to the intermittent production of hot water for a breeding facility. Sixteen "Water-in-glass" solar water heaters are arranged half in-series and half in parallel. A large volume of water at 85°C is required to prepare the calves' feed twice a day.

Three European climate countries are studied: two cities in France including the reference site, and two cities in Belgium and Ireland. For each location, 3 inclinations and 5 orientations are under investigation.

The results show the effect of the location on the hot water production. Over the selected period, which lasts for a whole breeding cycle, the solar installation in Marseille produces 25% more energy than those in France and Belgium and 68% more than in Ireland, thanks to its Mediterranean climate. The orientation has a large impact on the energy supplied, especially in cities with higher global solar irradiance. The optimal tilt angle is 45° for three of the cities, but not for Sligo, although the difference is very small. This may be due to the very poor conditions during the period, which led to the prevalence of diffuse radiation.

The share of energy supplied to the energy required is also studied. The simulations in Marseille show a high coverage ratio with a maximum of 80.3% with the solar water heaters facing south at an angle of 45°. The long-term simulations helped to determine the viability of those specific type of solar installation. Unfavourable Irish weather conditions do not allow a massive reduction of energy fuel consumption with the same solar water heaters configuration. Numerical model is a great tool to help design and optimise the solar energy production.

The developed dynamic numerical model is an excellent tool to help design and optimise the solar energy produced. Compared to a static model, it can take into account the variability of weather conditions and demand as well as the inertia of the installation, making it more reliable and accurate. It is also possible to evaluate the loss due to the constraints of the site, in particular an imposed orientation and the presence of surface shading. This study is based on a single set of weather data, which is not sufficient to draw a conclusion on the relevance of the solar installation.

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