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Original Research Article

Analysis of the Effect of Mains Water Temperature on Energy and Economic Performance of a Flat-plate Solar Collector System

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ABSTRACT

This study evaluates how the assumed temperature of water supplied from the mains affects the energy and economic performance of a residential solar thermal system for domestic hot water preparation. The system consists of flat plate solar collectors connected to a storage tank through a lower internal heat exchanger and a natural gas boiler supplying heat through an upper internal heat exchanger. A numerical model was developed and intrinsically validated using manufacturer data and then simulated in transient conditions in TRNSYS environment. Two approaches were compared: a time-varying mains water temperature profile and a constant value equal to the mean ambient temperature. Simulations were performed for thirty four European capitals using typical meteorological data and national household gas prices. Results show that constant assumptions can overestimate annual savings and distort solar contribution indicators across climates. The study reveals that the mean difference in operation cost between the time-varying and constant mains water temperature cases among the considered locations was +36.6% for the proposed system.

KEYWORDS

Solar collector, Mains water temperature, Dynamic simulations, TRNSYS, Energy analysis, Economic analysis.

INTRODUCTION

Domestic hot water (DHW) preparation represents one of the main contributors to energy consumption in residential buildings, especially in small-scale applications where the relative share of space-heating demand has been reduced due to improved thermal insulation and efficiency standards. For this reason, solar thermal collector systems play an increasingly relevant role as a renewable technology for DHW production, particularly those based on flat-plate solar collectors coupled with stratified storage tanks and assisted by auxiliary natural gas boilers to guarantee continuity of service throughout the year [1]–[3]. The overall performance of such systems depends on several boundary conditions and operating parameters, including climatic conditions, solar resource availability, user demand profiles, thermal storage configuration, and auxiliary heater operation [4]–[6]. When long-term performance evaluations or cross-climate comparative analyses are carried out, the reliability of these performance indicators is strongly influenced by the adopted modelling assumptions.

Among the parameters affecting DHW production, the temperature of the cold water supplied from the mains constitutes a fundamental but often simplified boundary condition.

From a thermodynamic standpoint, the cold-water temperature determines the required temperature rise to reach the delivery setpoint, and thus directly influences the thermal energy associated with each draw-off event [4], [7], [8]. For a given DHW demand profile, the energy required for water heating scales with the difference between the outlet and inlet temperatures; therefore, any systematic deviation in the assumed mains water temperature propagates into the estimation of auxiliary energy use, solar fraction, primary energy savings, and related economic indicators. Nevertheless, in many simulation studies, the cold-water inlet temperature is still treated as a constant or approximated using simplified correlations based on annual average air or ground temperatures.

In practice, mains water temperature is influenced by multiple factors such as seasonal ground temperature variations, pipe burial depth, distribution network configuration, and water residence time in the piping system [9]–[11]. Experimental investigations have shown that the cold-water temperature supplied to DHW systems generally follows a pronounced seasonal pattern, with significantly lower temperatures in winter and higher values in summer, particularly in continental and northern climates [9], [12]. In [13] the authors experimentally measured the temperature of cold water entering solar storage tanks and reported seasonal variations exceeding 15 K across the year. Similar findings were observed in monitored DHW installations, where fluctuations in inlet water temperature influenced auxiliary boiler operation and the distribution of energy consumption over the heating season [14]. High-resolution measurements further indicated that short-term temperature transients may occur during draw-off events due to thermal interactions inside indoor plumbing, suggesting that the inlet condition may, in some cases, deviate from a purely quasi-steady assumption [15], [16].

In addition to experimental works, several numerical and simulation-based studies have underlined the relevance of accurately representing mains water temperature when assessing solar thermal DHW performance. In particular, Araújo et al. introduced time-varying cold-water temperature models within transient simulations of solar water heating systems and demonstrated that the use of constant temperature assumptions may lead to measurable deviations in auxiliary energy consumption and system efficiency indicators [4], [5]. Fernandes et al. analysed the performance of solar DHW systems with adsorption storage modules across different climatic locations and highlighted that the seasonal evolution of mains water temperature affects solar utilisation and tank stratification dynamics [17]. Hybrid DHW system analyses have similarly confirmed that inlet cold-water temperature influences auxiliary boiler cycling behaviour and overall energy balances [18].

Related research in DHW demand characterisation and system modelling also supports the importance of accounting for realistic cold-water temperature values. Reviews of domestic hot water consumption profiles have indicated that the conversion of draw volumes into thermal energy demand depends on an accurate definition of inlet temperature, which is often oversimplified in building energy simulations [19]–[21]. Other works have shown that DHW-related variables, including cold-water temperature, exhibit seasonal correlations with outdoor climatic conditions, thereby linking climatic variability to both user demand and system performance [22]–[24]. Sensitivity analyses and optimal sizing studies have identified mains water temperature as one of the parameters with the highest impact on heating energy demand and system performance metrics [25], [26]. Furthermore, studies concerning demand-response control and DHW scheduling strategies have shown that cold-water temperature affects storage operation, comfort margins, and thermal load shifting potential [27]–[29].

Although these contributions collectively confirm the importance of mains water temperature in DHW system energy assessment, most of the available studies are limited to individual buildings or single climatic regions. Large-scale comparative evaluations often retain simplified or mains constant temperature assumptions to preserve methodological uniformity across locations [2], [6], [30]. As a consequence, the effect of replacing realistic time-varying mains water temperature profiles with constant temperature assumptions on the energy and economic performance of traditional flat-plate collector systems has not yet been systematically quantified in a multi-country context.

In this framework, the present study examines the influence of mains water temperature modelling on the energy and economic performance of a conventional solar thermal DHW system for residential applications. The analysed system consists of flat-plate solar thermal collectors transferring heat to a storage tank through an internal heat exchanger located in the lower part of the tank, while auxiliary energy for DHW production is supplied by a natural gas boiler connected to a second internal heat exchanger located in the upper part of the tank. Cold mains water is supplied directly to the bottom of the tank, making the inlet condition particularly relevant for tank stratification and for the operating temperature levels of both the solar and auxiliary heat exchangers. The investigation is carried out by means of a validated numerical model developed in TRNSYS, based on manufacturer data and realistic operating conditions.

Two operating scenarios are considered: (i) a time-variable mains water temperature profile representative of each selected location, and (ii) a mains constant water temperature equal to the mean annual ambient temperature of that location. The analysis is extended to 34 European countries by adopting climatic data from the PVGIS database for each capital city and residential natural gas prices from Eurostat for the associated economic assessment. The novelty of this work lies in the Europe-wide comparative evaluation of traditional flat-plate solar DHW systems under dynamic and mains constant water temperature assumptions, providing a systematic quantification of their impact on solar fraction, auxiliary gas consumption, and DHW production costs. The obtained results aim to support more accurate performance assessments and to contribute to improved modelling practices for solar thermal DHW systems across different European climatic conditions.

METHODOLOGY

In this section the layout of the solar collector system used to carry out the analysis, the numerical modelling developed in TRNSYS environment and the adopted case study have been presented in dedicated subsections.

Layout and Operation Strategy of the System

In the proposed solar-assisted domestic hot water system (Figure 1), thermal energy is primarily harvested by a flat-plate solar collector and transferred to a stratified storage tank through an internal heat exchanger located in the lower part of the tank, with circulation ensured by a dedicated pump in a closed solar-fluid loop.

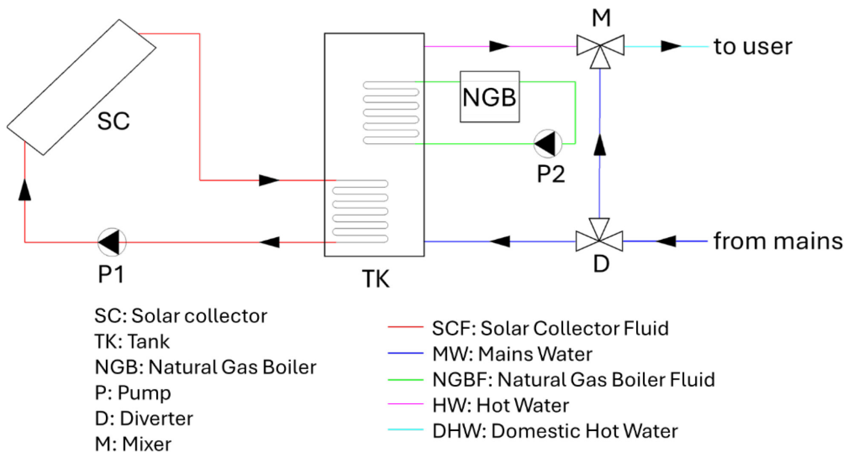

Figure 1. Layout of the solar collector system: main components and fluid loops

In order to ensure domestic hot water availability under low solar energy availability, a natural gas boiler supplies auxiliary heat to a second internal heat exchanger positioned in the upper part of the tank, again via a dedicated pumped closed loop. Cold water from the mains is routed through a diverter that splits the flow between direct charging of the tank at its bottom and a branch feeding a mixer; simultaneously, hot water drawn from the top of the tank is directed to the mixer, where it is blended with mains water to deliver domestic hot water to the user at the required temperature. The proposed system layout is suitable and universal for all climates because the fluids used for heating the water are decoupled, and in this way mains water flows only inside the tank and diverter-mixer setup.

In particular, the layout under evaluation comprises multiple hydraulic circuits, identified as follows:

- SCF, Solar Collector Fluid (a mixture of 40% propylenic glycol in water), is the heat transfer fluid circulating in the solar thermal loop (between SC, P1, and the lower internal heat exchanger of TK);
- NGBF, Natural Gas Boiler Fluid (pure water), is the heat transfer fluid circulating in the auxiliary boiler loop (between NGB, P2, and the upper internal heat exchanger of TK);
- MW, Mains Water, is the cold potable water supplied from the aqueduct and routed to the system through the diverter (D);
- HW, Hot Water, is the hot water withdrawn from the upper part of the storage tank and sent to the mixer (M);
- DHW, Domestic Hot Water, is the tempered sanitary water delivered to the end user downstream of the mixer (M).

Furthermore, the system incorporates the following primary components:

- SC, Solar Collector, a flat-plate solar thermal collector providing renewable heat to the storage system;
- TK, Tank, a storage tank containing water and equipped with two internal heat exchangers:
  - A bottom coil coupled to the solar collector loop (SCF);
  - A top coil coupled to the natural gas boiler loop (NGBF).
- NGB, Natural Gas Boiler, ensuring auxiliary/supplementary thermal input for DHW production via the top internal coil of the tank;
- P1, Pump, driving circulation in the solar collector closed loop (SCF);
- P2, Pump, driving circulation in the boiler closed loop (NGBF);
- D, Diverter, splitting the incoming mains water (MW) into two branches:
  - One branch feeding the bottom part of TK (tank charging with cold mains water);
  - One branch feeding the mixer (M) as cold/tempering water.
- M, Mixer, receiving hot water (HW) from the tank and a portion of mains water (MW) from the diverter, and delivering the resulting domestic hot water (DHW) to the user.

The control strategy of the investigated system is based on the following assumptions, pointing out the way how the system operates:

- P1 is activated when the temperature difference between the outlet of the solar collector and the temperature inside the tank at the inlet to the internal heat exchanger of TK overcomes a fixed upper dead band, and it deactivates then the same difference decreases to fixed lower dead band;
- P2 and NGB are activated once the temperature difference between the fixed set point temperature of TK and the top part of TK increases to a certain upper dead band, and they are deactivated when the same difference decreases to a certain lower dead band;
- NGB provides NGBF at a fixed temperature suitable to heat the water in TK top part to the fixed set point temperature;

- D and M are operated in order to keep the temperature of DHW exiting the system at a constant value (as a thermostatic valve), diverting and mixing the mains water, respectively.

Model of the System

To perform the dynamic simulation of the solar-assisted domestic hot water (DHW) setup, the system was modelled in the widely adopted TRNSYS environment, which is extensively used for the analysis of conventional and advanced thermal systems. The modelling workflow follows the same general approach typically adopted in TRNSYS studies: starting from the conceptual layout of the plant, the required input data were defined (i.e., weather data, technical parameters of the components, and user demand profiles), then the numerical model was implemented by interconnecting available TRNSYS library components, and finally the simulation outputs were post-processed as both dynamic trends and integrated performance indicators. For sake of brevity, in this section only the overall energy and economic model of the system has been presented in detail.

The developed model reproduces the operation of a solar collector loop charging a storage tank through a lower internal heat exchanger, while an auxiliary natural gas boiler loop provides additional heat through a second internal heat exchanger located in the upper part of the same tank. The sanitary cold water from the mains is routed through a diverter that splits the flow into (i) direct tank charging at the bottom and (ii) a branch feeding a thermostatic mixer, which also receives hot water drawn from the top of the tank, delivering DHW at the required supply temperature.

The TRNSYS implementation relied entirely on validated built-in component models. In particular, the flat-plate solar collector was modelled using Type 539, which calculates collector thermal output as a function of incident solar radiation, ambient conditions, inlet temperature, and collector parameters, including thermal capacity. The storage tank was represented by Type 60d, enabling a stratified thermal storage simulation (10 nodes for tank vertical discretization) with internal heat exchangers positioned at the bottom (solar loop) and top (boiler loop), thus capturing the key dynamic effects of stratification on DHW production. The auxiliary natural gas boiler was modelled using Type 122, providing thermal power to the boiler loop based on a control signal and accounting for efficiency characteristics. Pumps for both the solar loop and boiler loop were implemented with Type 114, which allows the definition of mass flow rate and electrical consumption (when required) under an external control signal. The diverter and the mixer were implemented with Type 11f and Type 11h, respectively, to represent the flow splitting of mains water and the mixing process to achieve a target DHW delivery temperature. The DHW load was imposed through Type 9e, which provides a prescribed draw-off profile over time. Weather boundary conditions (ambient temperature, solar irradiance on the collector plane and mains temperature) were provided via Type 15-3 processing .epw files.

The control logic was implemented using Type 165 on/off controllers, which were used to manage pump and boiler operation according to the selected temperature-based control strategy, enabling the solar loop when collector outlet temperature exceeds the tank bottom temperature by a fixed differential, and enabling boiler charging when the tank top temperature falls below a DHW setpoint. The DHW outlet temperature downstream of the mixer was monitored using an additional Type 114 instance used as a temperature-reading/handling block for the delivered water stream.

To support performance assessment, key energy flows (e.g., heat transferred by the solar loop, heat provided by the boiler, and useful heat delivered as DHW) were integrated over the simulation horizon using Type 24, allowing the derivation of cumulative energy indicators from instantaneous thermal power variables. Results were visualized through Type 65d (online plotting of relevant state variables such as tank node temperatures, loop temperatures, mass flows, and control signals) and exported with Type 25c for post-processing and reporting.

The adopted component models are part of the TRNSYS standard libraries and are based on manufacturer data and/or prior validation processes, thus they provide a robust basis for predicting the transient behaviour and overall performance of the investigated solar-assisted DHW system.

Energy and economic model. In order to assess the energy and economic performance of the system as a function of the effect of the mains water temperature and the energy flows involved in the system a user defined model has been developed. In particular, a comparison was made between a reference system (RS), based only on a natural gas boiler for the production of DHW, and the proposed solar collector system (PS) assuming that both must deliver the same amount of DHW to the user at the same fixed temperature conditions.

The efficiency of the solar thermal collector η_{SC} has been calculated as the ratio between the thermal energy produced and the solar energy incoming on the surface of the collector, while the solar factor F_{sol} has been computed as the ratio between the solar energy used to produce DHW and the total one needed.

The primary energy consumption/saving and economic performance of PS versus RS systems were determined assuming a boiler system efficiency of 0.90 [31], while the energy consumption of circulating pumps has been neglected since three orders of magnitude lower than the thermal energy flows involved in the system.

The economic analysis has been performed calculating the operation cost for the production of DHW for both PS and RS in two scenarios, one assuming a mains constant water temperature equal to the yearly mean ambient temperature of a certain location, and one where the mains water temperature is dynamic and changing over the year. In the second case, the mains water temperature has been calculated according to [32], adopting the following equation:

$$T_{\text{mains}} = (\bar{T}_{\text{amb}} + 3 + r\left(\frac{T_{\text{amb,max}}}{2}\right)\sin\left[\frac{360}{365}(d - 15 - l) - 90\right]$$

where:

- T_{mains} is the dynamic mains temperature [°C];
- $\bar{T}_{\text{amb}}$ is the mean ambient temperature [°C];
- r is the ratio [-] defined by the equation $r = 0.22 + 0.0056(\bar{T}_{\text{amb}} - 6.67)$;
- d is the day of the year [-];
- l is the lag [-] defined by the equation $l = 1.67 - 0.56(\bar{T}_{\text{amb}} - 6.67)$.

The actual specific costs for the natural gas have been taken from Eurostat for all the considered countries/locations in the present study [33]. On this basis operation cost of PS and RS and savings of PS versus RS have been calculated.

Case Study

The analysis of the system performance has been carried out assuming realistic domestic hot water demand for household users. Demand profiles for the user type studied in this paper were taken from existing literature [18]. In particular, three representative average user profiles, recorded at 5-minute intervals, were used to construct the domestic hot water (DHW) demand. The profiles were then normalized to define the demand, assuming water use equivalent to four occupants with a specific consumption of 50 kg/day per person at 45 °C. The resulting DHW demand is shown in Figure 2.

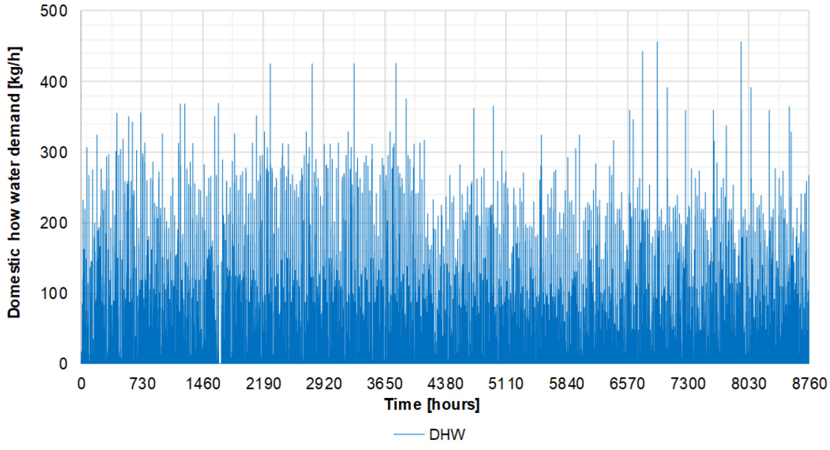

Figure 2. Domestic hot water dynamic profile

The simulation of the weather conditions for capitals of 34 countries was performed on the basis of weather files in .epw format taken from PVGIS portal [34] and implemented in TRNSYS. The selected locations have been listed in Table 1, where main climatic data has been included, as mean ambient temperature, mean mains temperature and horizontal yearly irradiance.

Table 1. Selected locations for the analysis with main climatic conditions

Nr	Location, Country	Mean ambient temperature [°C]	Mean mains temperature [°C]	Horizontal yearly irradiance [kWh/m^{2}year]
1	Brussels, Belgium	11.5	12.7	1088.3
2	Sofia, Bulgaria	9.8	12.4	1442.2
3	Prague, Czechia	10.4	11.9	1160.3
4	Copenhagen, Denmark	9.1	10.1	1051.0
5	Berlin, Germany	10.3	11.5	1102.9
6	Tallinn, Estonia	7.6	8.3	967.6
7	Dublin, Ireland	9.8	10.6	998.4
8	Athens, Greece	18.4	22.5	1827.5
9	Madrid, Spain	15.3	19.2	1747.8
10	Paris, France	11.8	13.3	1171.3
11	Zagreb, Croatia	11.4	13.3	1261.6
12	Rome, Italy	15.9	19.2	1607.1
13	Riga, Latvia	7.8	8.6	1012.7
14	Vilnius, Lithuania	6.7	7.5	1024.3
15	Luxembourg, Luxembourg	10.1	11.5	1163.6
16	Budapest, Hungary	12.4	14.4	1268.5
17	Amsterdam, Netherlands	10.4	11.4	1054.4
18	Vienna, Austria	11.9	13.8	1271.0
19	Warsaw, Poland	9.7	10.7	1046.4
20	Lisbon, Portugal	16.2	19.7	1677.5
21	Bucharest, Romania	13.3	15.7	1416.6

Nr	Location, Country	Mean ambient temperature [°C]	Mean mains temperature [°C]	Horizontal yearly irradiance [kWh/m^{2}year]
22	Ljubljana, Slovenia	10.5	12.6	1338.3
23	Bratislava, Slovakia	11.6	13.5	1255.2
24	Stockholm, Sweden	8.2	8.8	963.1
25	Vaduz, Liechtenstein	5.5	6.7	1116.8
26	London, United Kingdom	11.1	12.1	1040.1
27	Sarajevo, Bosnia and Herzegovina	8.1	10.1	1288.7
28	Chișinău, Moldova	11.6	13.7	1325.9
29	Skopje, North Macedonia	12.2	14.7	1398.4
30	Tbilisi, Georgia	11.3	14.0	1471.6
31	Tirana, Albania	13.0	16.3	1615.1
32	Belgrade, Serbia	12.8	15.3	1396.5
33	Ankara, Türkiye	11.2	14.5	1619.2
34	Kyiv, Ukraine	10.0	11.4	1144.0

For the technical parameters of solar thermal collectors and tank manufacturer data were used. In particular, for the flat-plate solar collectors parameters of commercially available unit have been used (VITOSOL 200-FM Model SV2F [35]), and the same approach has been used for the tank with two internal heat exchangers (Vitocell 100-B/100-W 300 l [36]).

As concerns the system design, the parameters of the collector setup, tank and control system have been set to allow a proper operation of the system and to cover a part of the domestic hot water demand. The main system parameters have been listed in Table 2.

Table 2. Main parameters of solar collector system

Parameter	Value	Unit
SC area	2.51	m^2
SC optical efficiency	0.737	-
SC 1st order efficiency coefficient	3.88	W/(m^{2}K)
SC 2nd order efficiency coefficient	0.0220	W/(m^{2}K^2)
SC slope	35.0	°
SC azimuth	0.0	°
P1 specific flow rate per SC unit area	40.0	40 kg/(h m^2)
TK volume	0.300	m^3
TK height	1.734	m
P2 flowrate	600	kg/h
NGB thermal power	10.0	kW
NGB set point temperature	60.0	°C
P1 activation dead band (SC-TK temperature difference)	5.0	°C
P1 deactivation dead band (SC-TK temperature difference)	0.5	°C
DHW set point temperature	45.0	°C
DHW daily demand	200	kg/day
DHW daily demand	200	kg/day

RESULTS

The analysis of the dynamic performance of the system has been carried out from the temperature point of view for the selected location of Warsaw, Poland. In the daily analysis, the differences in system operation under dynamic (realistic mains water temperature) and constant (average environment temperature) for mains water temperature have been investigated for two days in winter and summer. In such selected days the mains dynamic temperature achieved the maximum variation with respect to the yearly average ambient temperature.

Moreover, the system energy performance has been analysed for the selected location on monthly basis using the two considered assumptions for the mains temperature, while in the yearly analysis the energy and economic results have been shown for all 34 considered locations. Finally, some correlations between main assumption/boundary conditions and obtained results have been presented.

Daily Analysis

In order to perform the simulations under the same conditions for both cases of mains water temperature (dynamic and constant), the same initial temperature regime has been assumed for SC and TK. From the top to the bottom nodes of the tank the following temperatures have been assumed to 55, 53, 50, 47, 42, 37, 32, 27, 22 and 20 °C, while the initial collector temperature has been set to 20 °C.

The analysis of the effect of mains water temperature has been analysed from the dynamic point of view for the selected day of 17th February and 19th August, when the mains dynamic water temperature achieved the maximum variations with respect to the yearly mean ambient temperature.

In **Figure 3** and **Figure 4** the main temperature trends in the solar collector system for the selected day of 17th February have been shown for the dynamic and mains constant water temperature assumptions, respectively. The dynamic results allow one to state that the overall effect of mains water temperature is not negligible, though it does not change significantly the temperature trends in the system from the qualitative point of view. The main characteristics of the dynamic operation of the system are primarily affected by the solar radiation intensity, ambient air temperature and DWH demand trends.

For the investigated day of 17th February, the analysis of results shows that the effect of the mains dynamic water temperature is observable mainly for the temperatures of the system related to the bottom of the tank. In fact, the top tank temperature is practically the same for both cases of mains water temperature, indeed the difference between the average top temperature of the tank is only +0.15 °C between the case of dynamic and mains constant water temperature. This result is achieved despite the significant difference between the constant and dynamic (average) mains water temperature of +3.7 °C. The lower inlet water temperature to the solar collector system induced a lower temperature at the outlet of SC. The difference between the average, maximum and minimum SC outlet temperatures between the case with constant and mains dynamic water temperature are −0.21, −0.73 and 0.00 °C, respectively. Therefore, the mains water temperature does not influence the minimum temperature of the collector achieved at the end of the day. The lower mains water temperature, the lower the bottom TK temperature. In this case, the variation between the average values among the constant and mains dynamic water temperature is 1.8 °C.

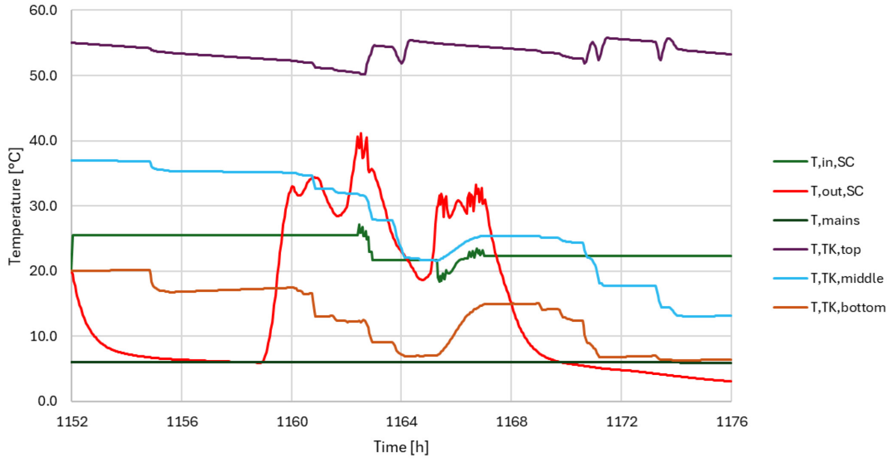

Figure 3. Main temperatures in the solar collector system,
17th February, mains dynamic water temperature over the year

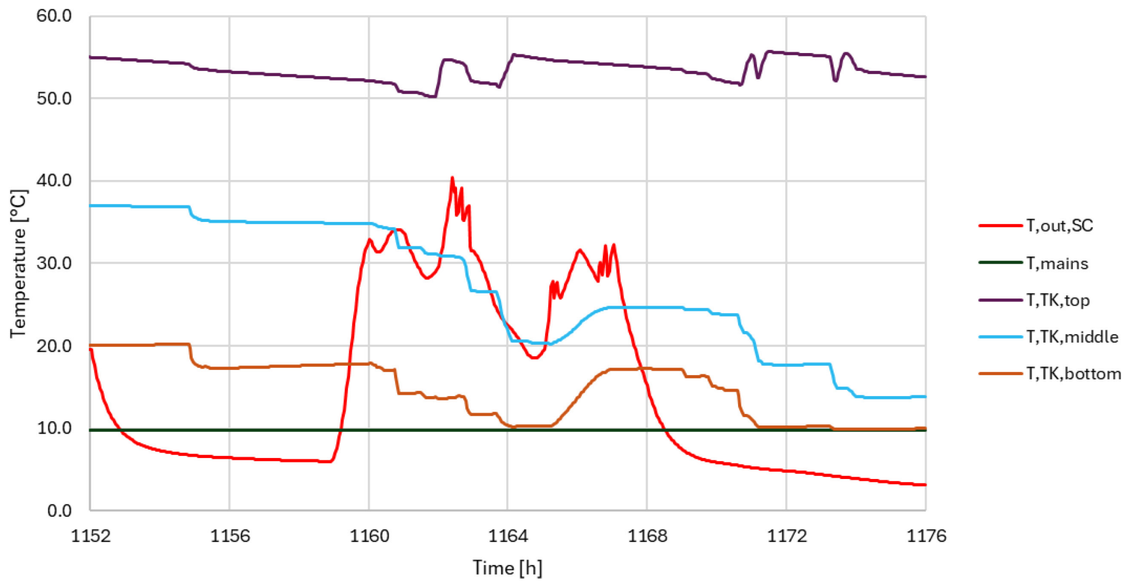

Figure 4. Main temperatures in the solar collector system,
17th February, mains constant water temperature over the year

A similar analysis has been carried out for the representative day of 19th August (**Figure 5** and **Figure 6**). During the investigated day, the average value of the mains dynamic water temperature is 5.7 °C higher than the constant one assumed equal to the mean ambient temperature, which is significantly higher than the variation observed in the winter day. For this reason the effect on the collector system temperature regime is higher. Indeed, for the bottom TK temperature, the difference between the average, maximum and minimum values of dynamic and mains constant water temperature is 3.4, 1.8 and 6.7 °C, respectively. This influences the output temperature of SC, with is averagely higher by 0.43 °C in case of mains dynamic water temperature compared to the constant one. Moreover, the comparison of the trends of TK top temperature points out a difference of 0.68 °C between the average values of dynamic and constant cases.

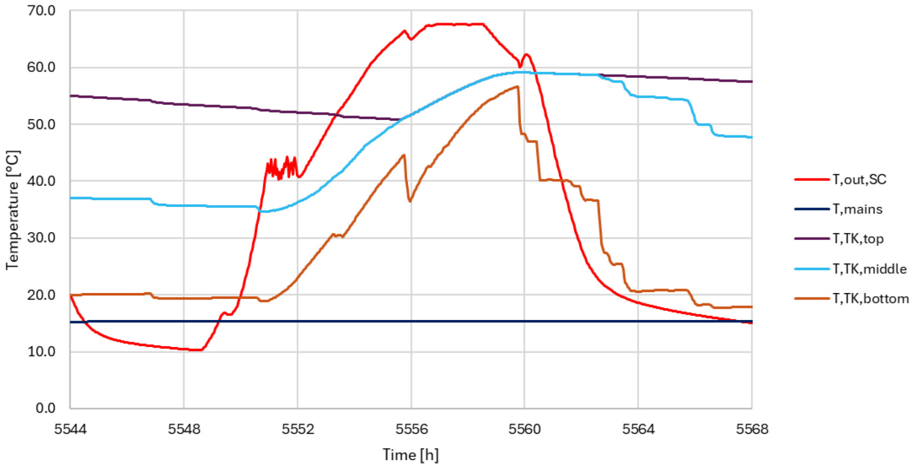

Figure 5. Main temperatures in the solar collector system, 19th August, mains dynamic water temperature over the year

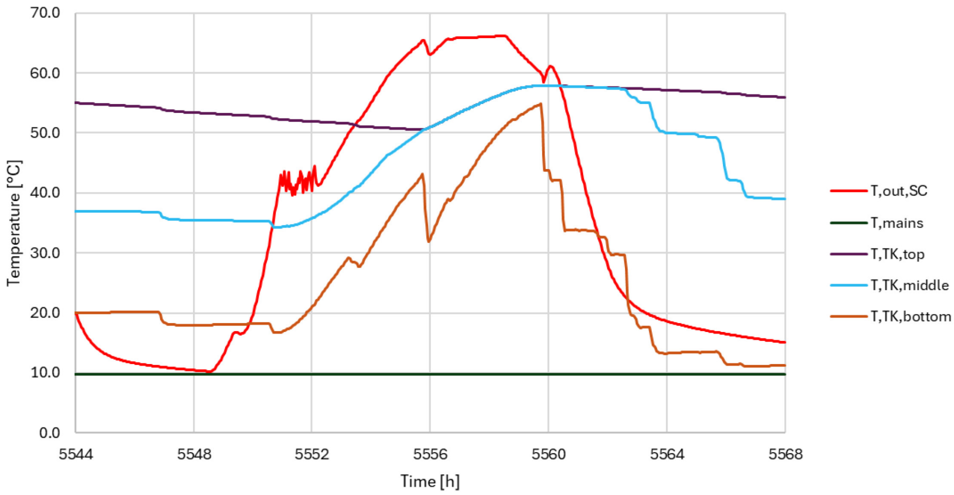

Figure 6. Main temperatures in the solar collector system, 19th August, mains constant water temperature over the year

Monthly Analysis

The monthly results presented in **Figure 7** and **Figure 8** confirm that the boundary condition adopted for the inlet water temperature has a measurable impact on the performance of the solar collector installation for the production of domestic hot water. In the constant-temperature case, the inlet temperature is fixed at 9.7 °C, whereas the dynamic profile exhibits an evident seasonal evolution, ranging from 6.1 – 6.8 °C in January – March to 14.5 – 15.4 °C in July – August. Consequently, the constant assumption overestimates the inlet temperature in the winter season and underestimates it in the summer season, and this affects both the estimated temperature increase needed for DHW preparation and the effective thermal load matched in part by the solar loop.

In winter, when the monthly averaged mains water temperature remains about 3 °C below the constant value, the simulated monthly thermal energy produced by SC is slightly higher under dynamic conditions: the energy produced under dynamic mains temperature exceeds the one achieved under constant conditions by about 3.5 and 4.9% in January and February, respectively. The same tendency is reflected by the solar collector thermal efficiency, being higher in dynamic scenario by comparable relative amounts. As the season progresses, the difference in energy production reduces and changes sign. In April, in the dynamic case, the energy production of SC becomes marginally lower than the one in the constant case, and from May onwards the useful solar heat delivered to the tank is systematically reduced with respect to the constant-temperature assumption. The largest deviations occur in the central summer months, when the dynamic inlet temperature is about 5 °C higher than the constant value and the SC thermal output is 9 – 10% lower. Over the entire year, this effect dominates, leading to an annual solar production of 1309.8 kWh for the dynamic case compared to 1396.4 kWh for the constant case, with a reduction of −6.2%, and to a slightly lower mean collector efficiency, 0.401 versus 0.420.

Conversely, the solar factor is higher in every month when the dynamic mains temperature is adopted. The increase ranges from about 12% in May to about 23% in January, and remains substantial in summer, where the maximum solar factor is observed in July, being 0.851 and 0.736 in dynamic and constant mains water temperature scenario, respectively. This behaviour indicates that, although a warmer dynamic inlet condition reduces the recoverable solar heat in warm months, it reduces the overall DHW heating requirement and the auxiliary contribution even more, thus increasing the solar share. Overall, the mean monthly solar factor rises from 0.358 to 0.416, thus by +16.1%, when dynamic mains temperature is considered, highlighting that the constant-inlet assumption may overestimate summer solar yield while simultaneously underestimating the solar contribution.

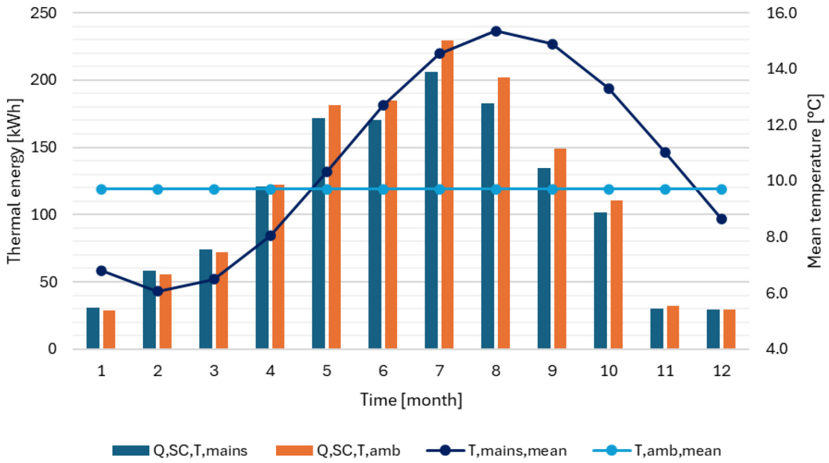

Figure 7. Thermal energy produced monthly by SC in case of dynamic and constant temperature of mains water, mean monthly mains temperature and constant yearly ambient temperature

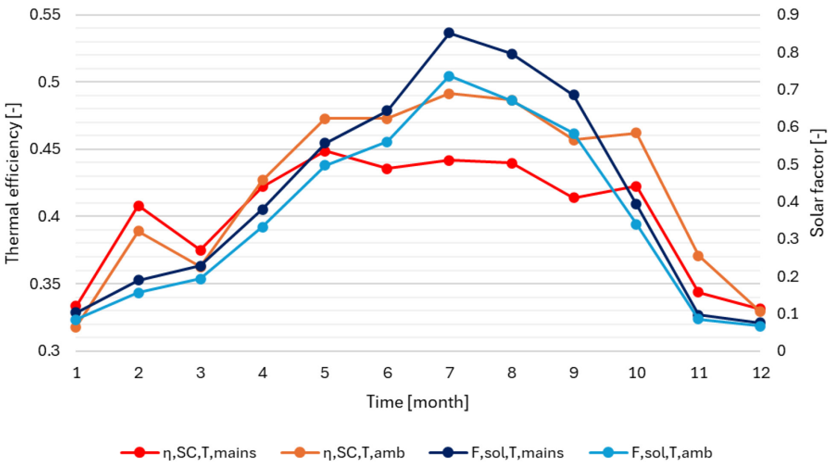

Figure 8. Thermal efficiency and solar factor of solar collector in case of dynamic and constant temperature of mains water

Yearly Analysis for All Locations

The yearly results obtained for the 34 European capitals indicate that the representation of mains water temperature constitutes a relevant modelling assumption, since the mean dynamic value of the mains water temperature is systematically higher than the constant one adopted a simplified approach for modelling mains water temperature.

The difference among dynamic and constant assumption ranges from about 0.6 °C in northern locations (like Stockholm) to more than 4 °C in Mediterranean climates (as Athens). As expected, the higher inlet temperature in the dynamic case reduces the temperature lift required for DHW preparation and leads to a consistent decrease of the yearly thermal demand, with the dynamic case always lower than the constant one by approximately 560 – 750 kWh, which is about 20% on average basis. This condition propagates directly to the contribution of NGB as an auxiliary heat, in fact the contribution in the dynamic scenario is lower than the constant one for all locations, typically by 22 – 38%. The effect is particularly noticeable in colder climates where the auxiliary heater dominates the energy balance, For example, in Vaduz and Vilnius the boiler production decreases from about 2650 and 2620 kWh (constant case) to 2010 and 2040 kWh (dynamic case), respectively. In warmer climates the auxiliary energy is smaller, however the difference remains significant, as shown by Athens, from 680 to 450 kWh, and Madrid, from 873 to 584 kWh, when constant and dynamic cases are compared.

A coherent trend is also observed for the solar contribution. In all locations, the thermal energy produced by SC in case of mains dynamic water temperature is lower than the constant one, with an average reduction of about 8%. The magnitude of the decrease increases with the difference between dynamic and constant temperature cases, reaching the largest values in southern capitals, as Madrid and Athens), whereas northern locations exhibit more limited deviations, like Stockholm. In contrast, tank thermal losses tend to increase when dynamic mains temperature is considered, with the dynamic case exceeding the constant one by roughly 20% on average and maximum increments again occurring in warm climates. This behaviour is consistent with a reduced draw-off driven cooling effect and longer periods at elevated storage temperatures. Overall, the constant inlet-temperature assumption leads to a systematic overestimation of annual DHW demand and, consequently, of both solar and boiler heat supplied, while underestimating storage losses, with deviations that become more pronounced as the climatic difference between dynamic and constant cases increases.

Table 3. Thermal energy produced by SC and NGB, thermal energy loss of TK, DHW demand for dynamic and constant mains water temperature

	Thermal energies [kWh]							
	Mains dynamic water temperature				Mains constant water temperature			
Location Nr	SC	NGB	TK,loss	DHW	SC	NGB	TK,loss	DHW
1	1350	1600	201	2760	1440	2120	176	3400
2	1790	1230	242	2790	1940	1780	194	3530
3	1500	1540	212	2830	1600	2060	181	3490
4	1370	1790	182	2980	1460	2340	158	3640
5	1420	1650	212	2870	1540	2150	178	3510
6	1260	2030	161	3140	1340	2590	141	3800
7	1230	1870	172	2930	1300	2420	153	3580
8	1950	450	469	1930	2190	680	384	2490
9	2040	584	408	2220	2300	873	315	2870
10	1440	1470	217	2710	1560	1970	186	3350

	Thermal energies [kWh]							
	Mains dynamic water temperature				Mains constant water temperature			
Location Nr	SC	NGB	TK,loss	DHW	SC	NGB	TK,loss	DHW
11	1520	1430	241	2710	1660	1910	198	3370
12	1910	670	375	2210	2140	989	297	2830
13	1310	1970	165	3120	1390	2520	143	3780
14	1310	2040	156	3200	1400	2620	135	3890
15	1440	1610	200	2860	1550	2140	170	3530
16	1580	1310	265	2630	1730	1740	215	3260
17	1300	1750	185	2870	1380	2280	163	3510
18	1620	1290	248	2670	1760	1770	205	3330
19	1310	1800	185	2930	1400	2340	162	3580
20	1940	585	367	2160	2160	947	293	2820
21	1700	1110	297	2510	1880	1500	236	3150
22	1660	1350	241	2770	1800	1860	196	3470
23	1580	1350	239	2700	1710	1840	199	3360
24	1270	1970	161	3090	1340	2540	143	3740
25	1410	2010	152	3270	1480	2650	128	4010
26	1290	1700	191	2810	1370	2230	170	3440
27	1610	1570	201	2980	1730	2160	166	3730
28	1600	1330	257	2690	1760	1780	206	3350
29	1700	1160	273	2600	1860	1620	220	3270
30	1850	1070	275	2650	2020	1550	216	3370
31	1970	818	335	2460	2180	1230	264	3160
32	1730	1100	286	2550	1900	1530	230	3210
33	1870	1060	318	2620	2100	1480	243	3340
34	1410	1660	200	2880	1510	2180	169	3540

Table 4. Percentage variation of energies between for dynamic and constant mains water temperature referred to constant temperature case

	Percentage difference dynamic vs constant [%]			
Location Nr	SC	NGB	TK,loss	DHW
1	-6.25	-24.53	14.20	-18.82
2	-7.73	-30.90	24.74	-20.96
3	-6.25	-25.24	17.13	-18.91
4	-6.16	-23.50	15.19	-18.13
5	-7.79	-23.26	19.10	-18.23
6	-5.97	-21.62	14.18	-17.37
7	-5.38	-22.73	12.42	-18.16
8	-10.96	-33.82	22.14	-22.49
9	-11.30	-33.10	29.52	-22.65

	Percentage difference dynamic vs constant [%]			
Location Nr	SC	NGB	TK,loss	DHW
10	-7.69	-25.38	16.67	-19.10
11	-8.43	-25.13	21.72	-19.58
12	-10.75	-32.25	26.26	-21.91
13	-5.76	-21.83	15.38	-17.46
14	-6.43	-22.14	15.56	-17.74
15	-7.10	-24.77	17.65	-18.98
16	-8.67	-24.71	23.26	-19.33
17	-5.80	-23.25	13.50	-18.23
18	-7.95	-27.12	20.98	-19.82
19	-6.43	-23.08	14.20	-18.16
20	-10.19	-38.23	25.26	-23.40
21	-9.57	-26.00	25.85	-20.32
22	-7.78	-27.42	22.96	-20.17
23	-7.60	-26.63	20.10	-19.64
24	-5.22	-22.44	12.59	-17.38
25	-4.73	-24.15	18.75	-18.45
26	-5.84	-23.77	12.35	-18.31
27	-6.94	-27.31	21.08	-20.11
28	-9.09	-25.28	24.76	-19.70
29	-8.60	-28.40	24.09	-20.49
30	-8.42	-30.97	27.31	-21.36
31	-9.63	-33.50	26.89	-22.15
32	-8.95	-28.10	24.35	-20.56
33	-10.95	-28.38	30.86	-21.56
34	-6.62	-23.85	18.34	-18.64

The yearly energy and economic indicators and their variation between dynamic and constant case presented in **Table 5** and **Table 6**, respectively, confirm that the inlet-water temperature assumption affects not only the energy flows but also the energy and economic performance of the solar-assisted DHW system. For all locations, the mean dynamic mains temperature is higher than the constant value adopted in the simplified approach, reducing the annual temperature increase required for DHW preparation. As a consequence, both the reference system and proposed system operating costs decrease when the dynamic mains temperature is considered. On average, the operation cost of the reference system under dynamic case is 288 EUR/year compared to 357 EUR/year in the constant temperature case, while for the proposed system decreases from 203 to 152 EUR/year. The reduction is larger for the reference system, with a mean of about 69 EUR/year, than for the proposed system, where the mean is about 51 EUR/year, so the annual saving attributed to solar integration is lower under the dynamic assumption. The mean operation cost saving is 136 EUR/year in the dynamic case and 154 EUR/year in the constant case, i.e., the constant-temperature approximation overestimates the expected saving by about 13% on average. This difference increases with the gap between dynamic and constant mains water temperature and is most relevant in warm capitals, where the constant inlet temperature is distinctly lower than the realistic mains profile. In Lisbon and Rome the saving decreases from 263 and 254 EUR/year (constant) to 221 and 212 EUR/year (dynamic), respectively. Madrid and Athens show reductions of about 32 and 34 EUR/year, whereas in locations with smaller temperature offsets the difference is limited to a few euros per year. From a performance point of view, the dynamic inlet condition yields a lower yearly collector efficiency due to reduced useful heat extraction in warm periods, while the solar factor increases, reflecting the stronger reduction of auxiliary contribution relative to total DHW requirement. In general, adopting a constant mains temperature equal to mean ambient temperature tends to overestimate the economic benefit of the solar DHW system, especially in mild and Mediterranean climates. For PS, the mean difference in operation cost between the time-varying and constant mains water temperature cases among the considered locations was +36.6%.

Table 5. Thermal efficiency of SC, solar factor, operation cost of RS and PS for dynamic and constant mains water temperature

	Mains dynamic water temperature				Mains constant water temperature			
Location Nr	η_{SC} [-]	F_{sol} [-]	Operation cost, RS [EUR/year]	Operation cost PS [EUR/year]	η_{SC} [-]	F_{sol} [-]	Operation cost, RS [EUR/year]	Operation cost, PS [EUR/year]
1	0.418	0.420	281.8	163.4	0.446	0.375	347.2	216.5
2	0.425	0.557	237.2	104.6	0.460	0.496	300.1	151.3
3	0.424	0.456	304.1	165.5	0.455	0.410	375.0	221.3
4	0.420	0.400	432.4	259.7	0.447	0.359	528.2	339.6
5	0.418	0.423	387.8	222.9	0.454	0.389	474.2	290.5
6	0.422	0.353	298.6	193.1	0.449	0.319	361.4	246.3
7	0.413	0.363	396.5	253.1	0.437	0.323	484.5	327.5
8	0.373	0.767	185.1	43.2	0.420	0.727	238.8	65.2
9	0.395	0.737	211.9	55.7	0.446	0.695	273.9	83.3
10	0.420	0.456	390.8	212.0	0.452	0.411	483.1	284.1
11	0.417	0.474	138.8	73.2	0.454	0.435	172.6	97.8
12	0.402	0.697	304.5	92.3	0.449	0.651	389.9	136.3
13	0.424	0.369	288.4	182.1	0.450	0.332	349.4	233.0
14	0.423	0.365	237.2	151.2	0.450	0.327	288.3	194.2
15	0.422	0.439	295.2	166.2	0.453	0.393	364.4	220.9
16	0.423	0.502	89.7	44.7	0.464	0.467	111.2	59.4
17	0.415	0.391	515.6	314.4	0.443	0.350	630.6	409.6
18	0.424	0.518	361.9	174.9	0.459	0.469	451.4	239.9
19	0.421	0.386	306.4	188.2	0.448	0.347	374.3	244.7
20	0.399	0.729	303.6	82.2	0.445	0.664	396.4	133.1
21	0.409	0.560	155.9	68.9	0.453	0.524	195.7	93.2
22	0.424	0.513	261.3	127.4	0.460	0.465	327.3	175.5
23	0.426	0.499	176.1	88.1	0.461	0.451	219.1	120.0
24	0.421	0.361	730.6	465.8	0.445	0.321	884.3	600.6
25	0.439	0.386	474.5	291.7	0.464	0.340	581.9	384.5
26	0.416	0.396	293.8	177.8	0.441	0.352	359.7	233.2
27	0.427	0.475	166.9	87.9	0.458	0.421	208.9	121.0
28	0.415	0.504	286.0	141.4	0.456	0.468	356.2	189.3
29	0.420	0.553	351.9	157.0	0.459	0.504	442.5	219.2
30	0.429	0.597	49.5	20.0	0.468	0.540	62.9	28.9
31	0.412	0.668	257.2	85.5	0.457	0.611	330.4	128.6
32	0.417	0.567	266.6	115.0	0.459	0.523	335.6	160.0
33	0.402	0.595	60.8	24.6	0.451	0.556	77.6	34.4
34	0.424	0.424	301.1	173.6	0.455	0.383	370.1	227.9

Table 6. Percentage variation of energy and economic results between for dynamic and constant mains water temperature referred to constant temperature case

	Percentage difference dynamic vs constant [%]			
Location Nr	η_{SC}	F_{sol}	Operation cost, RS	Operation cost, PS
1	-6.28	12.00	-18.84	-24.53
2	-7.61	12.30	-20.96	-30.87
3	-6.81	11.22	-18.91	-25.21
4	-6.04	11.42	-18.14	-23.53
5	-7.93	8.74	-18.22	-23.27
6	-6.01	10.66	-17.38	-21.60
7	-5.49	12.38	-18.16	-22.72
8	-11.19	5.50	-22.49	-33.74
9	-11.43	6.04	-22.64	-33.13
10	-7.08	10.95	-19.11	-25.38
11	-8.15	8.97	-19.58	-25.15
12	-10.47	7.07	-21.90	-32.28
13	-5.78	11.14	-17.46	-21.85
14	-6.00	11.62	-17.72	-22.14
15	-6.84	11.70	-18.99	-24.76
16	-8.84	7.49	-19.33	-24.75
17	-6.32	11.71	-18.24	-23.24
18	-7.63	10.45	-19.83	-27.09
19	-6.03	11.24	-18.14	-23.09
20	-10.34	9.79	-23.41	-38.24
21	-9.71	6.87	-20.34	-26.07
22	-7.83	10.32	-20.16	-27.41
23	-7.59	10.64	-19.63	-26.58
24	-5.39	12.46	-17.38	-22.44
25	-5.39	13.53	-18.46	-24.14
26	-5.67	12.50	-18.32	-23.76
27	-6.77	12.83	-20.11	-27.36
28	-8.99	7.69	-19.71	-25.30
29	-8.50	9.72	-20.47	-28.38
30	-8.33	10.56	-21.30	-30.80
31	-9.85	9.33	-22.15	-33.51
32	-9.15	8.41	-20.56	-28.13
33	-10.86	7.01	-21.65	-28.49
34	-6.81	10.70	-18.64	-23.83

CONCLUSION

The present work investigated, by means of an intrinsically validated TRNSYS model based on manufacturer data, the influence of the assumed mains water temperature on the energy and economic performance of a conventional flat-plate solar DHW system with a stratified storage tank and auxiliary natural gas boiler. Two approaches were compared: a time-varying mains temperature profile representative of each location and a simplified constant value equal to the mean ambient temperature.

The results show that the inlet-temperature assumption represents a non-negligible boundary condition. On a monthly basis, dynamic mains temperature leads to slightly higher useful solar gains and collector efficiency in winter, when the realistic inlet temperature is lower than the constant value. Conversely, in late spring and summer, when the realistic inlet temperature exceeds the constant assumption, the useful solar gain and the apparent collector efficiency decrease because of the reduced DHW temperature lift and the lower effective thermal load matched by the solar loop.

When extending the analysis to 34 European capitals, the mean dynamic mains temperature was systematically higher than the constant value derived from mean ambient temperature, with differences that were small in northern climates and more pronounced in Mediterranean locations. As a consequence, the dynamic case yielded a consistent reduction of the annual DHW thermal demand, which translated into a marked reduction of auxiliary boiler contribution for all locations. At the same time, the annual solar collector contribution was also reduced under dynamic inlet conditions, while the annual tank thermal losses increased, coherently with reduced draw-off driven cooling and longer periods at elevated storage temperatures. Overall, the constant-temperature approach tended to overestimate annual DHW demand and auxiliary gas use, and to underestimate tank losses, with increasing deviations as the climatic offset between the two temperature assumptions increased.

The economic analysis confirmed that the inlet-temperature assumption affects the operating costs of both the reference boiler-only system and the proposed solar-assisted system. Although both costs decrease when dynamic mains temperature is adopted, the reduction is larger for the reference system. Therefore, the annual cost saving attributed to solar integration is overestimated when a constant mains temperature equal to mean ambient temperature is assumed. This difference is particularly relevant in warm climates, where the constant inlet temperature is significantly lower than the realistic mains profile.

In general, the results indicate that simplified constant assumptions for mains temperature may distort both performance indicators and household-level economic indexes in comparative studies. For more reliable assessments, location-dependent time-varying mains temperature profiles (or validated correlations) should be adopted, especially in climates with large deviations between mains and mean ambient temperature.

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NOMENCLATURE

Symbols

F	solar factor	[-]

Greek letters

η	efficiency	[-]

Subscripts and superscripts

mains	referring to dynamic mains temperature
loss	thermal loss
out	outlet

Abbreviations

DHW	Domestic Hot Water
HW	Hot Water
NGB	Natural Gas Boiler
NGBF	Natural Gas Boiler Fluid
MW	Mains Water
PS	Proposed System
RS	Reference System
SC	Solar Collector
SCF	Solar Collector Fluid
TK	Tank

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