Analysis of the Influence of Thermal Losses of the Recirculation Flow Loop in a Residential Hot Water Solar System

Paolo Valdiserri – University of Bologna – paolo.valdiserri@unibo.it

Abstract

Water heating for domestic needs contributes significantly to energy demands in the residential sector. The paper reports an energetic analysis of a solar hot water system performed on a dwelling located in Rome, Italy. The study is focused on a group of apartments, where the domestic hot water is provided by a solar system coupled with a storage tank. A recirculation loop, composed by a pump and a system of pipes from the tank to the more distant apartment is also considered in the study. The loop overcomes the problem of long waiting times for hot water for the user by keeping it flowing inside the system. Since the recirculation loop is compulsory in this kind of plants, a dynamic energetic analysis is performed in order to analyse the pipe heat loss influence on the solar fraction. Dynamic simulations are performed using TRNSYS by setting different parameters (insulation thickness, pipe length, mass flow rate) and by interrupting the flow in the recirculation loop during the night. The study shows the sizing process of the whole system, the variation of the solar fraction and heat loss fraction for all the analysed cases.

1. Introduction

Water heating for domestic needs contributes significantly to the energy demands in the residential sector. The Member States of the European Union have to achieve at least 20 % of renewable sources in the final energy consumption by 2020. Solar Water Heating (SWH) is a well-known technology able to allow energy savings and reductions in CO_2 emissions in water heating for residential needs. The performance of SWH systems has been studied theoretically and experimentally over the past several decades (Duffie and Beckman, 2013). Different computational tools have been developed to numerically evaluate the long-term performance of solar systems and to study the effect of the design parameters. TRNSYS 17 (Klein et al., 2010) is an extensive software for transient simulation that provides good agreement with experimental data. Shrivastava et al. (2017) provide a critical review of the SWH system simulation, a comparative analysis of popular simulation tools, and their architecture in the TRNSYS perspective.

Hobbi and Siddiqui (2009) used TRNSYS to model a forced circulation SWH system for domestic hot water requirements in Montreal, Canada. In their study, they optimized the system and collector parameters by changing, among others, collector area and mass flow rate, storage tank volume, size and length of connecting pipes. The authors reported that by utilizing solar energy, the modelled system could provide 83–97 % and 30–62 % of the hot water demands in summer and winter, respectively.

For circulation of the hot water in the system piping a big amount of energy is required (Lee, 2009). Once the hot water leaves the storage tank and flows through the pipes, the water temperature drops due to the travel distance and ambient air temperature. The solution for the problem, without using a circulation loop, is to reheat the water before use.

Since water circulation in pipes has an energetic cost, it is desirable to interrupt the hot water flow in the pipes when the water requirement is low. For this reason, it is important to know the hourly hot water consumption. Moreover, data of domestic hot water consumption are pivotal to compute the energy demand and to design the SWH system. Studies based on measured data or simulations are available to estimate DHW consumption focusing on a daily average, hourly average, appliance consumption, and number of occupants (Ahmed et al., 2016; Edwards et al., 2015). Ahmed et al. derived the

hourly DHW profiles for 5 groups of a different number of people as a function of the number of occupants. In the study weekday (WD) and weekend (WE) consumption variations were reported.
In the present study, the entity of energy losses in the circulation loop between the hot water storage tank and the final hot water outlet has been analysed both in terms of *solar fraction* and *heat loss fraction*.

2. SWH System Under Investigation

In the present study a forced circulation system with a secondary flow loop and a storage tank is modelled (Fig. 1). The secondary flow, that absorbs and transports the solar energy collected by the solar collector (SC), circulates between a heat exchanger, inside a storage tank (SSD), and a collector. When the produced water is cooler than the desired set temperature in the tank (50 ± 2.5 °C) or during overcast days, the water inside the tank is warmed up by a hot fluid through a heat exchanger placed inside the tank (Aux). The produced hot water reaches the final user through a system of pipes (HW). A tempering valve adds cold water (CW) to adjust the temperature in order to supply the water (ws) at the user's desired temperature (38 °C).

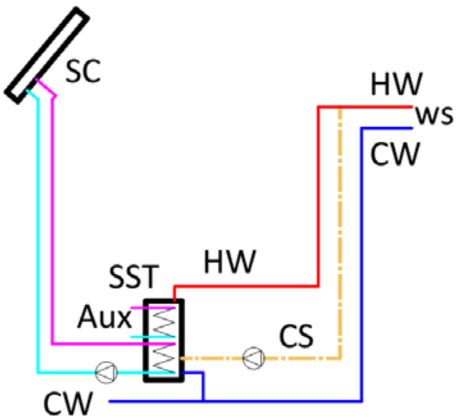

Fig. 1 – Sketch of the SWH system

A recirculation flow loop (CS) can keep the water warm from the storage tank to the final user. The described system is simulated using the TRNSYS simulation program.

The solar heating plan is located in Rome, and it provides hot water for a residential building of 20 apartments (48 people). The average daily consumption of hot water is set to 2400 litres (50 l per person). The solar radiation and ambient temperature data as a function of time are from Meteonorm.

2.1 Hot Water Load Profile

The hourly distribution of domestic hot water consumption during a day is affected by several factors. It varies from day to day, from season to season, and from family to family. The daily water profiles used in this study are presented in Fig. 2 and are derived from Ahmed et al. (2016) in the case of a community of ≥ 50 people.
In the graph, for each hour of the day the hourly water consumption (l/h) is reported for an average daily consumption of 2400 litres. Four different profiles are used in the present study according to: i) the period of year: winter (WIN), summer (SUM), and ii) the day of the week: weekday (WD), weekend day (WE). The winter period goes from the last Monday in October to the last Sunday in March, while the summer season starts on the last Monday in March and ends on the last Sunday in October.

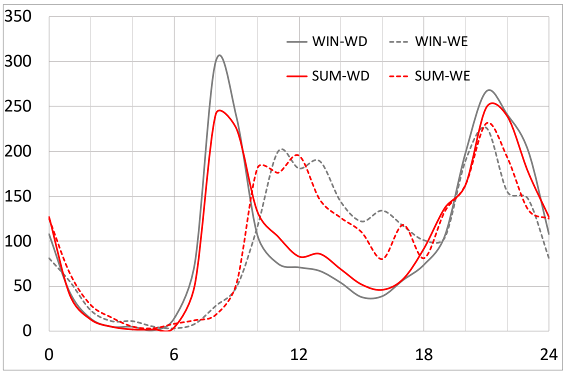

Fig. 2 – Daily water profiles for winter and summer, weekdays and weekend (from Ahmed et al. 2016)

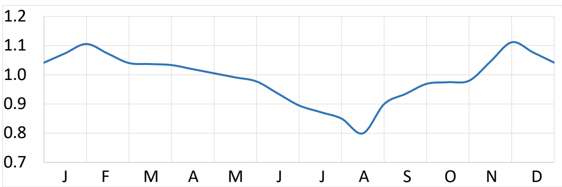

Fig. 3 – DHW monthly consumption factor for Italian apartment buildings (modified from Ahmed et al., 2015, see text for further explanation)

The monthly correction factor was modified from the one proposed by Ahmed et al. (2016), since the majority of people in Italy are on vacation in August and therefore the consumption of hot water drops in that period of the year (Fig. 3).

2.2 Description of System Components

Solar collector (SC): Flat-plate collectors are used with a total area of 30 m^2, oriented toward south with a 50 ° slope. The set parameters are summarised in Table 1: η_0 indicates the optical efficiency of the collector; a_1 and a_2 represent the thermal loss parameters.

Table 1 – Solar collector characteristics

η_0	a_1 (W m^{-2} K^{-1})	a_2 (W m^{-2} K^{-2})
0.807	3.766	0.0059

Storage water tank (SST): A fully stratified 3 m^3 storage tank (10 nodes) is employed in the simulation. Two heat exchangers provide heat from the solar collector and from the auxiliary system.

Solar circuit: A pipe system connects the solar collector to the upper heat exchanger inside the storage water tank. A mixture of water and glycol flows in the circuit. The total length of the circuit is 60 m and the pipes are insulated with the minimum thickness of insulation required by the Italian law (DPR 412/93).

Circulation system (CS): A pipe system connects the storage water tank to the apartments where the hot water is supplied. A mass flow of 500 kg/h is moved by a pump. This is the pipe system under investigation in the present paper. Different pipe lengths and different thicknesses of pipe insulation are taken into account.

3. Results and Discussion

Monthly or annual solar fraction, which is the fraction of the total hot water energy (Q_{Load}) that is supplied by solar system, are calculated using the equation by Buckles and Klein (1980),

$$f = (Q_{Load} - Q_{Aux})/Q_{Load} \quad (1)$$

where Q_{Aux} is the energy supplied by the auxiliary system to integrate the part of the total load that is not provided by the solar energy.

In Fig. 4 the solar fraction in three different cases is shown: i) without taking into account the heat losses from the tank and the pipes of both the solar and the recirculation system (no circuit losses, NCL); ii) by considering only the losses of the solar circuit and the tank but not the recirculation flow loop (no recirculation loop losses, NRL); iii) by considering the three heat losses mentioned above (total circuit losses, TCL). In the latter case the length of the recirculation pipe is 30 m (CS in Fig. 1); the overall length of the circuit is 60 m including the hot water pipes (HW in Fig. 1). The considered insulation thickness, with an insulation material having a thermal conductivity λ = 0.036 Wm^{-1}K^{-1}, is set at 19 and 13 mm respectively for a pipe of 1”1/4 (HW in Fig. 1) and 3/4 (CS in Fig. 1). In the present work these insulation parameters are considered a *standard insulation*.

Fig. 4 shows the yearly solar fraction fall from 81.7 % (NCL) to 66.5 % (NRL) and 60.2 % (TLC). The difference between the three cases is more evident in the winter months, likely due to pipe heat losses that are not counteracted by the solar energy. Neglecting pipe losses may lead to overestimate the solar factor.

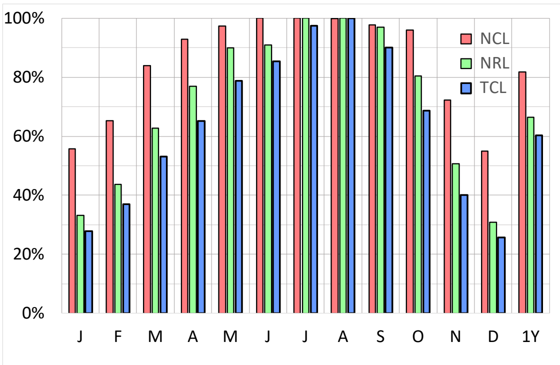

Fig. 4 – Monthly and yearly solar fraction average in three different cases (see text for more details)

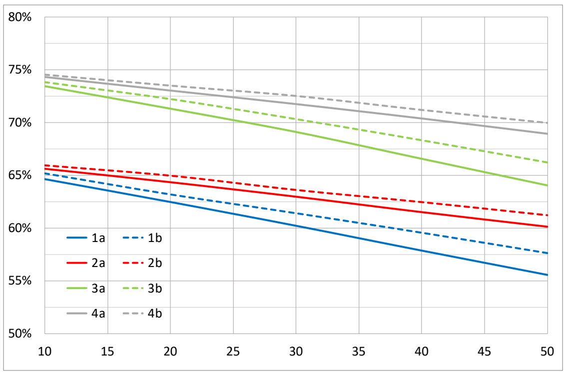

Fig. 5 – Solar fraction vs different pipe length of the circulation system

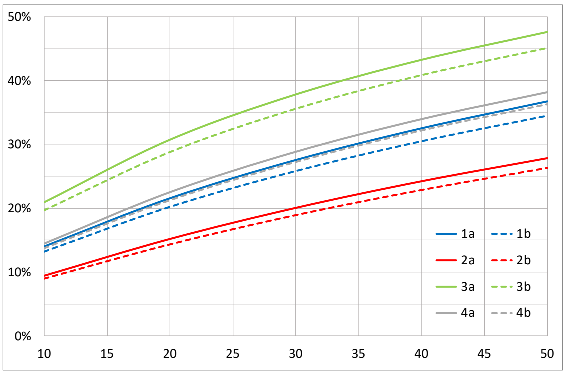

Fig. 6 – Heat loss fraction vs different pipe length of the circulation system

Fig. 5 shows the yearly solar fraction by varying the length of the recirculation pipes in eight different cases: 1a) *standard insulation* and an average daily consumption by the occupants of the apartments set to 2400 litres; 2a) insulation with the same insulation material as in case 1a) but with an increased thickness of 40 mm and 25 mm respectively of 1”1/4 and 3/4 pipes, the average daily consumption set to 2400 liters; 3a) *standard insulation* and an average daily consumption reduced to 1600 liters; 4a) insulation with the same insulation material and thickness as in case 2a). The average daily consumption was reduced to 1600 liters. Cases 1b-4b have the same pipe features and averaged daily consumptions as in cases 1a–4a, whilst the recirculation pump was switched off every day between 11 pm to 6 am. So, during the night, when the hot water demand is lower than during the day, no water circulates through CS pipes and only the hot water required by the users flows in HW.

As expected, the solar fraction increases by reducing the water flow from 2400 to 1600 liters per day, and by increasing the insulation thickness. Vice versa, if the length of the pipes is increased, the solar fraction decreases. Interestingly, the solar fraction increases during the night interruption of the flow, and it becomes more evident if the thickness of the insulation and the length of the pipes are reduced.

The same cases (1a–4a and 1b–4b), described above, are evaluated in terms of *heat loss fraction* (Fig. 5). The heat loss fraction is defined by:

$$hlf = Q_{Loss} / Q_{Load} \quad (2)$$

where Q_{Loss} is the energy waisted through the pipes from the tank to the final user and in the recirculation circuit.

As expected, increasing the pipe length leads to an increase in the heat loss fraction. Two possible strategies can be used to reduce the heat loss fraction: either by increasing the thickness of the insulation, or by switching the circulation pump off when the user demand is low (i.e. during the night). As seen in Fig. 6, better results in terms of reducing the heat loss fraction can be obtained doubling the insulation thickness instead of switching the circulation flow off during the night. Reducing the water flow from 2400 to 1600 liters per day leads to a heat loss fraction increase.

Fig. 7 shows the heat loss fraction for different values of the daily water consumption. The circulation pipes have a *standard insulation*, the same thickness and thermal characteristics of the cases 1a and 2a, and the length of 30 m (CS in Fig. 1).

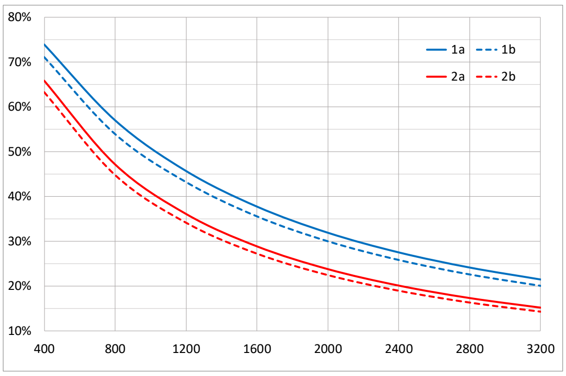

Fig. 7 – Heat loss fraction vs different daily water consumption by the occupants of the apartments

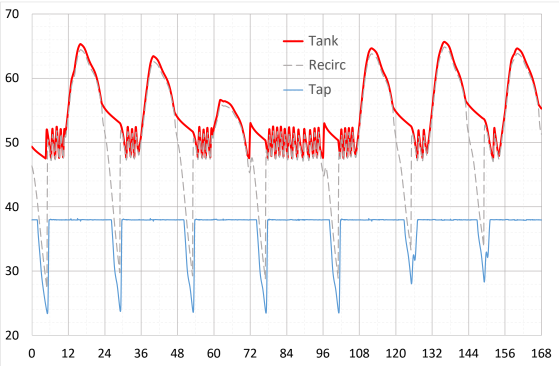

Fig. 8 – Water temperature oscillation during one week in winter, circulation pumps switch off during the night

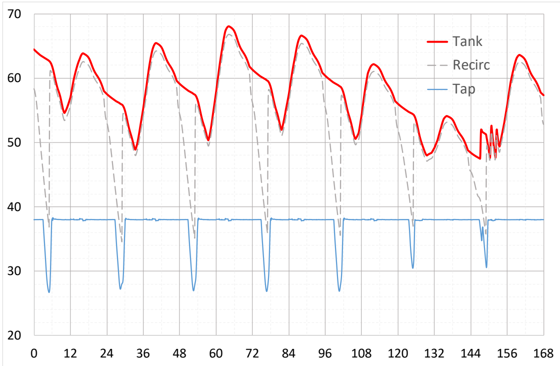

Fig. 9 – Water temperature oscillation during one week in summer, circulation pumps switch off during the night

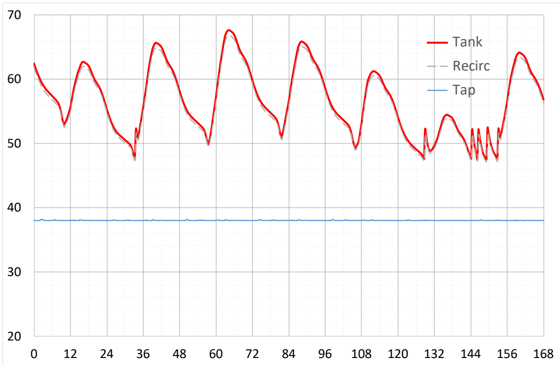

Fig. 10 – Water temperature oscillation during one week in summer, circulation pumps switch on during the night

The curves, the one with the 24 h daily circulation (cases 1a, 2a) and the one operating only during the daytime (dotted line, cases 1b, 2b), are reported in the graph. Reducing the daily water consumption leads to a dramatic increase in heat loss fraction.

Despite the advantages in energy saving obtained by switching the circulation pump off, the system is not able to provide the warm water set at 38 °C at the user level during the night period, as can be seen in Fig. 8. This figure displays the variation of the water temperature during one week in winter (middle of February) in three different sections. The pipes have a *standard insulation*, the average daily consumption by the occupants of the apartments was set to 2400 litres (case 1b). The red line represents the temperature of the hot water exiting the tank, the dotted line is the temperature of the water leaving the hot water pipes at the three way valve with the circulation pipes (end of the circuit before mixing with the cold water); the light blue line is the temperature of the water at the user's tap after mixing with the cold water. The control of the auxiliary system starts to provide energy to the tank water when the temperature falls below 47.5 °C and ends when it reaches 52.5 °C. The peak (i.e. T > 52.5 °C) of the red line in Fig. 8 is due to the energy from the solar collectors, while the sharp oscillations around 50 °C derive from the auxiliary energy.

During the night, the hot water at the user's tap falls below the setting point of 38 °C about 2h after the circulation pump is switched off. So to have water at 38 °C in the apartments, it is necessary to reheat the water locally (i.e. with an electric boiler).

If the pump is kept on during the night, it is not necessary to reheat the water at the user's end, but the tank water is heated in the storage tank by the auxiliary system (data not shown).

Fig. 9 shows the variation of the water temperature during one week in summer (end of June) in the three different positions previously described. As in Fig. 8, the pipes have *standard insulation* and the daily average consumption by the occupants of the apartments was set to 2400 litres (case 1b).

Like in winter, in the summer week (Fig. 9) during the night, when the circulation pump is switched off, the hot water at the user's tap falls below the setting point of 38 °C, it is therefore necessary to reheat the water locally.

Fig. 10 shows the variation of the water temperature during the same week in summer analyzed in Fig. 8 (end of June) when the circulation pump is on. By comparing the red lines of Fig. 9 and Fig. 10, it is possible to observe that during that week, the auxiliary system (heat exchanger inside the tank) provides energy 3 times when the pump is off during the night, and 6 times when the pump is working continuously. At the user level, when the pump is on, it is not necessary to locally reheat the water, while if the pump is off this is needed.

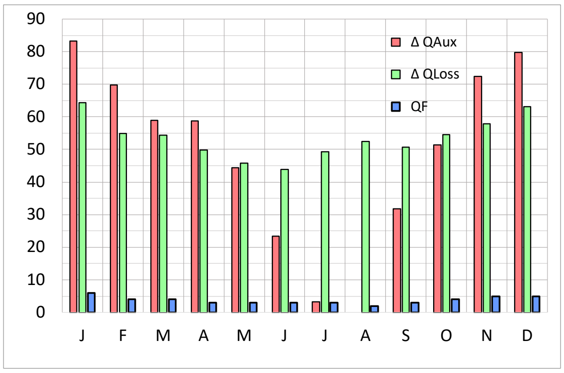

Fig. 11 – Difference in monthly energy consumption between having the circulation pump switched on or off during the night

Fig. 11 presents the difference in terms of energy (in kWh) between the case when the circulation pump is switched on 24 h/day and the case when it is off during the night. Both cases have a 30 m circulation system with *standard insulation* and a daily flow rate of 2400 liters (Cases 1a and 1b). The figure shows that: i) the energy needed to reheat the water during the night (Q_F) when the pump is switched off is always smaller than the energy dissipated through the pipes (ΔQ_{Loss}); ii) the auxiliary energy difference (ΔQ_{Aux}) between the two cases is irrelevant in July and August; iii) the energy needed to reheat the water during the night when the pump is switched off is smaller than the auxiliary energy difference in winter and in the summer months except in July and August. Since in summer the energy to heat the water is provided by the solar collector, it is not necessary to switch off the pump to save auxiliary energy.

4. Conclusion

In the present study TRNSYS software was used to model a forced circulation SWH system for domestic hot water requirements in Rome, Italy. The entity of energy losses in the circulation loop between a hot water storage tank and the final hot water outlet has been analysed both in terms of *solar fraction* and *heat loss fraction*.

The study demonstrates that neglecting pipe losses leads to an overestimation of the solar factor.

To improve the solar fraction, different strategies can be applied: increasing the thickness of the insulation, interrupting the recirculation flow when the mass flow rate is low (i.e. during the night). It was found that doubling the insulation thickness instead of switching the circulation flow off during the night ameliorates the solar fraction and reduces the heat loss fraction. In addition, reducing the daily water consumption leads to a dramatic increase in heat loss fraction.

The domestic hot water is heated by solar collectors and an auxiliary system. The study indicates that in sunny summer days, the energy to heat the water is fully provided by the solar collector, it is thus not necessary to switch off the pump to save auxiliary energy. To decide if it is economically convenient to interrupt the circulation flow during summer nights it is necessary to monitor whether the heat is provided by the solar collector or the auxiliary system.

Further studies are required to set up an appropriate circulation pump control system related to the hot water mass flow rate and the temperature in the pipes. With a customer tailored control system on the pump, it would be possible to reduce or increase the switching off period during the entire day, not only during the night. Moreover, the present strategy could be applied to other cities with different climatic conditions.

Nomenclature

Symbols

Q	Energy (kWh)
T	Temperature (°C)
λ	Thermal conductivity (W $m^{-1}K^{-1}$)

Subscripts/Superscripts

Aux	Provided by auxiliary system
F	Necessary to reheat the water locally
Load	Necessary to heat the requested water
Loss	Waisted through the pipes

References

Ahmed, K., P. Pylsy, J. Kurnitski. 2016. "Hourly consumption profiles of domestic hot water for different occupant groups in dwellings". *Solar Energy* 137: 516–530. doi: 10.1016/j.solener.2016.08.033.

Buckles, W.E., S.A. Klein. 1980. "Analysis of solar domestic hot water heaters". *Solar Energy* 25(5): 417–424. doi: 10.1016/0038-092X(80)90448-X.

Duffie, J.A., W.A. Beckman. 1974. *Solar Engineering of Thermal Processes.* Hoboken, U.S.A.: John Wiley & Sons, Inc.

Edwards, S., I. Beausoleil-Morrison, A. Laperrière. 2015. "Representative hot water draw profiles at high temporal resolution for simulating the performance of solar thermal systems". *Solar Energy* 111: 43–52. doi: 10.1016/j.solener.2014.10.026.

Hobbi, A., K. Siddiqui. 2009. "Optimal design of a forced circulation solar water heating system for a residential unit in cold climate using TRNSYS". *Solar Energy* 83: 700–714. doi: 10.1016/j.solener.2008.10.018.

Klein, S.A., et al. 2010. *TRNSYS Version 17*. Madison, U.S.A.: Solar Energy Laboratory, University of Wisconsin-Madison.

Lee, M.C. 2014. "Reducing CO_2 emissions in the individual hot water circulation piping system". *Energy and Buildings* 84: 475–482. doi: 10.1016/j.enbuild.2014.07.094.

President of the Italian Republic. 1993. *D.P.R. 26 agosto 1993, n. 412. Regolamento recante norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia, in attuazione dell'art. 4, comma 4, della L. 9 gennaio 1991, n. 10.*

Shrivastava, R.L., V. Kumar, S.P. Untawale. 2017. "Modeling and simulation of solar water heater: A TRNSYS perspective". *Renewable and Sustainable Energy Reviews* 67: 126–143. doi: 10.1016/j.rser.2016.09.005.