Solar thermal systems for domestic water heating applications in residential buildings. Efficiency and economic viability analysis of monitored plants.

Master thesis in Renewable Energies and Energy Efficiency

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Abstract

Climate change and energy have become the trend of universal discussions in the recent years. It is true that the use of conventional fossil fuels negatively affects our planet, hence the whole renewable energy movements. However, at the current state, the world still cannot be entirely reliant on renewable energies for its needs. On the other hand, utilizing the maximum renewable energy opportunities would have a positive impact on climate change.

Many forms of renewable energy can be exploited, wind energy, tidal energy, sun energy and so on. The most common renewable energy is solar energy, it can be used for various ends (electricity generation by photovoltaic/thermal power plants, domestic water heating…).

Governments around the world encourage the use of solar domestic water heating, for it’s simple usage, low maintenance requirements and efficiency of the solar heating systems. The Spanish government approved a law in March of 2006, named “Código Técnico de la Edificación”. This regulation is mandatory, and set the minimum quality requirements that residential buildings must have. One of them forces that new and renovated buildings have to produce part the energy demand for heating water by means of a solar thermal system.

The aim of this work is to study a domestic solar water heating system in a residential building, to develop a numerical model based on the f-chart method by William Beckman and John Duffie, in order to predict thermal behavior of the solar system and compare the results with real data collected from the solar system using an energy counter called SunEye.

The solar system chosen for this study is located in Terrassa-Barcelona, it provides hot water for a residential building of 17 apartments. The solar system is composed of 8 solar collectors with 17 storage tanks (10 of 100L and 7 of 150). The Data collected from this solar system using SunEye will be downloaded from RDmes company cloud server named OMNILUS. An overview of the 12 monitor plants by this company from an energy, CO2 reduction and money saves point of view will be reviewed.
Chapter 1: Introduction

1-The Sun

The sun is the shining star of our solar system, it is the closest star to earth, it supports almost all life on earth by photosynthesis, and drives earth’s climate and weather [1]. It is a gaseous near perfect sphere, with a mass around \(2 \times 10^{30} \text{ kg}\), which is about 330 000 times that of the earth [2]. Nearly 73% of the sun’s mass consists of hydrogen, the rest is mostly helium with relatively small amounts of oxygen, carbon, neon and iron [3]. The sun is located around 150 Million km from the earth, its light takes around 8 minutes to arrive to us [4].

![Figure 1: Earth scaled to the sun](image1)

1.1-Earth movement around the sun

Earth’s orbit is the trajectory along which Earth travels around the Sun. The average distance between the Earth and the Sun is 149.60 million km [6]. One complete orbit takes 365.256 days (1 sidereal year), during which time Earth has traveled 940 million km [7].

The earth also spins around an axis called the celestial axis. This rotation takes place in one day (23 hours, 56 minutes and 4 seconds). The celestial axis and the ecliptic make an angle called declination, it is equal to 23°27’, the declination angle varies plus or minus this value [8].

![Figure 2: Earth's orbit around the sun](image2)
1.2-Solar resources

Solar energy is the ultimate natural energy, the surface temperature of the big fiery star is around 5500 °C. The sun gives the earth light and heat, its role in the solar system’s activities is so important that there would be no life without it. The exploitation of the sun of technical purposes only began in the 17th century. Lavoisier, one of the first people to use convergent lens to concentrate the sun’s light to melt iron sticks placed in the focal point of the lens. [10] Within one hour, the earth receives enough energy from the sun to meet the energy demand of the whole planet for over a year, in other words, this amount of energy is 5000 times more than conventional energy provided on earth [11].

The total amount of energy received at ground level from the Sun at the zenith depends on the distance to the Sun and thus on the time of year. If the extraterrestrial solar radiation is 1367 watts per square meter, then the direct sunlight at Earth's surface when the Sun is at the zenith is about 1050 W/m², but the total amount (direct and indirect from the atmosphere) hitting the ground is around 1120 W/m². [13]

The energy coming from the sun gets altered at entry through the atmosphere, only a portion of the total energy coming from the sun (1367 W/m²) arrives to the surface of the earth. Hence, one defines the light as follows:

- **Direct radiation**: Direct radiation is received from sun rays travelling in a straight line from sun to the earth. Direction radiation is also termed as beam radiation or direct beam radiation. As direct radiation is sun rays travelling in a straight line, shadows of the objects which come in the way of sun rays are formed. Shadows indicate the presence of direct radiation.
-**Diffuse radiation:** Diffuse radiation does not have any fixed direction. When sun rays are scattered by particles present in the atmosphere, these scattered sun rays account for the diffuse radiation. Shadows of the objects will not form if only diffuse and no direct radiation is present.

-**Reflected radiation:** Reflected radiation is the component of radiation which is reflected from surfaces other than air particles. Radiation reflected from hills, trees, houses, water bodies accounts for reflected radiation. Reflected radiation generally accounts for a small percent in the global radiation but can contribute as much as 15% in snowy regions.

-**Global radiation:** Global radiation is the sum of direct, diffuse and reflected radiation

![Solar radiation types](image)

*Figure 4: Solar radiation types [14]*

The distribution of solar energy in the bands of the thermal radiation spectrum is summarized in the following table:

<table>
<thead>
<tr>
<th>Attribution</th>
<th>Ultra Violet</th>
<th>Visible Light</th>
<th>Infra Red</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>0-400</td>
<td>400-700</td>
<td>700 +</td>
</tr>
<tr>
<td>Percentage (%)</td>
<td>3-5</td>
<td>42-43</td>
<td>52-55</td>
</tr>
</tbody>
</table>

*Table 1: Sunlight distribution at the surface of the earth [15]*

![Wavelength spectrum](image)

*Figure 5: Wavelength spectrum [16]*
1.3- Solar energy uses

Nowadays, the most important uses of solar energy are for industry and residential buildings, for producing electricity through solar thermal power plants or photovoltaic installations, or for domestic water heating and electricity production through domestic photovoltaic modules. However, solar energy can be used for other means: Solar powered ventilation, heating swimming pools, water pumping, power charge electronic devices and cooking.

2- Heat exchange phenomena

Heat is defined in physics as the transfer of thermal energy across a well-defined boundary around a thermodynamic system. The thermodynamic free energy is the amount of work that a thermodynamic system can perform. Enthalpy is a thermodynamic potential, designated by the letter "H", that is the sum of the internal energy of the system (U) plus the product of pressure (P) and volume (V). Joule is a unit to quantify energy, work, or the amount of heat. Heat transfer is classified into various mechanisms, such as thermal conduction (transfer of energy between objects that are in physical contact), thermal convection (transfer of energy between an object and its environment due to fluid motion), thermal radiation (transfer of energy by the emission of electromagnetic waves), and transfer of energy by phase changes [17].

3- Solar Water heating

Solar water heating (SWH) is the conversion of sunlight into heat for water heating using a solar thermal collector [18]. This conversion of light uses the previously explained energy transfer mechanisms (Radiation, conduction, convection).

- Main Components of solar water heating systems

**Collector:** Solar thermal collectors capture and retain heat from the sun and use it to heat a liquid.

**Pump:** It forces the water to circulate through the system.

**Tank:** It stores the hot water coming from the solar collectors, normally the tanks are equipped with insulation to reduce heat loss.

**Controller:** Senses temperature differences between water leaving the solar collector and the water in the storage tank near the heat exchanger. The controller starts the pump when the water in the collector is sufficiently about 8–10 °C warmer than the water in the tank, and stops it
when the temperature difference reaches 3–5 °C. This ensures that stored water always gains heat when the pump operates and prevents the pump from excessive cycling on and off [19].

Figure 6: Solar water heating system components [20]
Chapter 2: Literature review

1- Introduction

These last years the world has been noticing more and more the harmful effect of the use of conventional energy sources, and with the exponential growth of population, energy demand is going at the same pace, hence leaving a more serious footprint on the environment. With recent development of new technologies and the trend of the use of environment friendly energy sources, renewable energies in others words, the development of renewable energies became a priority, whether it is for industrial purposes, domestic uses or scientific research.

Domestic Water Heating is one of the fields that is most known for its use of renewable energies, especially Solar Water Heating for residential sector. With the abundance of solar energy, this domain is very promising. However, if many technologies were developed and studied, only a few were feasible, beneficial and became available for public use. While it looks very promising and fruitful, there is still many aspects of this domain to be enhanced and optimized, whether it is for type of technology, energy storage-wise, cost-benefit optimization, or environment footprint dilemma.

2- Solar water heating systems

Solar heating systems are a set of assembled components and subsystems, with the main purpose of harnessing and converting solar energy to heat water for domestic use.

Figure 7: Convetional solar water heating system [31]
Domestic solar water heating systems can be divided into two categories [21].

**2.1-Passive DSWH systems**

This type of solar systems uses heat driven convection as a principle to circulate the water or the heat transfer fluid. The water works in an open loop, where it circulates from the storage into the solar collector with thermosyphonic effect.

**2.2-Active DSWH systems**

This type of solar systems uses pumps to circulate the working fluid. Two different systems can be found in this category, the first is direct circulation, where the water is the fluid that circulates from the storage thank and through the solar collector and back to the storage or to usage, whereas indirect circulation uses a heat transfer fluid that circulates in a closed loop between a heat exchanger and the solar collector, the heat transfer fluid gives away the energy to the water via a heat exchanger.

However, domestic water heating systems can be categorized into seven categories [21]:

**Category 1:** Solar heating only (no other form of energy is used), Solar preheating only (preheated water will be afterwards used in another heating system), Solar plus auxiliary system (Solar and auxiliary system are used in an integrated way to heat water).

**Category 2:** Direct (the used water circulates through the collector and gains the energy directly from the collector), indirect (the water gains its energy from the heat transfer fluid that circulates in a closed loop between a heat exchanger and the solar collector).

**Category 3:** Open (the heat transfer fluid is in full contact with the atmosphere), Vented (the contact between the heat transfer fluid and the atmosphere is restricted to the free surface of a feed and expansion tank or to an open vent pipe only), closed (heat transfer fluid is sealed from the atmosphere).

**Category 4:** Filled (heat transfer fluid fills the collector all time), drainback (heat transfer fluid is drawn from the collector to a storage unit to be used elsewhere), draindown (heat transfer fluid can be used and discharges after use).

**Category 5:** Thermosyphonic (heat transfer fluid circulates using density change driven convection), forced circulation (heat transfer fluid is forced to circulate by a pump or another mechanical means).

**Category 6:** Circulating (heat transfer fluid circulates between a heat exchanger or a storage
unit before usage), series-connected (heat transfer fluid circulates directly from supply point to point of use).

**Category 7:** Remote storage (Storage unit and collector are separated by a certain distance), closed-coupled collector storage (The collector and the storage unit are mounted on the same support), integral collector storage (the collector and the storage are in the same device).

### 3- Design of solar water heating system components

During recent years, many researchers concentrated their efforts to optimize the design of the components of solar systems in order to increase the efficiency of solar systems to ensure their market share.

#### 3.1- Solar collectors

A solar collector is the devise responsible of collecting solar radiation and converting it to heat, which is transferred to a heat transfer fluid. Two types of solar collector are widely used around the world:

- **Flat plate collector (FPC):** This type of collector is used to collect solar radiation in low ambient temperatures. It consists of a selectively coated flat plate absorber, a transparent cover to protect the absorber and to reduce heat loss at the top of the collector, a heat fluid to harness the energy from the absorber, tubes for the HTF circulation, an insulation system to reduce heat loss, protective casing to protect the components from surrounding harmful elements. Different designs and types of FPC are discussed in the paper by Shukla and al. [21] as well as recent development of FPC.

- **Evacuated tube (ETC):** This type of collector has a higher efficiency than FPC; this is due to less heat loss issues compared to FPC. However, it is not as competitive as FPC due to its high initial cost. It consists of evacuated tubes to minimize heat losses, copper heat pipes for a fast heat transfer, aluminum casing to support the other components and keep the integrity of the system. ETC systems have a number of important factors that make them more efficient and have less heat losses; one of them is the shape of the absorber tube which can absorb up to 16% more energy than FPC.
3.2- Storage tank

The storage tank is the component that stores hot water to provide it at the required temperature at the required time. It also plays an important role in imposing the performance of the system; they are generally composed of steel, plastic, concrete, fiber glass, or any other material used for water storage. Steel tanks are the most used due to the ease in installing them. Thermal losses are commonly known for the factor that dictates the efficiency of the storage tank. However, several studies found that stratification can solve this problem, transferring maximum energy from the top of tank where hot water inlet is situated, and cold water inlet can be in the bottom, as a result, water mixing is minimized, hence heat losses are also minimized, many types of storage tanks exist in the market (Horizontal, vertical, collector-integrated, remote…) [21].

3.3- Heat exchanger

Heat exchangers (HX) are generally used in systems with closed loops of working fluid. They are used to transfer the energy absorbed by the heat transfer fluid circulating between the collector and the heat exchanger to the water in the storage units. They are made from conductive and anti-corrosion material to ensure a good heat transfer and to preserve the HX. Many studies were performed on heat exchangers in order to increase the efficiency of all system; the shell-and-tube HX can reach 90% efficiency, other new designs such as double-tube and multi-tube HX show a very promising future [21].

3.4- Heat transfer fluid

The heat transfer fluid is responsible for the energy transfer between the collector and the water in the tank loop. The fluid absorbs heat from the absorber and transfers it via a heat exchanger to the water in the storage units. Several fluids are used as HTF in solar systems such as air, water, hydro-carbon oils, Glycol/water mixture among others. However, for the choice of the HTF, many parameters have to be taken into consideration (boiling point, freezing point, viscosity, thermal capacity…), but the commonly used are water and air, because they are non expensive and nature friendly, without mentioning the high thermal capacity of water and noncorrosive properties of air. Many studies were made to increase the efficiency of the HTF loop. Several designs were discussed such as refrigerant fluids with a heat pump, among other fluids such as R-11 refrigerant for thermosyphonic effect systems, CFC were commonly used for their inflammability and noncorrosive properties, however since CFC are very harmful to the environment and since the introduction of HCFC, CFC fluids were banned from use.
Recent studies have introduced CO2 as a promising HTF. It is inflammable, non-corrosive and non toxic. It can be used in systems with heat pumps. Such system would produce water at 90°C. A study showed that water at 55°C-75°C can be achieved with a heat pump of 4kW with CO2 as HTF. There are many developing opportunities in this field, and several options to be studied; but an economical study has to be made to validate the choice of certain HTF [21].

4- Modeling and simulation of solar water heating systems

For evaluation or design of solar systems, many parameters have to be studied and experimented. However, this is not always possible due to different weather types and the difficulty of data gathering and certainty. That’s why simulation presents various interesting options for design and simulation of physical behavior; there will be always errors and uncertainties, because solar energy systems are transient in nature. Therefore simulation and experimentation are complementary. However, modeling assumptions should be valid to avoid big uncertainties.

4.1- Assumptions and theory

Results of simulation largely depend on modeling assumptions and on degree of accuracy of mathematical model. Simulation makes carrying out series of experiments with iterative parametric configurations relatively easy. Hence, a number of assumptions had to be made as conditions to use a certain model.

To model the detailed transient thermal behavior of a ground buried hot water heat store, Raab et al. [22] divided a ground buried hot water tank into several, equal and mixed horizontal segments. They considered that the temperature in the tank is vertically stratified. In this case only a vertical one dimensional heat transfer is occurring. However, in the surrounding environment of the tank, Raab et al. took into consideration three dimensional heat transfer. Where the heat transfer coefficient between the stored fluid and the tank walls is considered infinite, and the heat transfer coefficient between the ground surface and surrounding environment is also considered infinite. Still, a number of free parameters had to be determined. The Gradient of thermal insolation thickness could not be modeled, hence a value of 50 cm of lateral thermal insulation is assumed. The volumetric heat capacity is assumed to have a fixed value, which is in good agreement with literature data for that specific geological location.

TRNSYS is transient system simulation software which provides good agreement within error ranging from 5% to 10% depending on the solar system and on the measured parameters. Shrivastava et al. [23] performed a critical review of this simulation software. In a TRNSYS
perspective, individual physical components are defined by algebraic and differential equations. These components are interconnected graphically in simulation user interface. Performance of transient system depends on large number of variables. In order to limit the effects of indefinite variables and simplify the modeling, the following assumptions are made:

- Temperature remains constant at any cross section and there is no significant variation in radial direction (vertical stratification).
- Conductive resistance of pipe is negligible in radial direction.
- The collector plate itself modeled to accumulated capacitance. It is assumed that fluid and base of tube remains at same temperature, and distribution of temperature in the direction of flow is linear.
- System is in equilibrium i.e. temperature of pipe and water at any cross section is almost equal.
- Mass flow rate is uniform throughout the system.
- Thermal properties of the materials used remains constant and do not vary with respect to temperature.
- Temperature gradient is established only in the direction of flow i.e. in longitudinal direction and it does not exist in transverse direction at any cross section.
- Thermal capacity of insulation is negligible.
- Heat transfer coefficients remain constant throughout the experimentation.

4.2- Merits

There are numerous advantages of using modeling and simulation, some of them are mentioned below [23]:

- Cost effective and consumes least time, instant results can be generated. Rare-to-rarest environment can be created for testing and rating.
- Expenses of constructing a prototype may be saved; it may also be termed as non-destructive testing.
- Complex and critical phenomenon can be analyzed easily.
- Capable to predict the performance in early stage of development.
- Resources may be deployed to more critical parameters, so that effective and optimum use may be ensured.
- Permits the comparison of measured and simulated values. Scaling is possible to suite the demand.
- Facilitates iteration through interpolation. Versatile report generation facility from economy to efficiency, marketing performance to subsidy proposal, life cycle to payback period and so on.
- Suggests optimum and alternate design to suite the requirement.
- Deficiencies and discrepancies in construction may be identified in early stage by preliminary and progressive simulations, so that capital investment on wrong installation may be avoided.
4.3- Limitations

Simulation has proved to be a powerful analysis tool. No doubt many options which cannot be determined by experimentation may be revealed by simulation. But there are limitations too which cannot be overruled. Some of them are mentioned below [23]:

- Initial capital investment is high for procurement of costly software.
- High level of knowledge base and skill is required. Most of the study is multidisciplinary in nature.
- Experts of own field but having little knowledge of computer programming face severe difficulty.
- The person having sound knowledge base and practical experience can only imagine the model and its behavior prior to prototyping.
- Complex and lengthy programming is required even for solving a simple problem.
- Limited flexibility in control and design optimization of system.
- The accuracy depends largely on the quality of user defined data.
- User defined constants remains constant for all simulation run, but in real world its value may get changed.
- Assumptions are mandatory while deriving expression for modeling, but it also deviates the results.
- Errors sometime may divert the whole study. Fixing and debugging sometimes are very cumbersome.
- It is very difficult to assume and account for all real world physical phenomenon in simulation e.g. scale formation, leakages, operating variables, human error, operator behavior, corrosion etc. but its repercussion cannot be neglected.
- External data is used extensively in simulation, but the limitations associated with the data cannot be neglected. For example, weather data is recorded at a particular geographical station, the data is not consistent and coherent for the experiments carried out at different location.

5- Solar water heating systems performance evaluation

Performance analysis is key for understanding whether the system is serving it’s purpose in a good way or not, whether the system is profitable or not. It allows specialist understand what technology works better, what heat transfer fluid is more efficient and to understand the limitations of the systems. Many studies were performed to evaluate different types of solar systems in different regions of the world to better understand the behavior of solar domestic water heating systems.

Ghorab et al. [24] performed a detailed analysis and performance evaluation of solar domestic hot water system, including DHW recirculation loop under Canadian Weather conditions for average family occupancy (2 kids and 2 adults), the system that was studied is illustrated by the scheme below:
Using a data logger, Ghorab et al. [24] collected data related to temperature, flow rate, and status of various devices in the solar system (thermocouples, flow meters, pulse meters…); The data was taken every 10s, and then stored in a memory for analysis. This collected and analyzed data is used to estimate the long term performance under real life circumstances of the system:

- Average solar tank temperature at different outside weather conditions
- Heat exchanger temperature profiles
- Solar tank and recirculation loop temperatures
- DHW temperature, nature gas consumption, and DHW load

Valladares et al. [25] developed a simple and inexpensive way to evaluate the thermal behavior of solar domestic water heaters. Several conditions were fixed:

- Total solar energy higher than 16 MJm\(^{-2}\)
- Average wind speed should be lower than 1.5 m/s without periods of more than 30 min with constant velocities higher than 3 m/s (out of this range, the collector’s performance is sensitive to air speed)
- Water inlet temperature in the system: 22 ± 2 °C
- Average ambient temperature between 20 °C and 28 °C with oscillations between day and night average temperatures lower than 15 °C

This method [25] presents an experimental way in assessing SDHW systems by comparing different solar systems in the same solar, ambient and initial conditions, by measuring and analyzing the volume of hot water, temperature of used water, water volume/collector area relationship, global thermal efficiency. This method also allows the assessment of heat loss in the collector heat fluid loop during night time.
Another approach was used by Mazarron et al. [26] to evaluate SDHW performance, they used an energetic approach. The aim was to quantify the useful energy of the solar system, the fundamental variables for the characterization of the system have been calculated, namely:

- Energy collected by the collector: The energy captured by the collector and delivered to the heat- transfer fluid was calculated from the difference in water temperature at the collector water entry and exit points.
- Energy delivered to the tank: The energy delivered to the tank is considered useful energy of the SWHs, as the complementary delivery system would harness this energy.
- Supply pipe losses in the primary circuit: These were determined as the difference between the energy captured by the collector and that delivered to the tank.
- System efficiency.

The calculated energy values were presented with respect to the collector area, the results of this study show that the useful energy delivered to the tank increases as solar radiation increases. The differences between the energy extracted from the Evacuated Tube Collector and the energy supplied to the tank are due to losses in the pipes, which increases as the required tank water temperature grows. The greater the solar irradiation, the greater the differences in energy supplied among the different required tank water temperature. As a results, energy efficiency of the solar system can be determined by the irradiation of the area, the required tank water temperature, and the demand curve (heat load) [26].

6- Solar water heating systems economic and environmental evaluation

When evaluating a solar system, besides its performance, it is imperative to study its economical profitability and its environmental impact. Often the decision is based on the economical evaluation result; however, since many subsidies and governmental financial supports are conditioned by environmental footprint, many studies were performed to evaluate economical profitability and environmental footprint of solar systems.

-Life Cycle inventory analysis

Hang et al. [27] compared the life cycle energetic, environmental and economic impacts of six types of water heating systems (Flat Plate Collector with Electrical auxiliary heater, Flat Plate collector with natural gas auxiliary heater, evacuated tube collector with electrical auxiliary heater, Evacuated tube Collector with natural gas auxiliary heater, Electrical water heating system, Natural gas water Heating System). The solar system is presented as in the scheme below:
In this study [27], the life cycle was completed using two softwares called SimaPro 7.1 and Ecoinvent 2.0. The analysis includes manufacturing, use, disposal stages and transportation among these stages.

-Manufacturing phase: During this stage, Hang et al. [27] listed all the components of the solar system and the materials involved (Absorber, frame, Insulation, coating…). Using the Data base of Ecoinvent 2.0, the energy consumed in manufacturing and transporting these components was estimated.

-Use phase: In this stage, electricity and natural gas were considered as the two major conventional energy sources according to Energy Book 2010 [27]. Water withdrawal profiles were taking from the ASHRAE standard 90.2 (Reference for water withdrawal profiles made by American Society of Heating, Refrigerating and Air conditionning Engineers.)

-Disposal phase: It is assumed that all the materials will be sent to the land fill after the life span of 20 years. Although some metals, such as copper, can be recycled, this end-of-life treatment is not considered in this study.

In the following study, Tsilingiridis et al. [28] evaluated the environmental impact over the life span of a Solar Domestic Hot Water system. In this study, the life cycle analysis is conducted with the software Eco-it that covers all categories of environmental impacts. This software depends on the methodology and the Database of Eco-indicator ’99 covering a variety of manufacturing procedures and impacts. This indicator includes standard values for materials used in the system, production processes, transportation processes, energy generation processes
and disposal scenarios. The unit Pt was used to asses the environmental footprint in the life cycle analysis of the system. The study shows that the use of the SDHW system has a significant gain over the conventional electrical heaters; SDHW hybrid with electricity systems have over 696 Pt of net gain in environmental impact, however the study shows that pure natural gas domestic water heaters has a lower environmental impact than the SDHW hybrid with electricity system. This is due to the electrical contribution in the heating process, and since the study is made in Greece, and natural gas is imported, it might be more approachable to use SDHW hybrid with electricity in these conditions.

In another study, Wei et al. [29] compared SDHW systems with Building Integrated Photovoltaic BIPV systems in terms of roof area owned by households. The study compares the two solar utilization systems for different roof areas. The study shows that regardless of the initial system cost, the critical point of roof area between SDHW and BIPV systems is 6 m². If the roof area is more than 6 m² a BIPV system could provide more energy than SDHW to the households, while if the area of the roof is lower than 6 m², a SDHW system would be more beneficial.

The results [29] from the cash flow show that the optimal setting of SDHW system would require around 3-4 m² which could permit to the majority of households to acquire this setting. In addition, in an economic point of view with the present governmental incentives, it is suggested that SDHW is more beneficial than BIPV. Since the ROI (return of investment) of BIPV is higher than SDHW systems; as a result, for small roof areas, it is more beneficial to have SDHW. However, if there is more space to be spared, BIPV then should be considered.

7- Solar water heating systems limitations and common problems

7.1- Measurement uncertainties

While Solar Domestic Water Heating systems are considered a convincing alternative for conventional energy, all the results used by researchers to prove this assertion are theoretical. Since field test are not exactly precise, and solar radiation is not something that can be predicted, only results obtained from simulation can be used to theoretically assess a solar system.

Yuwu et al. [30] studied the effect of uncertainty in measurements on assessment of thermal performance of solar SDHW systems. Since China issued laws that specify controls what type of solar system would be allowed to be installed depending on its thermal performance, it was imperative to have a good idea about the effect of the uncertainties of measurements.
7.2- Hot water shortage/low water temperature

The most common problem of solar water heating systems is the insufficient hot water and low water temperature. Several parameters are merely estimated during the modeling and simulation of solar systems. Hence a number of elements can affect the temperature of drainback water (heat exchanger, heat transfer fluid, collector, water storage, orientation of the collector, slope, azimuth angle…). In addition, the shortage of hot water/Low temperature can be due to the excessive hot water usage in a specific time of the day, where solar energy is not at its peak. [26]

8- Conclusion

With all the information gathered from literature, related to solar domestic water heating systems, SDHW systems indeed have several benefits in comparison with conventional energy sources. However, evaluating the potential benefit of a SDHW system for a given location might not be accurate. Different simulation tools and evaluation methods are presented, but at the end, all of them are just approximations and projections for what will be in real usage conditions. In light of these results, the master thesis topic is presenting a method that evaluates thermal performance of certain type of solar systems, the F-chart method, which is based on correlations obtained using results from different simulations. These correlations are used to estimate the solar fraction and heat load of solar systems. The method is not entirely accurate, as any other method, but it is fast and it does not need a great level of knowledge to be used. While sizing SDHW systems, accuracy is essential, but for quick results, F-chart method is proven to be somewhat relevant.
Chapter 3: Case study

1- Spanish legislation for solar energy use

In March 2006, Spain has issued a law called “Código Técnico de la Edificación” which means “Building Technical Code”, it is referred to as CTE. This law is mandatory; it regulates the minimum quality requirements a building must have, one of these requirements is the production of sanitary hot water by solar energy. The CTE fixes the minimum percentage hot sanitary water produced by solar systems. The minimum solar percentage is called minimum solar coverage; it depends on three parameters [32]:

- Hot sanitary water demand per day in the building.
- Geographical position of the building.
- Type of auxiliary energy for water heating.

Table 2: Minimum percentage % of solar contribution for heated sanitary water [33]

<table>
<thead>
<tr>
<th>Hot water demand (l/day)</th>
<th>Climatic zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
</tr>
<tr>
<td>50-5000</td>
<td>30</td>
</tr>
<tr>
<td>5000-10000</td>
<td>30</td>
</tr>
<tr>
<td>&gt;10000</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 10: Climatic zones of Spain [34]

The mentioned percentage, minimum solar coverage, is proposed to be calculated by the CTE with the f-chart method. This practical method is used for dimensioning the optimal size of Sanitary Hot Water Systems heated by solar energy.
Table 3: Hot water demand references [32]

<table>
<thead>
<tr>
<th>Demand criterion</th>
<th>Sanitary hot Water at 60°C (l/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>single family house</td>
<td>30 per person</td>
</tr>
<tr>
<td>Multifamily housing</td>
<td>22 per person</td>
</tr>
<tr>
<td>Hospitals and clinics</td>
<td>55 per bed</td>
</tr>
<tr>
<td>Hotel ****</td>
<td>70 per bed</td>
</tr>
<tr>
<td>Hotel ***</td>
<td>55 per bed</td>
</tr>
<tr>
<td>Hotel **/Hostal</td>
<td>40 per bed</td>
</tr>
<tr>
<td>Elderly/student residence</td>
<td>55 per bed</td>
</tr>
<tr>
<td>Schools</td>
<td>3 per student</td>
</tr>
<tr>
<td>Factories and workshops</td>
<td>15 per person</td>
</tr>
<tr>
<td>Administrative buildings</td>
<td>3 per person</td>
</tr>
<tr>
<td>Restaurant</td>
<td>5 to 10 per meal</td>
</tr>
</tbody>
</table>

2- System definition

The studied solar system is located in Terrassa, Barcelona, Spain. The Solar Domestic Water Heating (SDWH) system is providing sanitary hot water for a building of 12 apartments of approximately 67 people. The building is located in the climatic zone 2.

Figure 11: Geographical location of the studied system [35]

The purpose of the installed solar system is to provide sanitary hot water for the residents of building. In order to have a good idea on how the solar system works, a brief description of the working process will follow.
The previous figure does not portray correctly the studied system, but the working process is the same as the studied solar system. The solar radiation is absorbed by the solar collector and transferred to the working fluid. Then, the working fluid runs through the open water circuit and yields its energy to the cold water in the storage tank. There are several mechanisms of heat transfer between the working fluid and the water circuit (External heat exchanger, internal heat exchanger, coil pipe…). The hot water is then used directly if needed, if not, it is stored in the tank until need. When hot water is needed, it is drained from the tank, goes through the auxiliary water heating, also called boiler, the controls system measures the water temperature, if the temperature is not high enough (generally under 60°C), it turns the boiler on so that the water is at the wanted temperature, if the water’s temperature is high enough, the boiler is kept off.

2.1-Solar panel, Flat Plate Collector

The solar collector is the most important part of the solar system, they harness the energy coming from the sun and convert it to heat that is absorbed by a heat transfer fluid. There are several types of solar collectors: Flat Plate Collector (FPC), Evacuated Tube Collector (ETC)… In order to achieve the mandatory minimum solar contribution impelled by the CTE, a surface of approximately 16 m² was needed. While dimensioning the system, it was found optimal to use 8 solar panels of 2 m² each. The solar collector used for this system is the “Collector XX-SEL”. Some of the features of the collector are listed below:
2.2-Heat Transfer fluid

The working fluid is the manager of heat transfer between the solar collector and the open water circuit. It has to be chosen carefully, in the case of this project, the studied system is located in an area where the winter is very cold, and the water in the tubes can freeze, hence the working fluid has to be freeze resistant. In this case the heat transfer fluid is water mixed with 20% Ethylene Glycol, the mixture has a freezing point of -10°C [38].

2.3-Accumulator

The storage tanks store hot water when there is no need for hot water. A storage tank has to have several important features. It has to be well insulated in order to keep all the energy that the hot water has inside the the tank, to reduce heat loss through the tank walls. It also has to have efficient internal coil in order to have a maximum heat exchange between the heat transfer fluid and the water filling the accumulator. In the case of the studied system, two models of accumulator are used:

<table>
<thead>
<tr>
<th>Frame</th>
<th>Aluminium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar glass</td>
<td>low iron Glass with reduced reflection grade; float ESG; thickness: 4mm</td>
</tr>
<tr>
<td>Absorber</td>
<td>AS+, stainless steel, black chromium selective coating</td>
</tr>
<tr>
<td>Connections</td>
<td>2 x Ø 1/2”</td>
</tr>
<tr>
<td>Insulation</td>
<td>PU with aluminium sheet (free of CFC)</td>
</tr>
</tbody>
</table>

### Table 4: technical features of installed solar collector [37]

<table>
<thead>
<tr>
<th>Technical data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active surface area</td>
</tr>
<tr>
<td>Inner volume of the absorber</td>
</tr>
<tr>
<td>Transmission rate of the solar glass</td>
</tr>
<tr>
<td>Maximum service pressure</td>
</tr>
<tr>
<td>Nominal flow</td>
</tr>
<tr>
<td>Minimum flow</td>
</tr>
<tr>
<td>Pressure drop at nominal flow</td>
</tr>
<tr>
<td>Maximum stagnation temperature</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weight and dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (unfilled)</td>
</tr>
<tr>
<td>Dimensions</td>
</tr>
<tr>
<td>Height</td>
</tr>
</tbody>
</table>
Table 5: technical features of water tanks [38]

<table>
<thead>
<tr>
<th>Accumulator</th>
<th>ZANI 48 BSMV 100</th>
<th>ZANI 48 BSMV 150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>100 L</td>
<td>150 L</td>
</tr>
<tr>
<td>Number of units in system</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Maximum pressure</td>
<td>8 bar</td>
<td>8 bar</td>
</tr>
<tr>
<td>Maximum temperature</td>
<td>99°C</td>
<td>99°C</td>
</tr>
<tr>
<td>Total volume</td>
<td>1000L</td>
<td>1050L</td>
</tr>
<tr>
<td></td>
<td>=2050L</td>
<td></td>
</tr>
</tbody>
</table>

2.4-Auxiliary boiler

The boiler is responsible of heating the water when the temperature is not enough by solar means. It uses an external energy source to heat the water (natural gas, electricity…). When choosing an auxiliary boiler, several characteristics have to be taken into consideration. The type of external energy source is important, it has to be considered for its price and availability. Also, the power of the boiler is vital, it is selected according to the energy demand, the more the system is big and needs more energy, the more the power of the boiler is.

Figure 13: Studied system’s global scheme in AutoCAD [45]
3- The f-chart model

The f-chart method was developed in 1976-1977 by Klein and Beckman [40], This method is based on the results of many numerical simulations of different solar systems. These results served as the basis for correlations to calculate dimensionless variables.

This method is used to estimate the annual thermal performance of active heating systems for building, where the minimum temperature of energy delivery is near 20°C.

It provides a way of estimating the fraction of total heating load supplied by solar energy for a very specific heating system. However, as all empirical models, this method has limitations. It was designed for a standard water heating system, where the conditions of the simulations were varied over appropriate ranges of parameters of the system design. This makes the f-chart method viable for a very limited range of parameters (Collector area, Tank volume, tilt angle…), otherwise the results obtained with the correlations would be wrong.

3.1- Development of the model

These correlations were inserted in an excel file to obtain quick results by providing input Data about the solar system. This model is used for both Domestic Water heating and ambient heating of the building, but in the case of the present work it will only be used for Domestic Water Heating.
The two dimensionless variables are:

\[
X = \frac{\text{collector energy loss during a month}}{\text{total heating load during a month}} = \frac{F_R U_L}{F_R} \left( T_{ref} - T_a \right) \frac{A_c}{L} \Delta t
\]

(1)

\[
Y = \frac{\text{total energy absorbed on the collector surface during a month}}{\text{total heating load during a month}} = \frac{F_R (\tau \alpha)_n}{F_R (\tau \alpha)_n} \frac{H_T}{L} N \frac{A_c}{L}
\]

(2)

Where:

- \( A_c \) = Area of solar collector (m²)
- \( F_R' \) = Collector-heat exchanger efficiency factor (%)
- \( F_R \) = Collector heat removal factor (%)
- \( U_L \) = Collector overall energy loss coefficient (W/m²°C)
- \( \Delta t \) = Total number of seconds or hours in the month
- \( T_a \) = Monthly average ambient temperature (°C)
- \( L \) = Monthly total heating load (GJ)
- \( H_T \) = Monthly averaged daily radiation incident on collector surface per unit area (MJ/m²)
- \( N \) = Number of days in the month
- \( \tau \alpha \) = Transmittance-absorptance product (%)
- \( T_{ref} \) = Reference temperature (100 °C)
The overall loss coefficient \( F_R U_L \) and the optical performance \( F_R (\tau \alpha)_n \) are necessary parameters to insert in the numerical model, however these parameters change depending on the efficiency of the solar collector and on the weather data of the solar system, and they have to be calculated manually beforehand. The calculation steps of \( F_R U_L \) and \( F_R (\tau \alpha)_n \) will be explained below:

In order to calculate \( F_R U_L \) and \( F_R (\tau \alpha)_n \), it is required to visualize the variation of the efficiency of the collector \( \eta \) with ambient temperature, feed water and different irradiations.

The collector manufacturer defines its efficiency by means of the following quadrant curve [43]:

\[
\eta = \eta_0 - a_1 \frac{T_m - T_a}{I_T} - a_2 \frac{T_m^2 - T_a^2}{I_T}
\]

(3)

Where:

\( \eta_0 = 0.816 \)
\( a_1 = 3,804 \text{ W/m}^2\text{°C} \)
\( a_2 = 0.0176 \text{ W/m}^2\text{°C} \)

\( T_m \): Average collector temperature
\( T_a \): Ambient temperature

To determine the efficiency of the collector, the quotient between the useful power and the incident radiation must be calculated, which is also expressed as:

\[
\eta = \frac{Q_u}{A I_T} = \eta_0 - a_1 \frac{T_m - T_a}{I_T}
\]

(4)

Having different temperature conditions (with monthly ambient temperature for the year 2016, average collector temperature=50°C) for \( \frac{T_m - T_a}{I_T} \) and for different radiation values with which the performance curve can be represented graphically.

### Table 6: Efficiency of the solar collector for difference radiation values [45]

<table>
<thead>
<tr>
<th>G</th>
<th>1000 W/m²</th>
<th>800 W/m²</th>
<th>600 W/m²</th>
<th>400 W/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ta</td>
<td>x</td>
<td>n</td>
<td>x</td>
<td>n</td>
</tr>
<tr>
<td>Tm</td>
<td>x</td>
<td>n</td>
<td>x</td>
<td>n</td>
</tr>
<tr>
<td>21.63</td>
<td>0</td>
<td>0,82</td>
<td>0,82</td>
<td>0,82</td>
</tr>
<tr>
<td>21.53</td>
<td>0,01</td>
<td>0,78</td>
<td>0,01</td>
<td>0,78</td>
</tr>
<tr>
<td>19.63</td>
<td>0,02</td>
<td>0,73</td>
<td>0,02</td>
<td>0,73</td>
</tr>
<tr>
<td>18.33</td>
<td>0,03</td>
<td>0,69</td>
<td>0,03</td>
<td>0,69</td>
</tr>
<tr>
<td>14.63</td>
<td>0,04</td>
<td>0,64</td>
<td>0,04</td>
<td>0,64</td>
</tr>
<tr>
<td>14.36</td>
<td>0,05</td>
<td>0,58</td>
<td>0,05</td>
<td>0,59</td>
</tr>
<tr>
<td>11.43</td>
<td>0,06</td>
<td>0,52</td>
<td>0,06</td>
<td>0,54</td>
</tr>
<tr>
<td>9.76</td>
<td>0,07</td>
<td>0,46</td>
<td>0,07</td>
<td>0,48</td>
</tr>
<tr>
<td>8,36</td>
<td>0,08</td>
<td>0,40</td>
<td>0,08</td>
<td>0,42</td>
</tr>
<tr>
<td>6,86</td>
<td>0,09</td>
<td>0,33</td>
<td>0,09</td>
<td>0,36</td>
</tr>
<tr>
<td>6,76</td>
<td>0,1</td>
<td>0,26</td>
<td>0,1</td>
<td>0,29</td>
</tr>
<tr>
<td>6,06</td>
<td>0,11</td>
<td>0,18</td>
<td>0,11</td>
<td>0,23</td>
</tr>
</tbody>
</table>
The parameters of the collector are as follows:

- Overall loss coefficient $F_R U_L = 5,1592 \text{ W/m}^2\circ\text{C}$
- Optical performance $F_R (\tau\alpha)_n = 0,8386$
How the model works

In F-chart method, the system’s performance is expressed in terms of $f$, which is the fraction of the heating load supplied by solar energy during each month [10]. The relationship between $f$ and the dimensionless variable $X$ and $Y$ is:

$$f=1.029Y-0.065X-0.245Y^2+0.0018X^2+0.0215Y^3$$ (5)

Subject to conditions $0 \leq X \leq 15; 0 \leq Y \leq 3$.

The calculations are repeated for each month. The fraction of the annual heating load supplied by solar energy $F$ is the sum of the product of monthly solar energy fraction $f_i$ and the monthly thermal load $L_i$ divided by the annual load $L$.

$$F=\frac{\sum f_iL_i}{\sum L_i}$$ (6)

The calculation of the variables $X$ and $Y$ requires information about the solar system (meteorological data, specifications about the solar collectors (absorptance-transmittance, area…), Tilt angle, inlet temperature, outlet temperature…). This data is to be inserted in the first sheet “Data input”, this data would be analyzed, and if any errors or if the data is not within the limitations of the f-chart method, an error messages would appear in the second sheet “Errors”. In the sheet “radiation”, the data in “Data input” is used to calculate the monthly average solar radiation on tilted plane which is necessary to calculate the variables $X$ and $Y$. The same thing goes to the sheet “heating loads”, the sheet “X and Y parameters” defines the dimensionless variables, then in the sheet “solar fraction”, the solar fraction $F$ is calculated for different areas of the solar collectors. This information is then plotted in a curve visualizing the evolution of the efficiency and the solar fraction for different values of the solar collector’s area, which can be used to determine the optimal area of the collector for a specific system.

3.2-Hot water demand

Another important parameter to insert in the model is the heat load, in other words, the hot water demand. This parameter is not easy to calculate as a consequence of the inconsistency of the water demand profiles (morning/evening difference, demographic customs, part of the year…). That’s why the Spanish government issued standards to estimate the heat load, by estimating the number of people occupying the residence and the daily hot water drain.
In the case of this project, the studied building has the following data:

Daily consumption: 22 l/day (table 2: Multifamily building)

10 flats of 2 bedrooms => 3 people
6 flats of 4 bedrooms => 6 people
1 flat of 1 bedroom => 1.5 people

Therefore:

Number of occupants: $10 \times 3 + 6 \times 6 + 1 \times 1.5 = 30 + 36 + 1.5 = 67.5$ people

Hence:

Daily Heat load: $67.5 \times 22 \text{ l/day/person} = 1485 \text{ l/day}$ (7)

4- Acquisition and measurement

4.1- SunEye, Omnilus Database

SunEye “Seye” is an intelligent energy counter/controller used by the RDmes company to monitor in real time their solar plants. The controller measures the temperatures and volumetric flows of the currents coming into and out from the solar collectors.
It uses this data to calculate the energy absorbed by the collectors and estimate the moneys saves and CO\textsuperscript{2} reductions by using thermodynamic parameters and equations integrated in its mini computer (Raspberry pi).

SunEye also has an integrated SIM card used to send the measured data to the Omnilus data base to be reviewed by the people working in RDmes. The Platform was developed by J. Cadafalch, R. Consul, A. González Valero and R. Ruiz, it presents applications to support market-oriented engineering, planning and maintenance tasks in the green heating and cooling sector (RHC). It uses several data bases for the design and maintenance of renewable heating and cooling plants: technical data, theoretical models (for solar collectors, heat exchangers…), commercial catalogs, locations, weather and legislation.

4.2-Data comparison

4.2.1-Ultrasonic flow meter Data vs Omnilus data

An Ultrasonic Flowmeter “Flexim” was used to calculate the energy absorbed by the solar collector for 3 days, this data was then compared to energy absorbed from the Omnilus platform.
In this part the f-chart numerical model will be used to calculate the monthly absorbed solar energy for the year 2016, these results will be compared to data from the Omnibus Platform. Weather data was used from the “meteo” application in the Omnibus platform (monthly average ambient temperature, monthly solar radiation, monthly clarity index, ground reflectance/absorptance…), the overall loss coefficient and optical performance previously calculated were also used in the calculations as well as the daily heat load previously mentioned in (7).
Table 8: Monthly absorbed energy from f-chart model and Omnilus platform [45]

<table>
<thead>
<tr>
<th>Date</th>
<th>Monthly energy from Omnilus (kWh)</th>
<th>Monthly energy from F-chart (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016/1</td>
<td>718</td>
<td>986</td>
</tr>
<tr>
<td>2016/2</td>
<td>864</td>
<td>1050</td>
</tr>
<tr>
<td>2016/3</td>
<td>969</td>
<td>1238</td>
</tr>
<tr>
<td>2016/4</td>
<td>888</td>
<td>1265</td>
</tr>
<tr>
<td>2016/5</td>
<td>1032</td>
<td>1358</td>
</tr>
<tr>
<td>2016/6</td>
<td>1129</td>
<td>1318</td>
</tr>
<tr>
<td>2016/7</td>
<td>1240</td>
<td>1435</td>
</tr>
<tr>
<td>2016/8</td>
<td>1116</td>
<td>1395</td>
</tr>
<tr>
<td>2016/9</td>
<td>1080</td>
<td>1265</td>
</tr>
<tr>
<td>2016/10</td>
<td>629</td>
<td>1218</td>
</tr>
<tr>
<td>2016/11</td>
<td>797</td>
<td>1010</td>
</tr>
<tr>
<td>2016/12</td>
<td>846</td>
<td>967</td>
</tr>
</tbody>
</table>

Figure 22: Monthly absorbed energy from f-chart model and Omnilus platform [45]

4.2.3-Overview of the 12 monitored plants by RDmes

In the following, an annual overview of the 12 monitored plants was made. Annual solar contribution, money saves and CO$_2$ reduction were calculated as follows:

- Annual solar contribution data was downloaded from Omnilus platform.
- Money saves depend on the fuel, whether it is electricity or natural gas:
Ex: 726.0 kWh \cdot 1/\eta \cdot 0.060 \, \text{€/kWh} = 45.9 \, \text{€}

Ex: 1386.0 kWh \cdot 1/\eta \cdot 0.170 \, \text{€/kWh} = 248.0 \, \text{€}

• CO₂ reduction, it also depends on the fuel, whether it is natural gas or electricity:

Ex: 1386.0 kWh \cdot 1/\eta \cdot 0.219 \, \text{kgCO₂/kWh} = 319.5 \, \text{kgCO₂}

Ex: 726.0 kWh \cdot 1/\eta \cdot 0.202 \, \text{kgCO₂/kWh} = 154.4 \, \text{kgCO₂}

Table 9: Overview of the 12 monitored plants [45]

<table>
<thead>
<tr>
<th>Monitored plant</th>
<th>Annual absorbed solar energy (kWh)</th>
<th>Annual money saves (€)</th>
<th>Annual CO₂ reduction (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JoanMaragull27, Cornella de Llobregat</td>
<td>5583</td>
<td>353</td>
<td>1187</td>
</tr>
<tr>
<td>DrVentallo5, Terrassa</td>
<td>6066</td>
<td>1085</td>
<td>1398</td>
</tr>
<tr>
<td>JoepIrla182-184, Sant Cugat del Vallès</td>
<td>9390</td>
<td>593</td>
<td>1997</td>
</tr>
<tr>
<td>FuturaCasaLola, Barcelona</td>
<td>2160</td>
<td>1676</td>
<td>9368</td>
</tr>
<tr>
<td>CtraEsplugues149, Cornella de Llobregat</td>
<td>11195</td>
<td>707</td>
<td>2380</td>
</tr>
<tr>
<td>MareDeLaFont45-47, Sant Cugat del Vallès</td>
<td>28733</td>
<td>1815</td>
<td>6110</td>
</tr>
<tr>
<td>PastoraMartos39-41, Sant Cugat del Vallès</td>
<td>29066</td>
<td>1836</td>
<td>6180</td>
</tr>
<tr>
<td>Clota46-48, Sant Cugat del Vallès</td>
<td>28880</td>
<td>2666</td>
<td>8975</td>
</tr>
<tr>
<td>PlaçaNova3, Terrassa</td>
<td>11584</td>
<td>732</td>
<td>2463</td>
</tr>
<tr>
<td>CatalaRoca10-12, Terrassa</td>
<td>16014</td>
<td>1011</td>
<td>3405</td>
</tr>
<tr>
<td>Ctra Barcelona85-87, Sabadell</td>
<td>10405</td>
<td>1862</td>
<td>2399</td>
</tr>
<tr>
<td>Celler7, Terrassa</td>
<td>24425</td>
<td>1543</td>
<td>5194</td>
</tr>
<tr>
<td>Volta213AlexanderBell16-18, Terrassa</td>
<td>11321</td>
<td>715</td>
<td>2407</td>
</tr>
</tbody>
</table>
5- Results and discussion

5.1- Data comparison and accuracy

In figure 11, the comparison between the absorbed energy from Omnilus platform and the data from the ultrasonic flowmeter “flexim” shows a slight difference between the values. The difference is due to the certainty of the measurement. The thermometers within the solar system that are used by SunEye take measurements continually, however, Suneye can only send data to Omnilus every 60 minutes (due to the price of data traffic fixed with telephone company), on the other hand, flexim was programmed to take values every 60 seconds. But what can be learned from this comparison is that sometimes certainty have to be traded for low price of operation. Having a flexim connected all the time to a solar plant is not feasible, the ultrasonic flowmeter costs around 8000 € and has a complicated setup, it also does not give real time data (data has to be stored during measurement and taken afterwards using a computer). Therefore, using a SIM card that can send data every 60 minutes is more feasible.

In figure 12, an important difference between the monthly solar contribution values is shown. It can be related to several reasons: the developed f-chart model is based on an empirical method and correlations, f-chart method has several usage conditions (limited range of areas of collectors, slope…), weather data accuracy among others. However, the data from Omnilus is more accurate, it is based on measured parameters and real time data.

5.2-Studied system energy saves, money saves and CO₂ reduction:

With the data from Omnilus, the annual solar contribution is 11584 kWh from June 2016 until June 2017.

The amount saved by using solar energy for water heating is 732 €, however the owner has to pay maintenance charges, for this case the maintenance charges are 680 €/year. So at the end of the year the owner has only around 52€ of savings. The system reduced CO₂ emission by 2463 kg, which is an important amount of reduced CO₂ in the atmosphere.
Conclusion

The aim of this thesis was to study a solar domestic water heating system, to develop a numerical model based on the f-chart method and to compare results obtained from the model with data obtained from the Omnilus platform.

The work starts with an introduction on solar energy, its uses, some physical principals that participate in solar energy uses. A literature review was made after to have a good idea on the recent works related to the f-chart method, solar domestic water heating, Solar systems modeling, and solar systems performance evaluation. After that, a solar system located in Terrassa-Barcelona was studied, Spanish legislation related to solar water heating was also reviewed in order to have a good idea on the legal requirements in Spain. Then the numerical model was developed based on the f-chart method by John A. Duffie and William A. Beckman. Afterwards, annual and monthly solar energy contribution were calculated using the numerical model and compared to data retrieved from the Omnilus platform. Money saves and CO2 reduction was calculated later on.

The results obtained from this work highlight the positive aspects of the use of solar energy to heat domestic sanitary water. On one hand we have the environmental aspect, the CO2 reduction are very important, the use of traditional fossil fuel was avoided, hence the emission
of not only carbon dioxide, but also methane nitrous oxide and so on. On the other hand, we have the economical aspect, the money savings made from the studied solar system are not that high, but in Spain it is mandatory to install solar domestic water heating system, so there is no choice but to install it. Even though the money saves are not that important, sometimes, in order to get a better environment for our life, the economical profits should be considered as a secondary factor.

Our planet is suffering severely from the technological development, the global warming is a real threat and it’s getting worse day by day, the ozone layer is degrading continuously, the sea levels are rising and some people are still denying these facts. Humanity has to find another way of development other than making our planet drown. It is imperative to try and globalize the use of renewable energies for the maximum that we can, using solar energy for sanitary water heating is not a very profitable way but it is surely extremely useful for our environment.
Appendices

Solar Collector
XX-SEL

Excellent price - performance ratio.
Maximum performance at a competitive price.

Optimum selectivity.
Solar absorptance: \( \alpha > 0.94 \)
Thermal emittance: \( \varepsilon < 0.07 \)

Quality and robustness.
Lifetime over 20 Years guaranteed thanks to the extensive use of durable materials (stainless steel, EPDM, aluminium, ...).

Universal size and compact dimensions.
3.0 m\(^2\) active surface area for horizontal and vertical mounting.

Reduced mounting height.
Height = 80mm.

Stainless steel absorber A5+
Stainless steel absorber with patented cushion geometry ensuring a perfect irrigation of the complete absorber.
Optimum contact with the fluid: 98% of the exposed collector area in contact with the heat-carrying fluid.
Improved heat transmission coefficient towards conventional absorbers.
Strong experience as the core component of several renowned glazed collector brands ranking tops at official tests.

Over 25 Years at the top of solar technology
www.energie-solaire.com
Technical data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active surface area</td>
<td>2.0 m²</td>
</tr>
<tr>
<td>Inner volume of the absorber</td>
<td>2.6 l/m²</td>
</tr>
<tr>
<td>Transmission rate of the solar glass</td>
<td>91 l/s</td>
</tr>
<tr>
<td>Maximum service pressure</td>
<td>3 bars</td>
</tr>
<tr>
<td>Nominal flow</td>
<td>40 l/h.m²</td>
</tr>
<tr>
<td>Minimum flow</td>
<td>30 l/h.m²</td>
</tr>
<tr>
<td>Pressure drop at nominal flow</td>
<td>&lt; 400 Pa</td>
</tr>
<tr>
<td>Maximum stagnation temperature</td>
<td>200 °C</td>
</tr>
</tbody>
</table>

Weight and dimensions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (unfilled)</td>
<td>52 kg</td>
</tr>
<tr>
<td>Dimensions</td>
<td>900 x 2400 mm</td>
</tr>
<tr>
<td>Height</td>
<td>80 mm</td>
</tr>
</tbody>
</table>

Other features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame</td>
<td>Aluminium</td>
</tr>
<tr>
<td>Solar glass</td>
<td>Low iron glass with reduced reflection grade; float ESG; thickness: 4mm</td>
</tr>
<tr>
<td>Absorber</td>
<td>AISI stainless steel. black chromium selective coating</td>
</tr>
<tr>
<td>Connections</td>
<td>2 x Φ 1/2&quot;</td>
</tr>
<tr>
<td>Insulation</td>
<td>PU with aluminium sheet (free of CFC)</td>
</tr>
</tbody>
</table>

Definition of the efficiency

\[
\eta = \eta_3 \cdot x_1 \cdot x_2 \cdot x^2 \cdot G
\]

\[
x = \frac{(T_m - T_1)}{G} \quad \text{(W/m²)}
\]

\[
T_m = \text{Average collector temperature (°C)}
\]

\[
T_1 = \text{Ambient temperature (°C)}
\]

\[
G = \text{Solar radiation (W/m²)}
\]

Efficiency data XX-Sel

(Ref. aperture area; with wind effect acc. to DIN EN 12975-2)

\[
\eta_3 = 0.016
\]

\[
x_1 = 3.804 \text{W/m²°C}
\]

\[
x_2 = 0.0176 \text{W/m²°C}
\]

![Efficiency curve acc. to DIN EN 12975-2, with $G = 800 \text{ W/m}^2$](image)

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www.energie-solaire.com
Polytechnic University of Barcelona:

Polytechnic University of Catalonia currently referred to as BarcelonaTech and commonly named just as UPC, is the largest engineering university in Catalonia, Spain. The university was founded in March 1971 as the Universitat Politècnica de Barcelona through the merger of engineering and architecture schools founded during the 19th century [46].

1-Structure of UPC:

The UPC is composed of 22 schools and faculties in 7 cities in Catalonia, it has over 30 000 students in Bachelor, Masters and PhD studies, and over 2500 professors and researchers [46].

2-School of Industrial Engineering-ETSEIB:

The School of Engineering of Barcelona was created in 1851 It's one of the schools who in 1971 came together and established the UPC, the Polytechnic University of Catalonia. The ETSEIB is the biggest engineering school in Catalonia, with more than 3100 students and about 410 professors [47].
3-RDmes, Solar energy systems installations and maintenance:

RDmes is a technological company founded in 2006 by energy experts of the Universitat Politècnica de Catalunya BarcelonaTech with the central objective of becoming a referent technology provider of the renewable energy and energy efficiency sector. RDmes also operates as an engineering and maintenance company in the field of renewable energies [48].
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