Unglazed Solar Thermal Systems for Building Integration, coupled with District Heating Systems. Conceptual Definition, Cost and Performance Assessment

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Abstract
In this paper, the energy performance of a solar thermal (ST) façade system is studied in relation to its connection to a district heating system. This concept allows for the direct use of ST heat in the building, while taking profit from the network for delivery/selling of excess heat and purchase of heat during periods of underproduction. The use of unglazed collectors for low-intrusive architectural interaction in façades is discussed.

Studies are carried out on the heat production of the system and its capacity to cope with local demands. Economic studies are carried out in order to balance the investment and operational costs/profits of the system.

Keywords
solar systems, thermal energy, building integration, energy systems

1 INTRODUCTION

In developed countries, there is a clear need, and political impulse, to achieve an energetic transition from fossil fuels to renewable sources. Within renewable energy sources, the potential of solar power and associated technologies is well known. In particular, solar thermal systems are a proven renewable heating technology. Although the exergy of this energy source is quite low, the potential of solar energy is still one of the greatest on the planet (Ehsanul, Kumar, Kumar, Adelodun, & Kim, 2018).

In this context, solar energy must be one of the main pillars of a renewable energy strategy. A clear example of the drive towards this transition is the minimum solar contribution required by national building codes in developed countries, such as the Spanish CTE (2013).

In most traditional heating system designs, Solar Thermal (ST) systems are sized to meet only a fraction of the entire demand for thermal energy. Solar production and heat loads in buildings have daily and seasonal variations due to transient and variable weather conditions. In most climates, space heating (SH) load is interrupted in summer periods, but domestic hot water (DHW) loads are stable all year round. In winter, the available ST heat is not sufficient to cover heat loads in buildings, while in summer, solar heat production clearly exceeds the demand of the building. ST systems are commonly sized not to exceed heat loads over the spring-autumn period.

Most ST systems are incorporated in roofs. In order to meet the increased requirements for ST installation, larger surfaces will need to be activated for ST installations. For this, building façades need to be considered as candidate areas due to their large available surface, although challenges of overshadowing in high urban building densities must still be resolved.

With the steady incorporation of nZEB (nearly Zero Energy Buildings) in cities, relevant reductions in heat loads can be foreseen in the near future. The utilisation of renewable energies in these same buildings will reach a point where the directionality in the production-consumption role will be altered. The increase in ST installation with the reduction of heat loads in buildings modifies traditional ST sizing criteria. As a result, excess heat may be available from these ST systems. In this paper, the connection to district heating (DH) is explored in order to allow this excess production to be used in adjacent buildings.

DH systems are one of the most efficient ways to cover heat loads in urban areas. Traditionally, DH systems have been based on large boilers or CHP (combined heat & power) systems. Nowadays, it is increasingly common to find DH networks that incorporate distributed energy sources (Monsalvete Álvarez de Uribarri, Eicker, & Robinson, 2017), commonly with lower exergy in comparison with traditional high temperature power plants.

This includes the exploitation of industrial waste heat and solar thermal systems, among others. All this results in a reduction of fossil fuel dependence and contributes to a de-carbonised environment.

Heat losses in the DH system are proportional to the temperature gradient between supply temperature and environment temperature. With lower operational temperatures and distributed energy sources, there is a substantial improvement in system performance.

In this paper, the potentialities, constraints, and performance levels of façade-integrated solar thermal systems coupled with low temperature district heating (LTDH) are studied, comprising their thermal and economic performance. The techno-economic viability of unglazed façade-integrated solar thermal systems when combined with low temperature district heating systems.

1.1 UNGLAZED SOLAR THERMAL COLLECTORS

In general, ST systems are composed of solar thermal collectors, where a heat transfer fluid is circulated in a pressurised circuit. Solar heat is absorbed and transferred to the fluid, resulting in an increment of the temperature. Depending on external conditions and collectors` characteristics, the performance of each collector is different. Their performance definition is described in detail in (Duffie and Beckman, 1980).

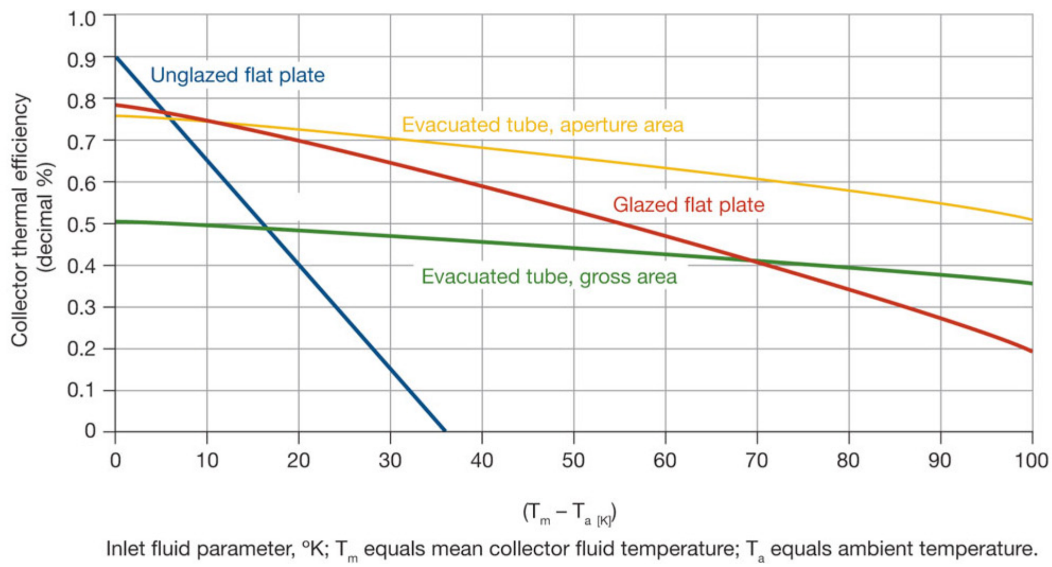

FIG. 1 Collector efficiency vs (T_m-T_a). G_T = 800W/m². Source: Stickney, B. & Soifer, B, (2009).

Fig. 1 shows that with a low temperature difference, unglazed collectors present better efficiency levels than other systems. The possibility to incorporate unglazed systems in buildings has been studied in diverse investigations such as (A. Giovanardi, 2016) but only a few companies propose integration into the façade, and the technology is still under-exploited.

1.2 ARCHITECTURAL INTEGRATION OF ST SYSTEMS

Building integration of ST systems has been historically limited due to the need to accommodate glazed areas and tubular assembles in the architectural composition of buildings. Despite this, smart but marginal integration solutions for vacuum tubes have been achieved in balconies or transparent areas (O'Hegarty, Kinnane, and McCormack, 2016)

As for the unglazed collectors, the method for their integration in façades is explained in (Garay Martinez, R., Arregi Goikolea, B., Bonnamy, P. & Lopez, J., 2017). Having no glass or tubular covers, the unglazed collectors are the only ones that can be integrated without modifying the aesthetics of the building. Specifically, the unglazed solar collector enables varied forms (shape, size, and typology) and materials (colour, texture, transparency etc.).

In broad terms, it must be considered that façades are the prominent image of the building. In the selection of ST technologies and their integration with solar thermal façades (STF), this aspect needs to be taken into account. The existence of a wide range of architectural façades requires delivery of a wide range of STF products, to ensure freedom of design intent. In (Garay Martinez, Arregi Goikolea, Bonnamy, and Lopez, 2017), an experimental study is performed on unglazed ST collectors and their potential to deliver heat to HVAC systems in buildings. In this work, it is identified that façades are the biggest area on to which collectors can be installed, and that unglazed collectors are one of the most sensible alternatives to achieve ST production and architectural integration.

1.3 ST CONNECTION TO DH NETWORKS

With the trend to incorporate decentralised and decarbonised heat, ST is an increasingly common alternative heat source being incorporated in DH. There are two integration alternatives for ST in DH: centralised and distributed ST systems. To date, most ST installations have consisted of centralised ST plants outside cities. This paper explores the possibility to integrate distributed ST systems in buildings, by means of their integration in building façades. This allows for the moving of energy sources closer to consumption points to reduce the transmission losses associated with the aforementioned centralised plant. DH connection of ST systems can be performed in different ways, with different functionalities. (Sanchez Zabala and Garay Martinez, 2017) describe several types of connections. Fig. 2. shows different types of ST integration schemes into a DH network.

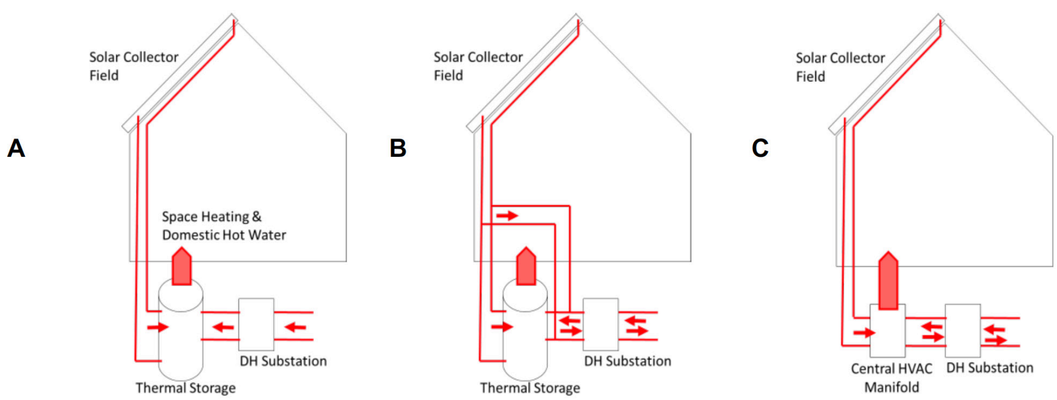

FIG. 2 ST integration into DH networks. A. ST & DH in parallel. B. Delivery of excess heat to DH. C. Hybrid system without storage (Sanchez Zabala & Garay Martinez, 2017)

This paper explores a direct ST and DH connection to central HVAC manifolds in building, allowing bi-directional heat transfer to the DH. In this concept, local storage is avoided.

2 METHODOLOGY

In this paper, simulations are performed in order to assess the technical and economic viability of unglazed ST systems connected to DH networks in order to deliver decarbonised heat within reasonable economic metrics.

For this purpose, simulation studies are performed for a multi-storey building in the region of Bordeaux (France). According to the Koppen-Geiger climate definition, described by (Kottek, M., Grieser, J., Beck, C., Rudolph, B., & Rubel, F., 2006), Bordeaux is classified as having a C_{fb} climate, which covers most climates in Western Europe, from the north of Spain to central EU latitudes such as UK, The Netherlands, etc... For this reason, Bordeaux is considered to be a representative location for West-EU climates.

The heat load, for DHW and space heating is calculated by means of dynamic simulation methods with an hourly resolution. Heat production of a south-oriented ST façade is simulated for the same climate with the same resolution.

The economic viability of DH-connected ST systems is evaluated by means of a comparative study against fossil-fuel alternatives. Various ST connection & heat pricing schemes are studied.

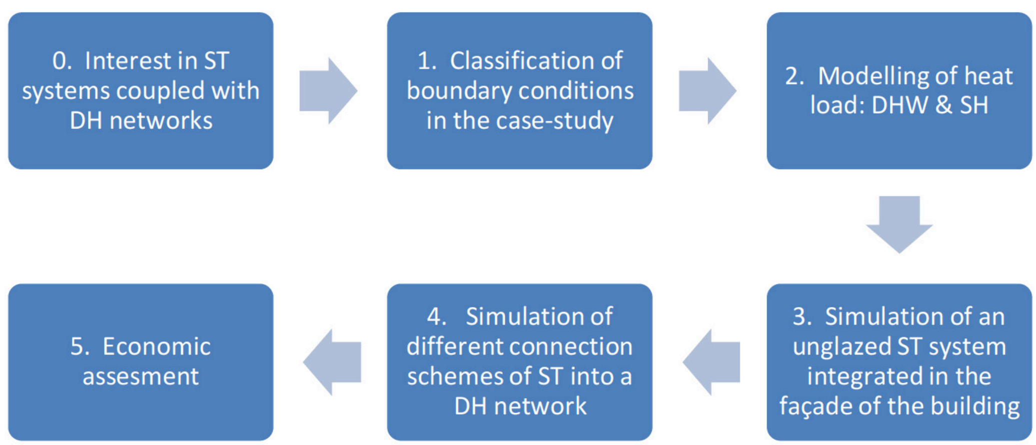

FIG. 3 Methodology description

2.1 HEAT LOAD MODELLING

The first step in this study is developing the building model and defining its main characteristics, depending on which the heat loads vary considerably. The selected case study comprises a 5-storey building, with a façade surface area of 1250 m^2. In Fig. 4, a general view of the building and its basic connection scheme to DH is shown. The U-value of the walls is 0.8 W/m^2. The window-to-wall ratio is 40% with a U-value of 1.4 W/m^2. Fig. 4 shows general prototypes for ST integration in the building and its connection to DH substation.

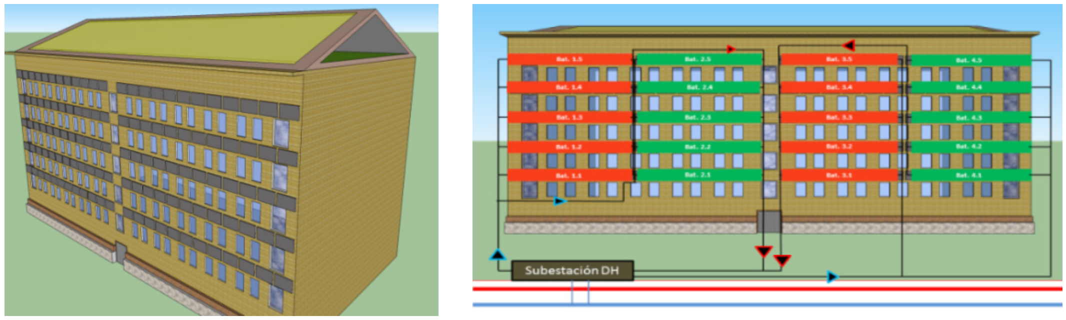

FIG. 4 3D model of the building geometry & ST system on the south façade (left); Connection scheme within the collector field and connection to DH (right)

DHW heat load has been calculated according to (Código Técnico de la Edificación [Technical Building Code], 2013), considering a total floor area of 5000m^2 divided in 80m^2 apartments inhabited by families comprising 3 people. According to the calculation procedure, 22 litres of DHW (60°C) are consumed per person per day.

For SH, a pseudo dynamic calculation has been used, with a self-developed procedure that is compliant with UNE-EN ISO 13790:2011.

2.2 MODELING OF THE UNGLAZED ST SYSTEM

For the modelling of the ST façade, a self-developed model in the software R has been used for thermal calculations. This software tool allows big databases to be worked with as vectors, thereby reducing calculation times. Within this model, specific collector Energie Solaire Kollektor AS (2012) data has been used in order to calculate efficiency and other parameters used in the model.

As for the working temperatures, the inlet temperature has been fixed in order to be the same as the DH return line temperature (± 30 °C) and the outlet temperature from the collector field has been set according to each of the simulation cases, which are further defined later in the text. Moreover, load losses have been estimated to be 10%.

2.3 CONSIDERATIONS FOR ECONOMIC METRICS

The economic assessment is based on general economic metrics which can be found in general purpose economic literature such as (Harris, 2018). For their calculation, the investment necessary for the installation and exploitation of each technology has been calculated, leading to the calculation of the yearly revenues and operational costs. This will include the consumption of primary energy sources and the heat purchase and delivery. As it is a theoretical study, the maintenance costs have been avoided for being much lower in comparison with other cash flows.

Specifically, the metrics used for this economic assessment are as follows: return on investment (ROI), which is the time taken to recover the investment; cash flow, the net amount of cash moving in and out of each technology; and net present value (NPV), which is the difference between the present value of cash inflows and the present value of cash outflows over a period of time.

3 THERMAL PERFORMANCE OF UNGLAZED ST SYSTEM

A ST collector system is studied in a high-rise building. This collector field comprises 240m^2 of south-oriented unglazed ST. The field is arranged in 20 parallel circuits, comprising 6 collectors in a serial arrangement, with each collector covering and area of 2m^2. Data relating to the specific collector used for this installation can be found in Energie Solaire Kollektor AS (2012).

In general, collectors achieve better efficiency when the temperature difference between the collector (average) and environment is low. In order to limit the average is the solar field, a sensitivity analysis is carried out to ensure that the inlet-outlet temperature difference is limited to 10 °C. That temperature difference is defined by difference between the average temperature in the collector battery and the ambient temperature. This results in the aforementioned configuration.

In an isolated system, the service temperature needs to be met by solar thermal collectors. In these systems, it is common to use the lowest possible service temperature to increase the overall performance of ST. In the case of considering ST systems coupled with DH, there is no need to configure ST systems to raise fluid temperature to the overall flow temperature in the DH network. There is a minimum temperature difference (normally 3-5°C) that the system must achieve before it is worth activating the pumps to circulate the fluid. If the heat output is delivered in the return pipe of the DH, greater performance is achieved due to the lower service temperature compared to insulated ST systems. In Fig. 5, the results from the simulation of unglazed ST when reacting to different situations are shown.

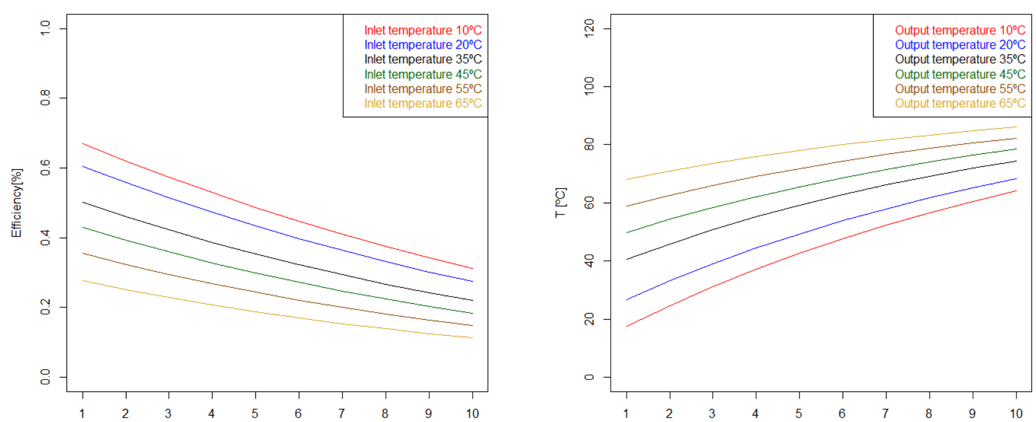

FIG. 5 Collector in serial arrangement performance for different situations

Depending on the service temperature required, the number of collectors arranged in series increases, so that the surface needed increases proportionally. Taking into account the fact that the inlet-outlet temperature difference is limited, the number of collectors is also limited.

Nowadays, LTDH (low temperature district heating) is considered as an alternative to conventional DH, and the working temperatures of this system are much lower, reducing heat losses in supply temperatures. In this case, the best solution for installing integrated ST is to install the ST system to the return pipe of LTDH system.

4 RESULTS

4.1 HEAT PRODUCTION

Solar production is simulated for the climate of Bordeaux for various operational conditions. These conditions consider various inlet temperatures, among which low temperatures are incorporated and used in line with LTDH. Temperatures in the range of 50-60°C are representative of flow temperatures, while temperatures of 20-30°C are representative of DH return lines. In Fig. 6, the total heat production of a solar unglazed collector (Energie Solaire Kollektor AS, 2012) and the total efficiency defined by the production, divided by the total solar radiation, are shown. The bar plot refers to the total solar production by the unglazed collector; the lines refer to the total efficiency. The results indicate that better results are achieved for the cases in which the inlet-outlet temperature difference is limited to 10°C, no matter what the inlet temperature is.

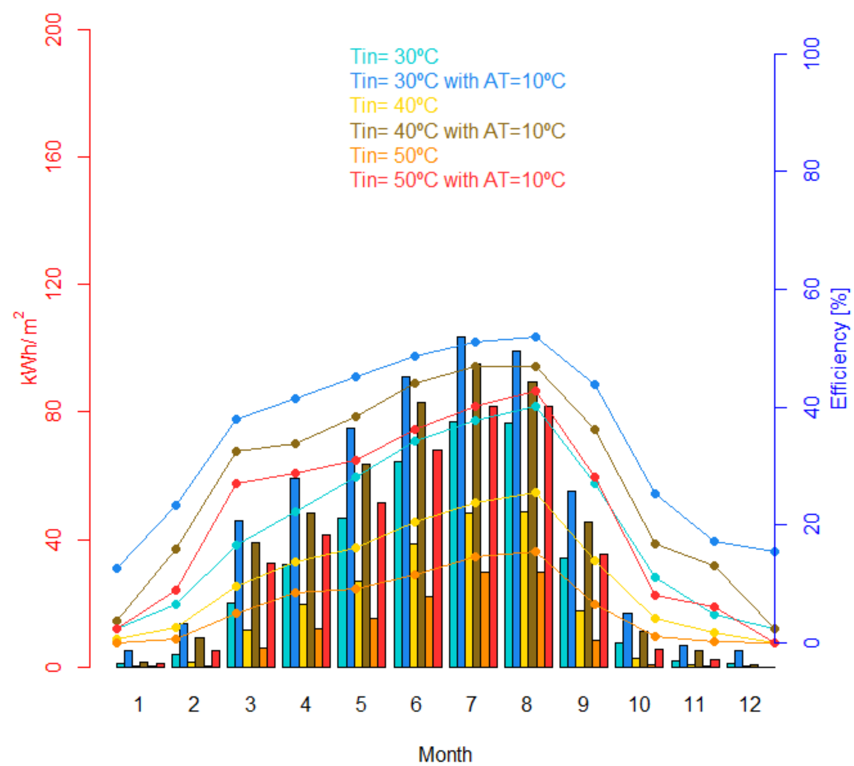

FIG. 6 Solar production and total solar efficiency for different inlet temperatures

Temperature differences in the range of 10°C can be used to inject heat to the return line of the DH system.

4.2 ECONOMIC VIABILITY

The economical assessment of DH connected ST system is studied against several benchmark cases (natural gas boilers, electric heaters etc.). Investment and operational costs are calculated and the economic performance of the system is calculated over the service life of the system.

Investment and operational costs have been calculated for the cases under review. Investment costs cover the equipment and installation costs of each system. Representative HVAC systems for multi-storey buildings have been used and their cost normalised per kW. Data has been taken from (Precio centro Guadalajara, 2018) and from (Tarifa de precios solar térmica Salvador Escoda, 2018).

Technology	Material installation costs (€/kW)
Natural gas boiler	85
Joule heater	5
Ground source heat pump	692
Unglazed collector without DH	915
Unglazed collector with DH	608

TABLE 1 Installation cost per unit of power for different technologies.

In Table 2, the breakdown of the investment costs is presented.

Concept	Unitary cost (€/unit)	Quantity	Total €
Solar Collector RK // ALPIN RKM 2001 $2m^2$	305	120	36630 €
Support assembly for façades // SFV-AR	120	120	14400 €
Valves and other installation materials	---	---	4041 €
Workforce costs	---	---	7251€
Total	---	---	62023 €

TABLE 2 Cost estimation for ST installation. Source: Tarifa de precios solar térmica Salvador Escoda [Salvador Escoda solar thermal price list] (2018).

Operational costs incorporate the primary energy consumed by heating systems. The cost of primary energy sources are shown in Table 3.

Primary energy	Price (€/kWh)
Natural gas	0.05
Electricity	0.14
ST	0
DH heat (UNE-EN ISO 13790:2011)	0.0685
Heat purchase (estimated 70% of DH heat cost) (UNE-EN ISO 13790:2011)	0.04795

TABLE 3 Prices for primary sources (2016).

The cost of DH has been obtained from the commercial price of heat in the DH network in Paris, specifically; data has been obtained from (Tarifs de Vente CPCU, 2016), which is one of the largest networks in EU. As for the DH cases, it has been assumed that the heat produced by ST system could be sold to DH network at two price points: 100% of heat price produced in DH and 70% of the heat price produced in DH. This is simply a consideration in order to simulate an ideal case, as well as a more realistic one.

Investment and operational costs of all alternative systems studied are recorded in Fig. 7.

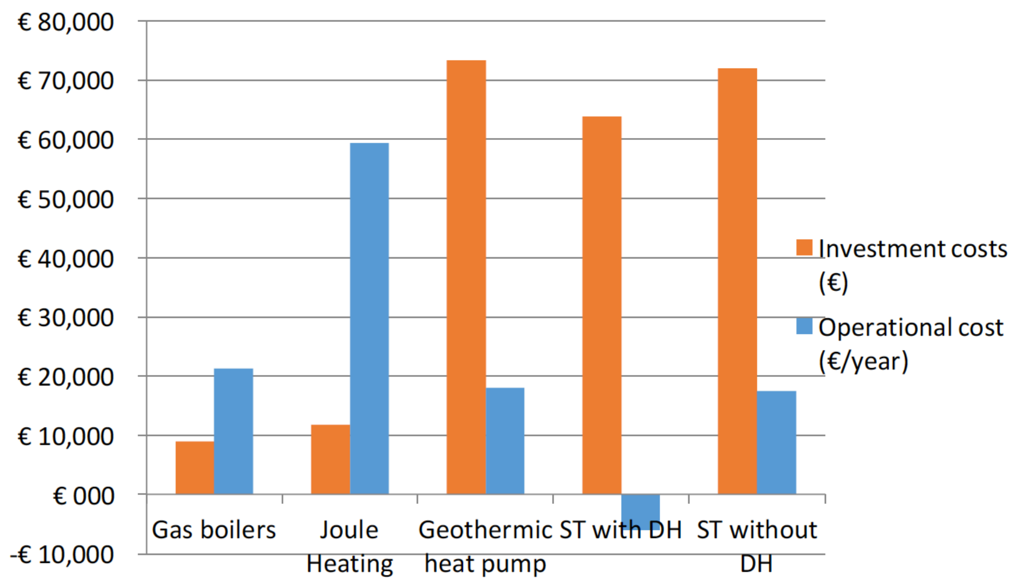

FIG. 7 Initial investment and operational costs for each technology

The case of the ST system coupled with DH has negative operational costs. For the calculation of such operational costs, it has been considered that all of the heat demand from the building is obtained from the DH supply line and the heat produced by the ST is, in its entirely, sold to DH. In this way, general data used for these calculations is recorded in Table 4.

Heat load (SH+DHW) (kWh/year)	424040
Solar production (kWh/year)	138196
Income from ST 70% (€/year)	9466
Income from ST 100% (€/year)	6626

TABLE 4 Operational cost overview

It is clearly seen that both ST systems, with and without the DH network, require a larger initial investment than typical natural gas boilers or electrical heaters. If a DH network is available, the possibility to deliver excess heat to the DH offsets the cost of heat purchased in winter periods. This results in negative operational costs. The income from heat sold to DH is higher than the cost of heat purchases from the DH network.

The evolution of the cumulative cost of each of the technologies is shown in Fig. 8. Natural gas boilers have been taken as a reference, thus, the accumulated differential cost against this technology is provided. The case of Joule heating has been removed due to its clearly anti-economic performance and in order to see the cost comparison in more detail. For the purposes of calculation in Fig. 8, the interest rate has not been considered.

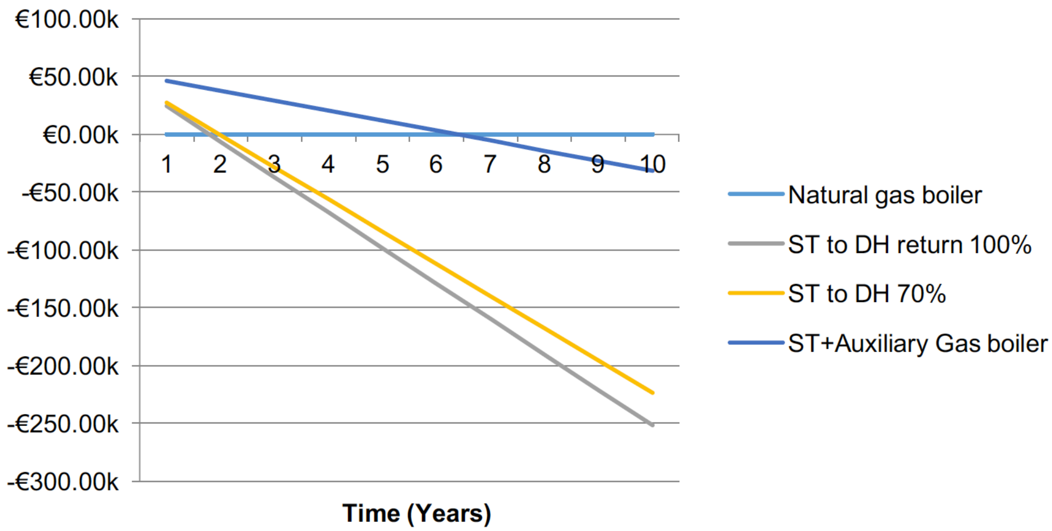

FIG. 8 Cost evolution for different technologies, with Gas boiler as reference

From Fig. 8, it is resolved that ST connected to DH return line shows better economic performance than conventional gas boilers when the second year has passed.

Table 5 presents the return of investment (ROI) for DH-connected ST façades for various interest rates. Interest rates of 5% and 10% are considered.

	ST to DH return 100%	ST to DH 70%
ROI (i = 5%)	5.554	6.858
ROI (i = 10%)	5.097	5.853

TABLE 5 Return of Investment for cases where DH is installed (years)

5 DISCUSSION

In this work the possibility to incorporate unglazed solar thermal collectors in the context of DH is studied.

The economic metrics of the presented case study show good feasibility, with ROIs in the range of 5-6 years. In this context, it is crucial to understand that heat purchase agreements need to be defined at a DH scale. These agreements substantially affect the economic metrics. In the presented study, the payback period is reduced by 1-2 years when heat purchase price is reduced to 70%.

Considering the data presented in Fig. 8, the connection to DH substantially improves the economic metrics of the ST systems, with payback periods reduced from 6-7 years to ~2 years.

Although the ST collector field incorporates relevant capital costs for the installation of the ST system, the connection to the DH avoids the need for large heat production systems to be installed for back-up, through reducing investments in auxiliaries, and reducing operational costs.

The main problem that may be faced by these installations is the capacity of the DH return line to absorb heat from ST when there are lots of distributed systems connected to them. Although, in actuality, this problem does not exist due to the development situation, in the future it will need to be taken into account to avoid the collapse of the DH network.

6 CONCLUSION & FURTHER WORK

This paper has studied the technical and economic feasibility for the integration of unglazed ST collectors in buildings, and its connection to DH infrastructure.

The presented solution relies on the DH in order to balance excess heat production and to supply energy in periods without local production. Overall, DH-connected ST seems to be a promising solution, as it pays back in the most favourable case within ~2 years when compared to traditional heating solutions.

With proven performance levels at collector level, and several standalone installations, the adaptation of ST into DH applications needs to be undertaken.

This activity will be carried out within the EU h2020 project RELaTED (2017). Within this project, among other activities, an unglazed ST system will be adapted for DH operation, and tested under a controlled test environment in the north of Spain. This same system will be integrated in up to 4 DH networks across Europe.

Acknowledgements

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