# “Building integration of domestic solar combi-systems: the importance of managing the distribution pipework”


## Abstract

This paper examines the inextricable link between the performance of solar combi-systems coupled with under-floor radiant heating and the architectural design of buildings where such systems may be used. It focuses on the impact of building fabric, area and rooms’ layout on both the system‘s performance and thermal comfort. The building integration of the distribution pipework is sensitively examined through an experimental analysis of a case study; a residence in South Europe, using dynamic thermal simulation and numerical modeling. It is found that pipe losses - regarded both as energy wastage and heat gains to the space - can be significant but also controlled if the pipe network is carefully planned. The results show that collector loop losses can be comparable to tank losses for most of the year or even higher in some months, and that the management of the collector loop piping length can be more effective in controlling these losses than improving the pipes’ insulation. The analysis further shows that there are times when distribution losses have the potential to cause noticeable local overheating e.g. long piping length or piping route passing through narrow spaces like corridors and lobbies.


| **Nomenclature** |
|---|
| CL collector loop |
| HL heating loop |
| DHW domestic hot water |
| UFRH under-floor radiant heating |
| Tb base temperature ($^0$C) |
| Tc comfort temperature / thermostat setting ($^0$C) |
| Qs solar gains (W) |
| Qo Gains from occupants (W) |
| Qi Internal Gains from lighting and appliances (W) |
| N air changes per hour (ACH) |
| V Volume ($m^3$) |
| A surface area ($m^2$) |
| f solar fraction |
| Eh Average daily energy for heating |
| Edhw Average daily energy for domestic hot water |
| n coefficient of solar utilization |
| Id Average daily radiation on collector |
| $\lambda$ thermal conductivity of insulation (W/mK) |
| Ln natural logarithm |
| Dwd the external diameter of the pipe with insulation (mm) |
| Dpipe the external diameter of the pipe (mm) |
| Tw water temperature ($^o$C) |

### 1.1 Introduction

This study examines the importance of managing the distribution pipework of both the heat collection and delivery loops (from hereafter CL and HL respectively) in solar combi-systems. It presents a quantitative exploration of distribution losses for small-scale arrangements, in a domestic scenario in Greece, focusing on contemporary low energy buildings where these effects are likely to be more significant. It assumes a typical set up of a solar combi-system coupled to an under-floor radiant heating (UFRH) system. Such a low-grade heat delivery system can enhance the system’s efficiency [1, 2, 3, 4] and

thus limit reliance on the auxiliary heater [5, 6]. The solar fraction of these systems can range from 10% to 100%, depending on the solar collectors and heat store size, the space heating, DHW demand, as well as on weather conditions [7].

Numerical simulation and two software tools, *HTB2* [8] and *T*SOL* [9], are employed. The results of the analyses presented are specific to the conditions and the scenarios assumed in these analyses. However the method employed could be further applied for studying these effects in a different climatic context, reference building, solar combi-system type and/or HL and CL variations.

**1.2 Background**

A typical solar combi-system comprises of solar collectors, one or more water tanks (T) to store the energy yield, an auxiliary heating source, a heat delivery system (often UFRH) and controls [1]. The examination of the distribution pipework is one of the many aspects of building integration of solar combi-systems and one that has not been adequately studied to date. The research community acknowledges that discrepancies in the design of solar combi-systems, such as those resulting from oversizing the system [10, 11], have often a greater impact on performance than installing more technologically advanced and expensive solar collectors [12]. Apart from the visual impact of solar thermal systems on the architectural identity of the building [13, 14, 15, 16, 17, 18, 19], appropriate integration can also minimize heat losses, as the collectors loop's pipework is not exposed [11] and the cost is reduced by replacing conventional building elements [11, 16, 20, 21]. The solar collector's positioning, orientation and inclination also defines the energy yield. Especially in the case of solar combi-systems a steep inclination of solar collectors may be beneficial in avoiding stagnation during summer, whilst maximising the solar yield during the heating period [22].

Previous studies have examined the effects of other building-related aspects affecting system performance such as the size of the heated zones, the building form and layout that influence the performance of the heat delivery system [5, 23, 24, 25, 26]. Such functional restrictions define the number and placement of the manifolds of the UFRH. In buildings with large number of zones or complex layouts, problems with non-uniform water flow rates can lead to uneven heat transmission. The longer the under-floor circuit in each zone, the higher the water resistance in the loop and the more significant the decrease of the water flow rate to the heated space [24, 25]. The presence of furniture has been shown to further affect the heat output of the system [26] and therefore it is advised that the pipework is not embedded under bathroom and kitchen equipment or areas where carpets will be placed [5].

Space availability and other building constraints can be decisive factors in sizing the thermal store and positioning the boiler room [10, 27]. The required water store size can be significant, commonly up to $3m^3$, and therefore deciding on its location within the building can be a challenge [11]. Compact versions of such systems, with consequently limited spatial demands and/or reduced hydraulic connections, not only result to lower capital costs but may also minimise heat losses [11, 28]. The location of the water store determines the distribution piping length from solar collectors to the store (Collector Loop) and from the store to the manifolds of the UFRH (Heating Loop). Therefore, the boiler room and especially the water store are key factors for the integration of the piping network into the building. To reduce distribution losses and optimize performance, pipes should be well-insulated [29]. Designing for shorter pipes by placing, for example, the boiler room in the attic to be close to the collector arrangement could help reduce cost and heat losses through the distribution pipes [11]. If the manifolds are located away from the heated zone and the distribution pipes pass through small spaces such as corridors, local overheating may occur [5]. The fact that pipe loops might affect the performance of the system has therefore been discussed in the literature. There is however inadequate quantitative evidence of how significant their role is. This study focuses on this aspect alone, aiming to provide a tangible answer to this question, by studying also the relative effect of these pipe losses to the spaces' energy balance and thus their contribution to localised overheating. The findings are expected to be of value to build environment professionals involved in the design of buildings that use solar combi-systems.

## 2.0 Methodology

### 2.1 Context and reference case

Greece can considerably benefit from the exploitation of solar energy [30, 31, 32]. By 1999, the country had the highest capacity of installed solar collector per capita in Europe, due to the widespread of 'thermosyphon' solar water heating systems [33]. Yet, for the last few decades Greek residences rely on imported fossil fuels to cover 70% of their energy needs i.e. oil or gas for space heating and domestic hot water (DHW), as well as electricity for cooling [1, 30]. Around 69% of the total residential energy needs account for space heating and 7% for hot water production [34], hence the potential of energy savings through the use of solar thermal combi-systems appears significant. Although there is limited data on actual solar combi-system installations in this context, performance appears promising [35, 36].

For this study the reference building is a typical residence, assumed to be at a suburban area of Athens to represent a case with no overshadowing risks. As illustrated in Figure 1, it is a single floor, detached house of 71 $m^2$ overall floor area, made of concrete and brickwork and a pitched roof covered with ceramic tiles, as in typical examples in this region [37, 38]. It is occupied by three adults and has four separate rooms [39].

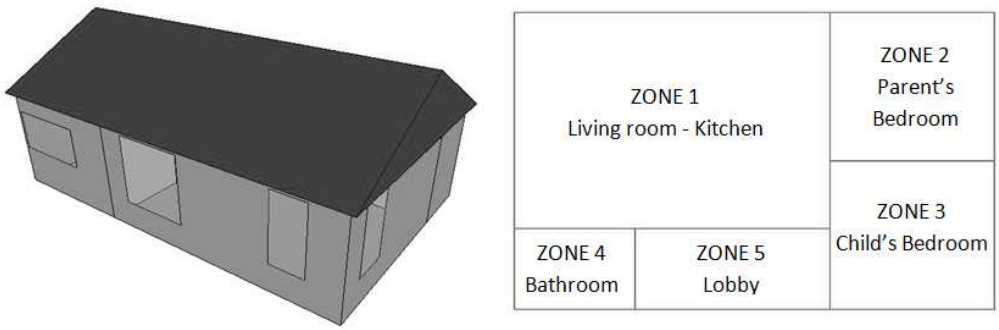


**Figure 1:** Perspective view of the reference building (left) and zonal layout (right)

The examined solar combi-system is shown in Figure 2. The simulation model used in the analysis presented is from the library of systems of the software employed (*T*SOL expert 4.5,* as discussed in 2.2). The *Feuron Combination Tank system* consists of a flat-plate collector, a store and an auxiliary heat source. The water store is a certified *Feuron TOPSOL 750/220* combined storage unit; a compact design that includes a buffer storage unit and a drinking water heater, eliminating space requirements and installation work for additional hot water elements [40]. The solar combi-system type was selected due to its similarities with systems previously examined for Greece or countries with analogous climatic conditions i.e. system #3a (used in South France) of TASK 26 of the International Energy Agency Solar Heating and Cooling programme [41], system #9 (used in Italy) of the Altener program [42] and system #A5 previously examined in the Greek context [36].

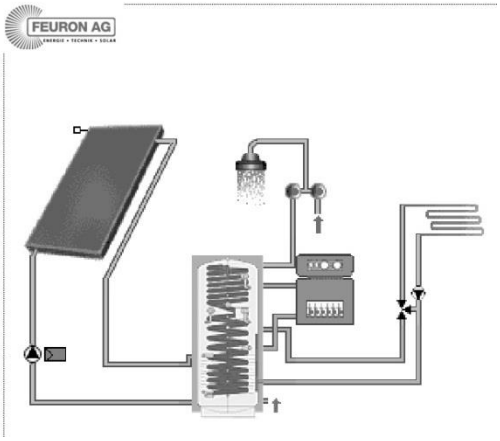


**Figure 2:** Hydraylic scheme of the selected solar combisystem [9]

## 2.2 Modelling

The software tool *T*SOL expert 4.5* [9] is used to model the performance of the solar combi-system in the reference building. The software is simple to use for examining the performance of solar combi-systems in buildings, as it allows for analyzing system performance via a user-friendly interface. The software comes with a library of systems that allows users to set up models and run simulations without necessarily getting into the details of the system modelling, although all system parameters can be easily modified if needed. The solar combi-system model used in this analysis is from the software's library of systems and has been previously validated and calibrated by the Institute of Thermodynamics and Heat Technology (ITW) of the University of Stuttgart using actual monitored data [43].

*T*SOL* treats the building as a single zone and is therefore unable to consider any architectural design complexities. To overcome this limitation, dynamic simulation of the thermal energy performance of the reference building is also conducted using the software *HTB2* [8] and the same weather data file used in the *T*SOL* analysis [44]. Unlike *T*SOL*, *HTB2* is able to estimate a building's thermal response - in terms of internal air and radiant temperatures' fluctuations - to the building geometry and fabric, the prevailing weather conditions, heating and cooling requirements, internal heat gains and occupancy schedules [45]. The validity of *HTB2* results has been previously tested for several multi-zone heat transfer scenarios with satisfactory outcomes through diagnostic trials, using the methodology suggested by the International Energy Agency (IEA BESTEST) [46]

- Heating requirement

Table 1 presents all the input data used to model the reference building in *HTB2*, in compliance with the Regulations of Energy Performance of Buildings of Greece (K.EN.A.K) [47]. The ventilation rate is assumed to be constant during the day, whilst occupants are considered to be absent during working hours 09:00-17:00, as illustrated in Figure 3. To estimate the heating requirement in *T*SOL*, the peak heating load is required as input. As the peak heating load is formerly calculated in *HTB2* considering all internal heat gains, these gains are considered as zero in the *T*SOL* model as recommended [48].

| HTB2 Software Tool - input data | U (W/m²K) | A (m²) | UA (W/K) | | Zonal Breakdown of Qo, Qi (W) and Ventilation Rate (m3/h) | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
| Roof | 0.45 | 94.1 | - | | | | | |
| External Walls | 0.48 | 70.9 | 45.1 | People (no) | 3 | 2 | 1 | - |
| Ceiling | 2.56 | 70.9 | - | Ventiltion (m³/h) | 45 | 30 | 15 | - |
| Soffit | 0.30 | 70.9 | 21.3 | Qo (W) | 240 | 160 | 80 | - |
| Ground Floor | 0.88 | 70.9 | 62.4 | | | | | |
| Internal Walls | 2.47 | - | - | Lighting (W) | 102,87 | 4.93 | 4.93 | 0.97 |
| Windows | 2.70 | 14.1 | 38.1 | Appliances (W) | 57.15 | 2.74 | 2.74 | 0.54 |
| Doors | 2.31 | 2.2 | 5.1 | Qi (W) | 160.02 | 7.67 | 7.67 | 1.51 |

**Table 1:** Modeling Specification of the Reference case
where:
U is the U-Value in W/m² K,
A is area in m²,
Qo is the Occupants' gains in W and
Qi is the Internal Gains from lighting and appliances in W

*Soffit is considered the 'sum' of the ceiling, the air occupying the space of the attic and the roof

Values produced in HTB2 | Values recommended in K.EN.A.K. [47]

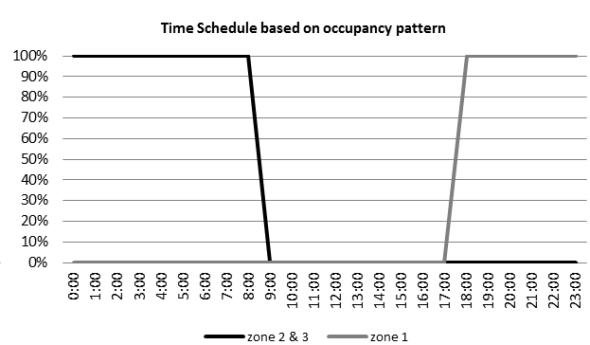


**Figure 3:** Daily schedules for each zone

For the estimation of the heating demand, *T*SOL* also asks for the base temperature (*Tb*) i.e. the external temperature above which there is no heating requirement, which is calculated here using the steady state heat balance as shown in *Equation A* for the coldest day of the year on 15th of January ($Tb_1$ = 14,3 °C). As the environmental profile during that day may not be indicative, *Equation A* is used for a second time for the typical day of January, the coldest month, ($Tb_2$ = 16.2 °C). Then, the two values are averaged (*Tb* = 15.3 °C) and the average value is used as input in *T*SOL*. The resulting annual heating requirement in *T*SOL* (50.8 kwh/m$^2$) is found to be in good agreement with the one produced in *HTB2* (50.9 kwh/m$^2$). The agreement in the calculation of whole building heating requirement between the two methods indicates that the two methods can be safely used together for the purposes of this study. Further to this the predicted heating requirement is found to be within the range presented by a relevant study for this climatic region[1] [49]

*Equation A:* $Tb = Tc - [(Qs_1 + Qo + Qi)] / \Sigma UA + NV/3)$, (Table 2)

| | | | | | | Tb1 | Tb2 |
|---|---|---|---|---|---|---|---|
| Tc (°C) | Qo (°C) | Qi (°C) | ΣUA (W/K) | N (ACH) | V (m$^3$) | $Qs_1$ (w) | $Qs_2$ (w) |
| 20 | 160.1 | 264.8 | 172 | 0.13 | 239 | 612.5 | 263.3 |
| | | | | | | 14.3 | 16.2 |

Values produced in HTB2 Values recommended in K.EN.A.K. [47]

**Table 2**: Input data for Equation A
Where *Tb* is the base temperature,
*Tc* the comfort temperature in °C,
*Qs* the solar gains in W,
*Qo* the occupant's gains in W,
*Qi* the internal heat gains from lighting and appliances in W,
*ΣUA* the sum of the U-Value multiplied with the area of the building elements in W/K,
*N* the air changes per hour (ACH) and,
*V* the volume of the building in m$^3$

- Solar collector's surface area

The solar collector's tilt angle is taken as equal to the latitude plus 15 °C, as suggested in K.EN.AK [50] for systems sized for winter use. The solar collector's surface area was estimated using *Equation B.* As shown in Table 3, the aim is to achieve a solar fraction of 50%, which is at the lower end of the range expected for optimum integration of solar collectors facing the Equator [22].

*Equation B: Area of solar collectors* ($A_{SC}$) $= f * (Eh + Edhw) / n * Id = 10m^2$ [51] (Table 3)

| | | | Average daily Energy | |
|---|---|---|---|---|
| Id (kwh/m$^2$/day) | f (%) | n | Eh (kwh/day) | Edhw (kwh/day) |
| 3.6 | 50 **[22]** | 0.369 | 19.9 | 6.13 |

Values produced in HTB2 Values recommended in K.EN.A.K. [47] Values produced in T*Sol after the input data recorded in Table 4

**Table 3**: Input data for *Equation B* [51]
Where *Id* is the average daily radiation in kWh/m$^2$/day,
*f* the solar fraction in %, *n* the coefficient of solar utilization,
*Eh* is the average daily energy for heating in kWh/day,
*Edhw* is the average daily energy for DHW in kWh/day

[1] The study presents annual space heating energy consumption estimates for a similar building typology, for both a 'contemporary' (post-2010) and a 'passive' construction detailing. The figures presented can only be compared against the whole building heating demand discussed here by roughly converting them to space heating demands, assuming a complete system COP at 2 and 3 respectively.

| DHW Demand | | | Desired DHW temperature | | 50 $^0$C |
|---|---|---|---|---|---|
| 50 lt/person [51] | 3 people/day | 150 lt/day | Cold Water temperature | February | 10.9 $^0$C |
| 30 lt/laundry (clothes) [51] | 2 times/week | 8.6 lt/day | | August | 25.7 $^0$C |
| 20 lt/laundry (dishes) [51] | 3 times/week | 8.6 lt/day | | | |
| Daily DHW consumption | | 167.2 lt | | | |

**Table 4**: Input data for T*Sol model, used to calculate the energy required to cover the DHW demand.

Values recommended in K.EN.A.K. [47, 51]

- Water tank volume

The water tank volume ($V_t$) for the system assumed is 710 lt [9]. This is at the top end of the recommended range estimated using *Equation C:* $V_t = A_{sc}*50<Volume<A_{sc}*70$ [51],

Where $A_{sc}$ is the surface area of the collectors in m$^2$ (in this case $A_{sc}$= 10 m$^2$ and thus 500lt < $V_t$<700lt).

- Piping

The collector loop (CL) and heating loop (HL) piping are assumed to be made of copper [5, 52]. *T*SOL* also requires a more detailed piping specification, including the value of Nominal Diameter (*DN*). This value relates to the water pressure drop, which has an impact on the heat transferred from the collectors to the storage [52]. It is suggested that a water velocity lower than 0.7m/s - 1m/s is achieved to avoid increased friction in the pipework, excess noise or even corrosion of the copper pipes. Therefore, a pipe Cu 18 x DN 15 [52], which results in velocity of around 0.63 m/s (as calculated in *T*SOL*), with insulation thickness of 19mm for the CL and 9mm for the HL, as recommended by K.EN.A.K [47] is assumed here. Another parameter required in *T*SOL* regarding the HL piping are the supply ($T_s$) and return ($T_r$) water temperatures. In this case 40˚C and 25˚C values are used respectively, in accordance with the software default values for the specific system and the recommended water temperature values for similar systems referred within literature [6, 53].

Table 5 summarises all the input data used in the *T*SOL* simulation. As *T*SOL* considers only CL losses [48], numerical modeling is also used here to estimate HL losses using *Equation D* as these are also required in the analysis that follows. To ensure that the way CL losses are accounted for in *T*SOL* is in agreement with the method employed here for accounting for HL losses, a sensitivity analysis of CL heat losses is performed using both the software and Equation D.

| HTB2 Software Tool - input data | | | | |
|---|---|---|---|---|
| | Heating Requirement | | | |
| | Peak Heating Load (kwh) | Tc ($^0$C) | Tb ($^0$C) | Qi + Qo (W) |
| | 2.33 | 20 | 15.3 | 0 |
| | SC's specification | | | |
| | Type | Orientation | Tilt angle | Surface area (m$^2$) |
| | Flat plate | South | 53 $^0$ | 10 |
| | DHW demand | Space Heating | | |
| | T size (lt) | type | Water temperature ($^0$C) | |
| | | | supply | return |
| | 710 | UFRH | 40 | 25 |
| | Piping Specification | | | |
| | Pipe diameter (mm) [52] | | Pipe insulation (mm) | |
| | External | Internal | Outside the building | Inside the building |
| | Cu 18 x DN 15 | 16 | 19 | 9 |

Values produced in HTB2

Values recommended in K.EN.A.K. [47, 51]

Values produced in T*Sol

Values produced in numerical formulas [50, 52]

**Table 5**: Input data in T*Sol
Where *Tc* is the comfort temperature,
*Tb* the base temperature,
*Qi* the internal gains from lighting and appliances,
*Qo* the gains from occupants,
*DHW* the domestic hot water and
*UFRH* the under-floor radiant heating system

*Equation D*: 2πλ * (Tw – Tc) / Ln (Dwd/Dpipe) [52] (Table 6)

| λ (W/mK) | Tc ($^0$C) | Dwd (mm) | Dpipe (mm) |
|---|---|---|---|
| 0.04 | 20 | 56 | 18 **[52]** |

Values recommended in K.EN.A.K. [47]

**Table 6**: Input data in *Equation D* [52],
Where *Tw* is the water temperature (from T*Sol), *Tc* is the comfort temperature in K, *λ* the thermal conductivity of insulation n W/mK, *Dwd* the external pipe diameter with insulation in mm and Dpipe the external diameter of the pipe, also in mm.

The results, illustrated in Figure 4 a-b for the 2nd April, show that when the CL is 10m or 20m one-way distance (double that for considering the return piping), the equation and the software are found to be in good agreement. Equation D is therefore used in the following analyses to estimate HL losses, with HL accounting for the piping from the water store to the manifolds of the UFRH system.

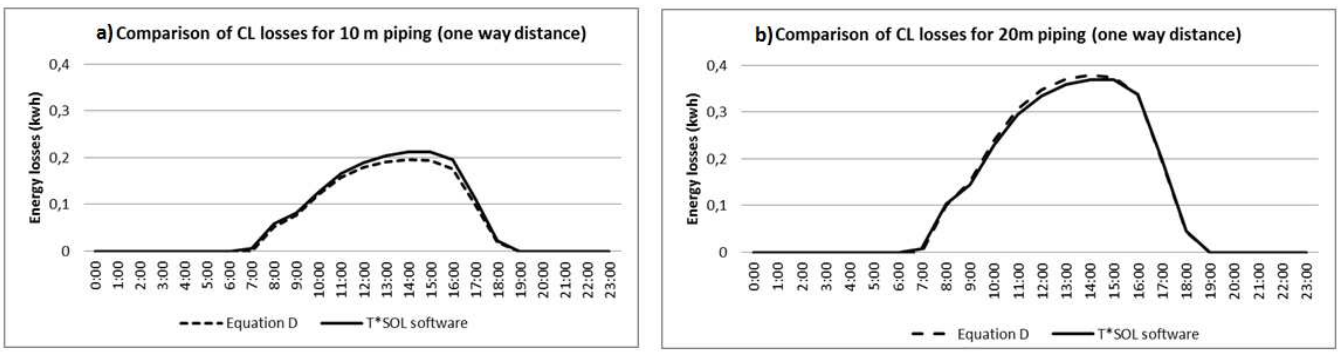


**Figure 4**: Calibration of the simulated results for different CL lengths: a) 10 m b) 20 m

### 2.3 Scenarios tested and purpose

Two sets of analyses are presented below. The first set of investigations [3.1] examine the pipe losses as energy wastage for the entire heating period. The objective is to examine both the impact of the system's losses on the useable solar energy and the proportion of those losses attributed to the piping design parameters.

The second set of investigations [3.2] examines two possible system configurations, considering two different pathways for CL and HL by altering the location of the hot water tank. The aim is to examine how the integration of the system into the building could impact on both the system performance (heat losses) and thermal comfort (potential for overheating) in the occupied spaces.

The combined results and conclusions are discussed in section 4.

## 3. Results

### 3.1 Pipe losses as wastage of energy

The first set of investigations look into the pipe losses as energy wastage for the entire heating period between October to April [47]. The objective is to examine both the impact of the system's losses on the useable solar energy and the proportion of those losses attributed to the piping design parameters.

Table 7 records the maximum energy yield (no losses considered) that the solar combi-system could theoretically achieve per month.

| | Heating Requirement | | Max. Energy Yield | Proportion of Energy Yield to Heating Requirement |
|---|---|---|---|---|
| | (kwh) | (kwh/m$^2$) | (kwh) | % |
| OCT | 66 | 0.9 | 445 | 674.2 |
| NOV | 325 | 4.6 | 412 | 126.8 |
| DEC | 658 | 9.3 | 373 | 56.7 |
| JAN | 886 | 12.5 | 475 | 53.6 |
| FEB | 779 | 11.0 | 407 | 52.3 |
| MAR | 649 | 9.2 | 442 | 68.1 |
| APR | 237 | 3.3 | 484 | 204.2 |

**Table 7:** Maximum potential share of the system if no losses are accounted (T*SOL software)

ed. In proportion, the highest reduction is noticed in October and the lowest in January. In the shoulder seasons the solar collectors do not operate at maximum efficiency as the higher ambient temperatures result in higher return water temperature to the collector's arrangement. A significant proportion of the energy loss is due to CL losses, which are comparable to losses from the water tank (T losses) during the whole heating period, and even exceeding them during October and April. Even in January, they represent 11.4% of the energy yield while T losses represent 11.2%.

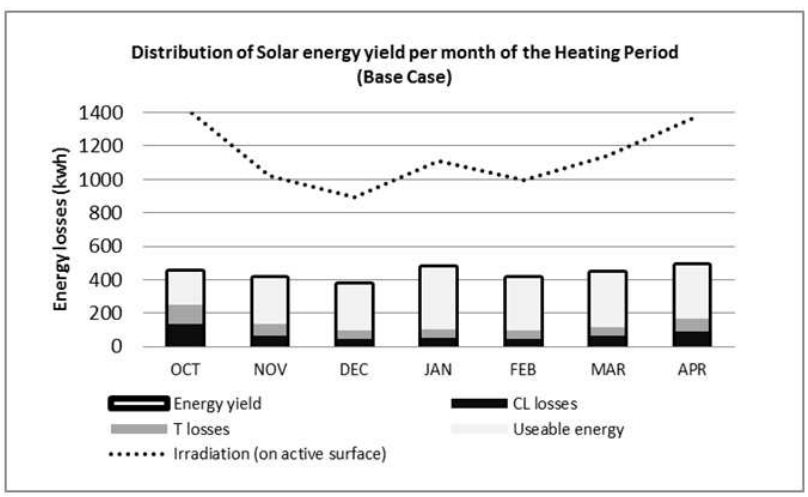


**Figure 5:** Distribution of CL and T losses and the useable solar energy for Base Case,
Where, CL losses are collector loop losses and
T losses are water tank losses (T*SOL software)

The results in Figure 5 suggest that the system's performance could considerably improve by optimising the CL's design parameters. Figures 6-7 illustrate the reduction in losses by varying CL insulation thickness and CL length (analysis done in *T*SOL*). The losses are significantly reduced with up to 19mm of insulation thickness. At this value, a 3.4% reduction of losses in relation to the energy yield is achieved (Figure 6). Furthermore, a pipe length decrease by 18m could result to a losses reduction of around 12.3% (Figure 7).

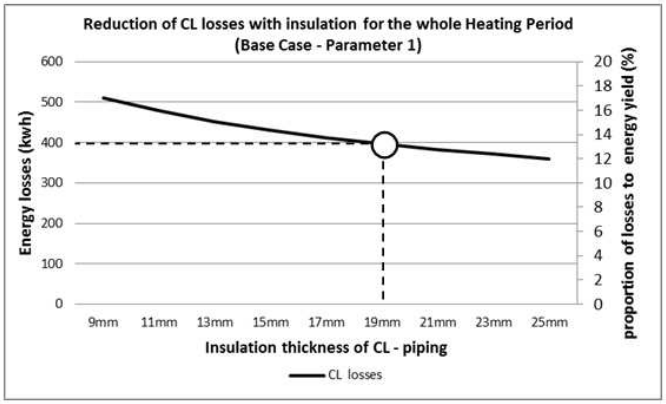


**Figure 6:** Sensitivity parameter 1: CL insulation thickness

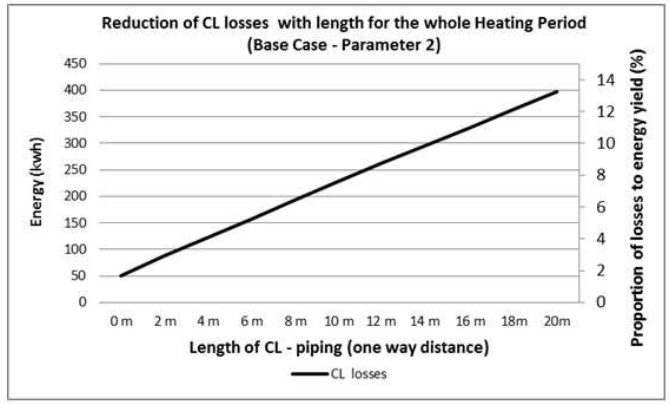


**Figure 7:** Sensitivity parameter 2: CL length

### 3.2 Pipe losses as potential heat gains

The second investigation examines two possible system configurations, considering two different pathways for CL and HL by altering the location of the hot water store. The aim is to examine how the integration of the system into the building could impact on both the system performance (heat losses) and thermal comfort (potential for overheating) in the occupied spaces.

The pipe routes examined are just indicative and they represent possible design scenarios that result in different pipe lengths. The analysis is done hourly, using a typical day for shoulder seasons rather than for winter when pipe losses would be mostly considered as beneficial heat gains to the space. April has a considerable heating demand while the 2nd of April is the day with the highest average incident daily irradiation for this month for the solar collector's tilt considered. In both configurations (Figure 8a-b) the solid line represents the CL (the piping from the solar collectors to the water store) and the dashed line represents the HL which is the piping from the water store to the manifolds of the UFRH system. Both lines represent one-way pipe length. The aim of this investigation is to compare the losses from the individual components, at first against the energy yield, and then against the maximum incidental gains from occupants. This approach helps to demonstrate the magnitude and the importance of these losses to both the system and the spaces considered (and consequently to the users of these spaces). At the next step, the investigation focuses on individual zones through which the different loops pass, by segmenting the piping path (Table 8, numbering for CL and HL piping parts corresponds to Figure 8a-b).

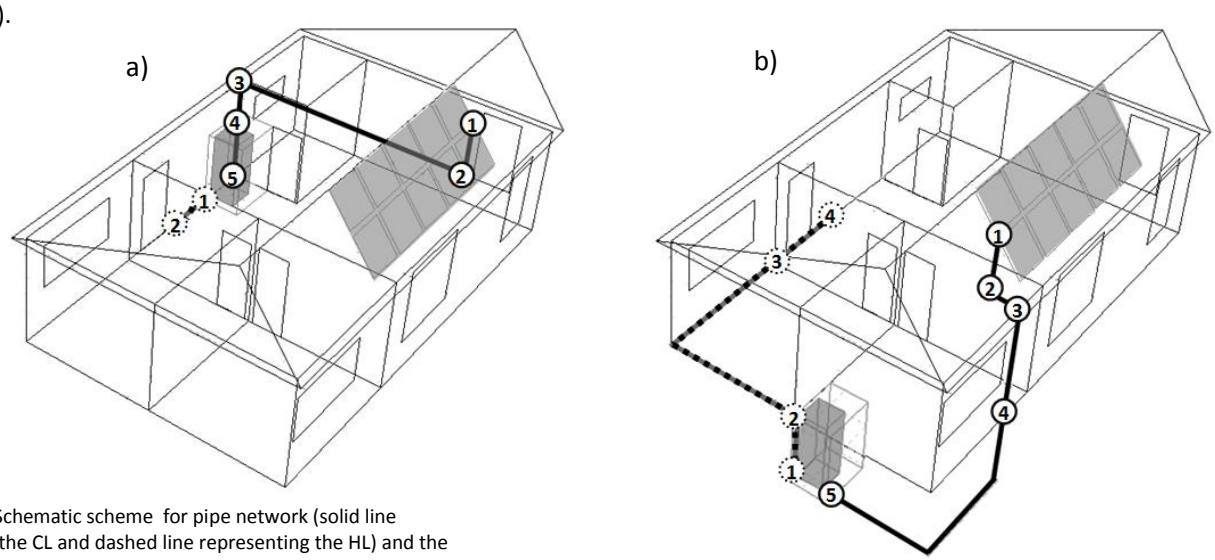


**Figure 8a-b:** Schematic scheme for pipe network (solid line representing the CL and dashed line representing the HL) and the subdivision scenarios a) Configuration 1 with the water store placed inside the heated zones (e.g. zone 5) b) Configuration 2 with the water store placed outside any heated zones (e.g. in the basement)

| CL | | | | HL | | | |
|---|---|---|---|---|---|---|---|
| Configuration 1 | | | | | | | |
| CL 1-2 | CL 2-3 | CL 3-4 | CL 4-5 | HL 1-2 | | | |
| (attic) | Zone 1+5 | Zone 1+5 | Zone 1+5 | Zone 1+5 | | | |
| Configuration 2 | | | | | | | |
| CL 1-2 | CL 2-3 | CL 3-4 | CL 4-5 | HL 1-2 | HL 2-3 | HL 3-4 | |
| (attic) | Zone 2 | Zone 2 | (basement) | (basement) | Zone 3 | Zone 1+5 | Zone 5 |

**Table 8:** Zones through which the several parts of the pipes pass,
Where CL is the collector loop and
HL the heating loop

The investigation for configurations 1&2 considers the entire distribution path from the collector array to the manifolds of the UFRH system. In both cases, there is a noticeable increase of T losses when CL losses increase (Figure 9). After their prolonged exposure to radiation, solar collectors are warmed up and that's why CL losses remain high from midday until sunset. This trend is similarly observed in both configurations, although in the second configuration the CL losses are higher due to the longer CL piping.

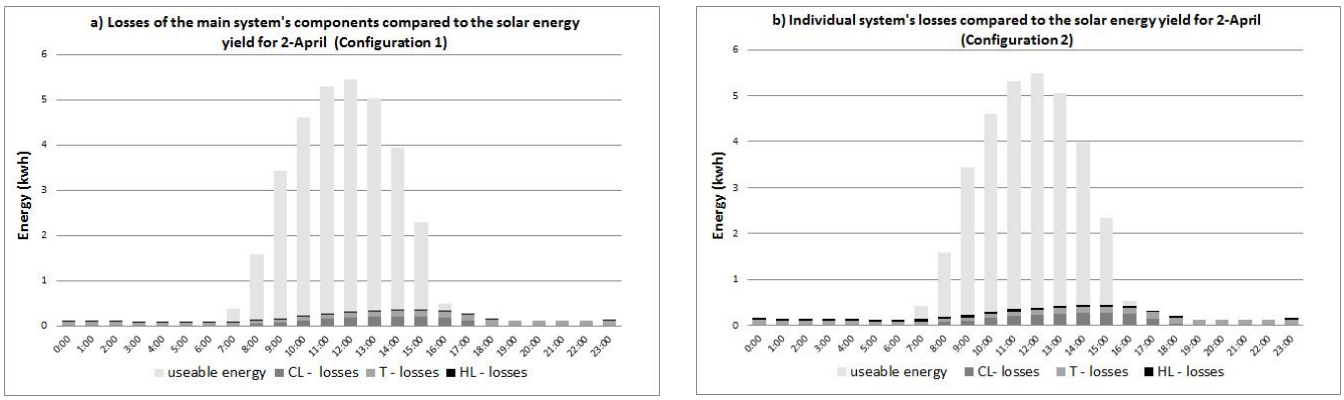


**Figure 9:** Total system's losses compare to energy yield: a) configuration 1 b) configuration 2,
Where CL losses are collector loop losses, T losses are water tank losses and HL losses are losses from the heating loop.

Although HL losses seem insignificant compared to the energy yield, they gain importance when comparing them with the occupancy gains (Figure 10 a-b). In particular, the HL of configuration 2 exhibits higher losses, due to longer HL pipe length. During the night, when CL losses are zero, HL losses, together with T losses, become significant heat gains. At the next step, the investigation focuses on the different building zones where the distribution losses (or potential gains) will be 'injected'. When the tank is placed outside the heated space (configuration 2), there are no direct T losses to the living space, but there would be significant losses from the pipes that travel longer distances to reach the manifolds of the underfloor heat delivery system or the collectors.

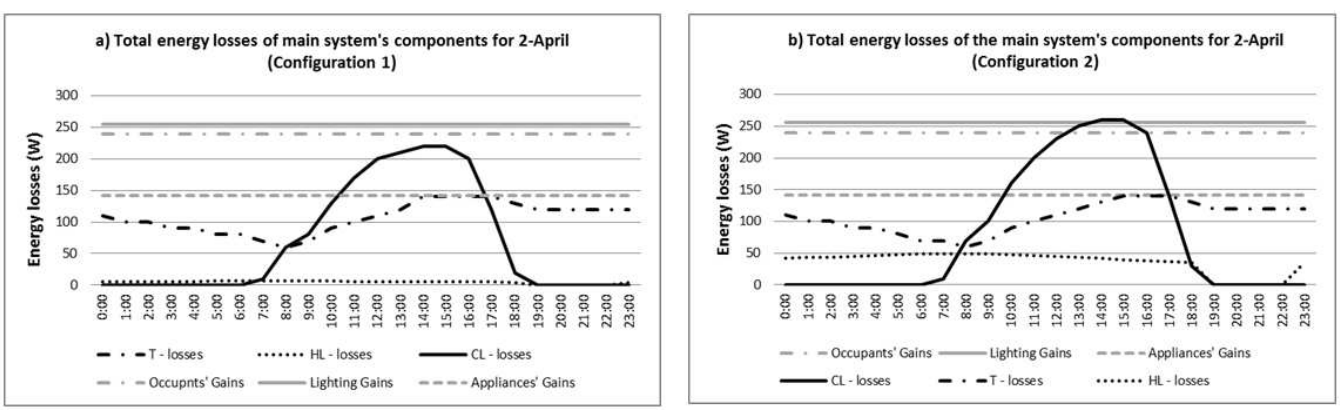


**Figure 10:** System's losses with regards to heat gains a) configuration 1 b) configuration 2
Where CL losses are collector loop losses, T losses are water tank losses and HL losses are losses from the heating loop.

In configuration 1 (Figure 11 a-b), HL 1-2 is very small and its losses are insignificant, compared to the T losses, which are 'enclosed' in the boiler room. Losses from CL 4-5 should be also considered as energy 'injected' in a more controlled environment. Similarly, losses from CL 2-3, can be either 'free' if this part passes through the ceiling and is included in a more controlled environment assuming that the pipework is separated from the living area with a suspended ceiling or placed in a non-heated zone (e.g. in the attic). Yet, in the last scenario what should also be considered is the likely higher temperature difference between the temperature of the heat delivery medium and the ambient temperature of the attic (non-heated space), causing excessive heat losses from the heat distribution network.

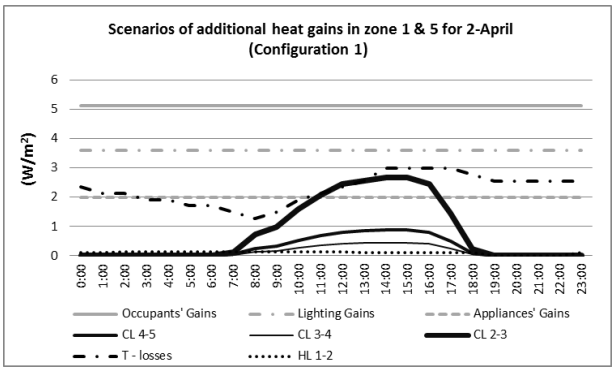


**Figure 11a:** Configuration 1: Estimation of potential heat gains in zone 1&5 Where T losses are water tank losses and CL or HL partitions are losses attributed to the specific collector or heating loop parts.

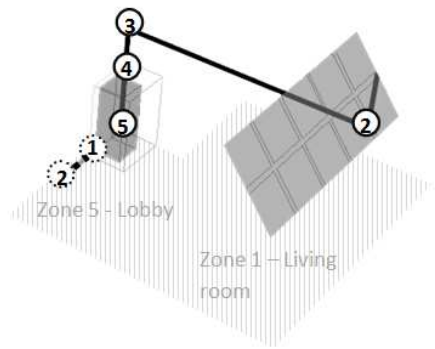


**Figure 11b:** Configuration 1: Schematic scheme for pipe network (solid line representing the CL and dashed line representing the HL) and the subdivision scenarios examined in Figure 11a

In configuration 2 (Figure 12 a-b) the CL losses are the only losses 'injected' in zone 2 (parents' bedroom), and they occur only during the sun-hours. Most of the these losses should be attributed to CL 3-4, which would definitely pass through zone 2, while losses from CL 2-3 exhibit similar potential scenarios with the CL 2-3 partition of configuration 1.

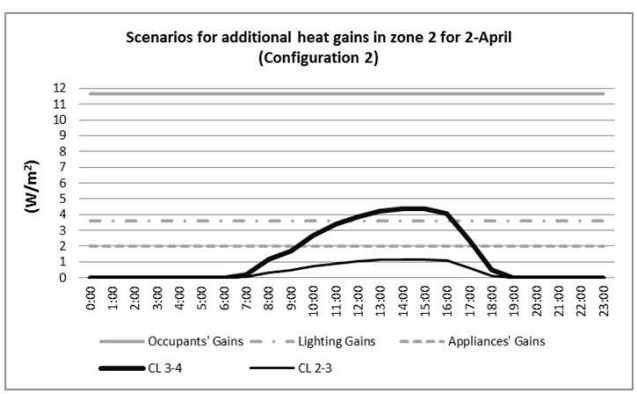


**Figure 12a:** Configuration 2: Estimation of potential heat gains in zone 2.

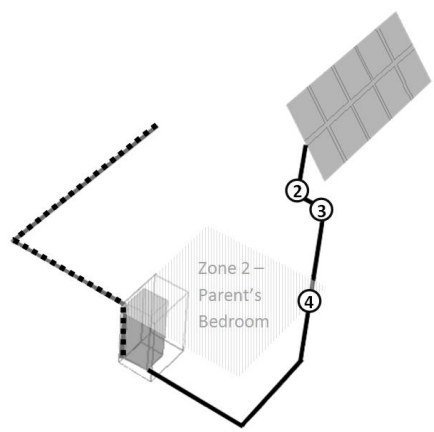


**Figure 12b:** Configuration 2: Schematic scheme for pipe network (solid line representing the CL and dashed line representing the HL) and the subdivision scenarios examined in Figure 12a

Additionally, losses from HL 2-3, 'injected' to zone 3 (children's Bedroom), equal to around one third of the occupants' gains or roughly the same as incidental gains from appliances. In other words, the potential heat gains from HL 2-3 could result to overheating, taking into account that for this space there is no heating requirement at all (Figure 13 a-b).

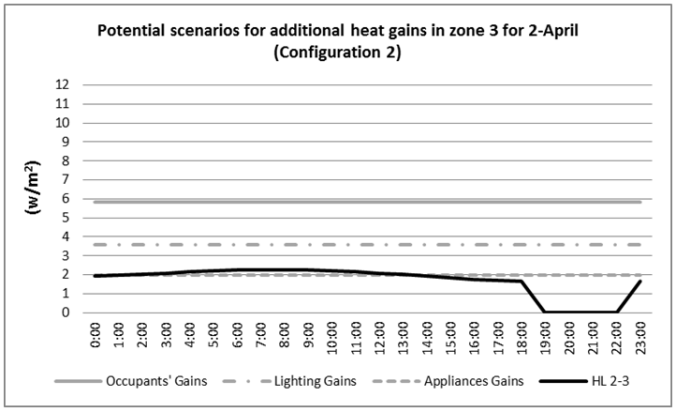


**Figure 13a:** Configuration 2: Estimation of potential heat gains in zone 3

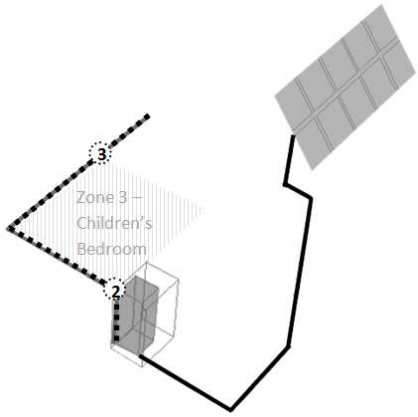


**Figure 13 b:** Configuration 1: Schematic scheme for pipe network (solid line representing the CL and dashed line representing the HL) and the subdivision scenarios examined in Figure 13a

On the other hand, if HL 3-4 losses are attributed to zone 1&5 (living room and lobby respectively) they seem insignificant (Figure 14), but if they are attributed to zone 5 (lobby), then they become more important (Figure 15-16). In this investigation the potential for causing local overheating is small, but highly depends on the heat distribution pipe length and the temperature of the heat delivery medium. In a case considering high temperature radiators, HL gains could be double and more unsteady during the day than in the UFRH assumed here.

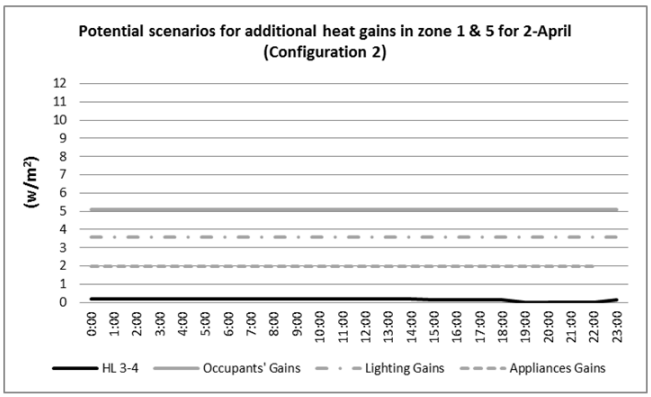


**Figure 14:** Configuration 2: Potential heat gains in zone 1 & 5

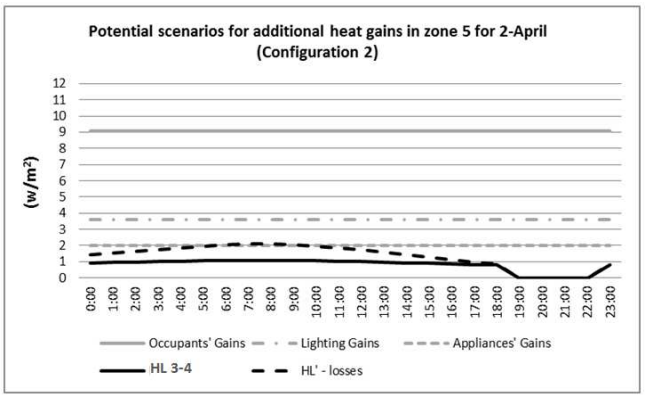


**Figure 15:** Configuration 2: Potential heat gains in zone 5

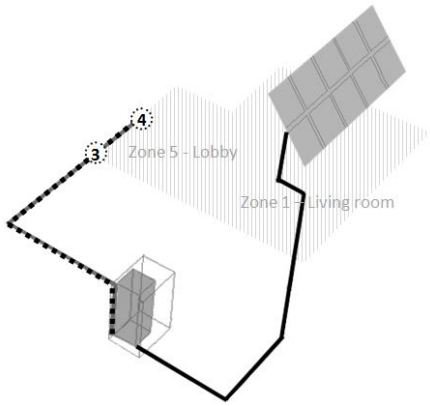


**Figure 16:** Configuration 2: Schematic scheme for pipe network (solid line representing the CL and dashed line representing the HL) and the subdivision scenarios examined in Figure 14 & Figure 15.

### 3.3 Results' discussion

In the context of a solar combi-system, pipe losses can be considered either as heat gains, beneficial in cold days but undesirable during intermediate-summer season, or as energy harvested but eventually lost. This study demonstrates that the distribution losses are often uncontrolled and should be carefully examined when sizing and designing a solar combi-system. Consequently, the integration of the pipe network is a complicated design process with several interdependent parameters that should be considered simultaneously. In the particular context studied, a significant proportion of the overall system energy loss is found to be due to CL losses, which are comparable to losses from the water tank (T losses) during the whole heating period, and even exceeding them during October and April. Furthermore the system performance is found to have the potential to be considerably improved by optimising the CL's design parameters, with the optimisation of the CL's length exhibiting a much higher potential to this end than that of the CL's insulation specification; it was shown that increasing the insulation thickness from 9mm to 19mm (Figure 6) could result to around one third of the heat loss reduction that would be achieved by decreasing the CL length from 20m to 2m (Figure 7). This study also demonstrates that the heat losses attributed to the distribution pipework may be comparable to other incidental gains experienced internally, such as those resulting from occupancy and equipment use. Depending on the room size, these losses could have an effect on thermal comfort perception in these spaces, contributing to overheating.

Furthermore the results give rise to the following considerations:

- Appropriate sizing of the system is essential from an economical perspective. However it is unavoidable that during periods of high heating energy requirement the solar energy will be, as expected, insufficient, but during periods with low heating requirement there will be a surplus. For the latter case this means that the CL water temperatures will be high, causing overheating because of the high heat gains and the low heating demand. Further to this the system will have to meet a relatively unchangeable DHW demand throughout the year, so undesirable losses or gains may be expected even outside the heating season (Table 7, Figure 5).
- Controlling HL losses needs to be by taking into account some crucial time intervals such as in the early morning when there is low energy yield. In such a case, if the heating requirement is high eg when a lower setback setting applies at night time, HL losses occurring when the pipework goes through unheated spaces can considerably affect the system efficiency. If the heating requirement is low it may cause local overheating (Figure 8).
- Careful positioning of the tank and the boiler room is required as it may result to considerable 24-hour losses. During the day, T losses (as CL losses) increase with the increase of the energy yield and during the night, T losses are likely to be the dominant losses of the system (Figure 9).
- Optimizing the distribution path is important for controlling the CL losses and avoiding the risk for high undesirable heat gains as they arise during day, when there is available solar radiation and high ambient temperature (Figure 10-12).
- Optimizing the distribution path is also essential for controlling HL losses as they can also become significant in extreme cases when for example the length of the piping is big and the space that the piping passes is small like a lobby or a corridor (Figure 13-16).
- The system examined included a low-grade space heating system. In the case of a high-grade space heating system, these effects can be expected to be more pronounced and more fluctuant, contributing significantly to exergy reductions for the system.

## 4 Conclusions

The findings presented here demonstrate how significant the impact of the management of the distribution pipework is with regard to both the useable energy (an aspect concerning system's performance) and the heat gains (an aspect concerning thermal comfort). Long CL pipes may result in a considerable reduction of the useable solar energy. HL losses can be equal or more significant than CL losses in certain circumstances e.g. significant HL length, hourly intervals with low

insolation levels or during night hours. Regarding thermal comfort, the different scenarios of distribution pathways considered here show that heat gains from both the CL and HL can be considerably decreased if the piping route is carefully designed.

Building integration affects the performance of a solar combi-system in all stages of the system's operation; from the collection, to the storage and the distribution of the heat to the living spaces. The heat transfer between these stages is also affected by building layout and interior space. This study signifies the importance of integrating the distribution pipe network in accordance with building related issues; a fact that is well acknowledged in literature, but as proven here worth examining further.

This study presented a method for examining energy wastage and overheating effects due to design choices affecting the distribution pipework of a solar combi-system coupled to UFRH system. The method makes use of two user-friendly software tools and simple numerical simulation to provide an accurate account of these effects. It is expected that such feedback would be valuable to both architects and system designers as it could guide towards effective integration of such systems in buildings. The results are linked to the conditions described in this paper, but the method could be easily further applied by built environment professionals to study such effects in different conditions, without the need for complex modelling representation for the system considered. The method could be particularly useful in studying the integration of the system at very early stages of a building design process, maximising the potential for holistic system optimisation.

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