REAL-LIFE CONDITIONS PERFORMANCE OF RESIDENTIAL SOLAR WATER PREHEATERS IN QUEBEC, CANADA

Normand Bédard, Marie-Andrée Leduc

Laboratoire des Technologies de l'Énergie d'Hydro-Québec, Shawinigan (Canada)

1. Context and objectives

To the request of the Energy Efficiency Direction of Hydro-Quebec (the main electric utility in the province of Quebec, in Canada), the Laboratoire des Technologies de l'Énergie (LTE) of Hydro-Quebec built a test facility in order to evaluate, in actual conditions, the performance of solar domestic water heaters (SDWH).

The test facility was set-up in the fall 2007 and a measurement campaign was carried out over two full periods of one year. The interest for the utility was to evaluate if the acquisition of a solar system by a domestic customer could be subsidised, based on the fact that these systems:

1. are saving electric energy (kWh) used to heat domestic water
2. have an impact on the DWH average power demand during winter peak periods

The project also aimed to judge the general performance of the systems, to identify the best installation and operation practices, the particularities of the different system types and eventual technical flaws.

2. The construction of the test facility

The solar panels were installed on the flat roof of a warehouse type building on the LTE site, facing south. An annex was built at the base of the wall. Inside this annex, solar storage tanks, pumps, heat exchangers and electric water heating tanks were installed. Thermocouples, flow meters and watt meters were coupled to a data acquisition system and a computer. A weather station was also installed on the roof of the building and the recording of temperature, wind speed and direction was performed continuously.

The solar panels were mounted on metallic frames fastened to the flat roof. The absorbing face of the panels was oriented 20° southwest. The following photos (Fig. 1) show the installation during winter.

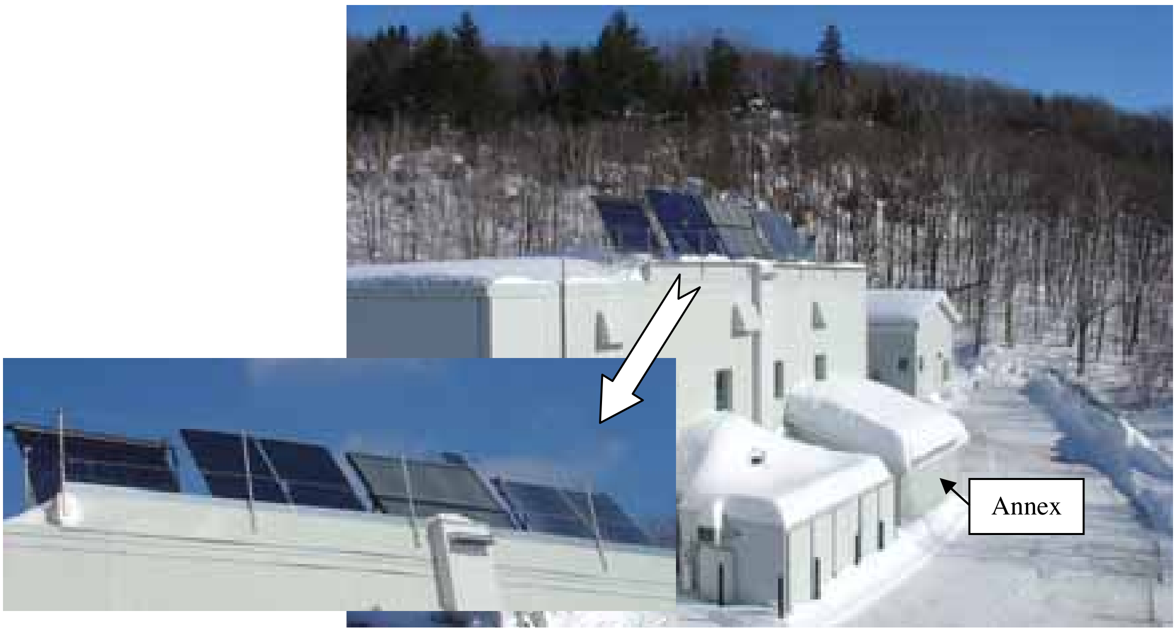

Fig. 1: Photographs of the solar panel testing facility at the LTE

3. Experimental approach and context

Four residential solar systems, including the solar panels, the tubing, a pump for the circulation of the calorific fluid (water-glycol), a controller, a heat exchanger and a storage tank, were each coupled with a standard electric domestic water heating tank (Fig. 2). A fifth, standalone, standard electric water heating tank was used as a reference system.

It has to be mentioned that in Quebec, more than 90% of the domestic customers are using electric water heaters to heat domestic water. This is mainly due to the fact that electricity is produced from hydroelectric dams, and sold at a domestic cost lower than any other form of energy. The majority of these tanks have a capacity of 60 imperial (UK) gallons (273 litres) and two electric heating elements of 4 kW each, heating alternatively the bottom and the top of the tank (flip-flop operation mode).

In the solar systems, the water from the water mains is preheated by the solar system and stored in a solar storage tank. The exit of the storage tank is connected to the water inlet of the standard electric water heating tank, which heats up the preheated water up to the usual set point temperature of 60 °C.

The electric consumption (kWh) of the electric elements of each of the electric water heating tanks was used as the base for the evaluation of the contribution of the different systems.

Fig. 2: Inside the annex: storage tanks, electric water heaters, control valves

3.1 Choice of the solar systems and storage capacity

The choice of the solar systems was based on the recommendations from the systems suppliers. The four systems are as follows:

- System A: flat plate collector (5,4 m^2), 364 litres (80 gallons) storage tank, thermosyphon heat exchanger
- System B: evacuated tubes (3,8 m^2), 300 litres storage tank, heat exchange coil inside the storage tank
- System C: flat plate collector (5,2 m^2), 400 litres storage tank, heat exchange coil inside the storage tank
- System D: flat plate collector (5,6 m^2), 364 litres storage tank, thermosyphon heat exchanger

3.2 Choice of tilt angle

The angle of the collector's plane from the horizontal has been adjusted to 60°. This choice was motivated by the fact that it is important to minimise the impact of snowfall, hail storm, and icy rain during the Canadian winter time. Also, such a relatively stiff angle contributes to increase the solar gains during the winter, this being of a particular interest for the electric utility's winter peak power demand. However, this stiff angle is not very representative of the usual practice, where the collector plane is directly fixed to the surface of the roof, which, in Quebec, has typically a lower angle from the horizontal.

3.3 Measurements

The parameters measured on the test facility are:
. solar watt density on the plane of the solar collectors
. temperature of the calorific fluid, at inlet and outlet of the collectors
. temperature of the calorific fluid, at inlet and outlet of the heat exchanger
. flow rate of the calorific fluid
. flow rate and cumulative withdrawal of domestic hot water
. temperature of the water at inlet and outlet of the storage tank and of the water heater tank
. energy (kWh every 5 min) associated with the water heater tank
. outside temperature, and several weather-related parameters

The following diagram (Fig. 3) shows the general arrangement and the location of the measurement points.

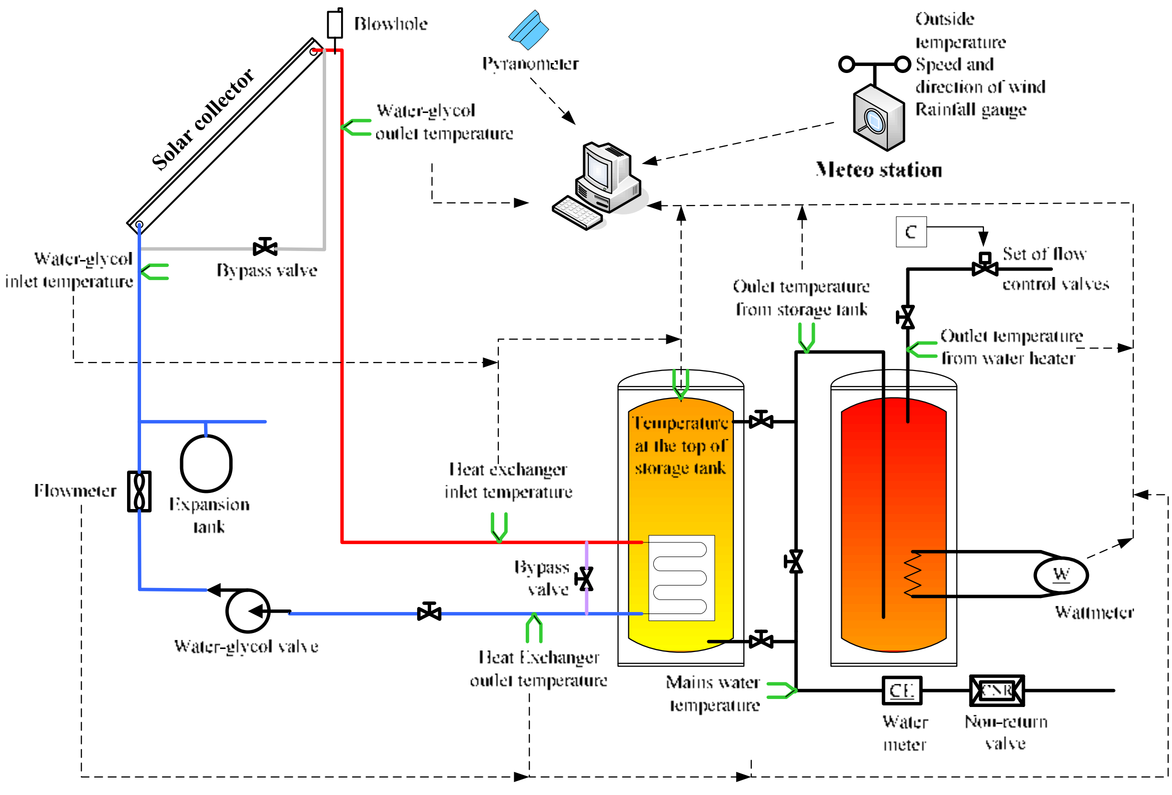

Fig. 3: Diagram of the test set-up

3.4 Domestic hot water withdrawal

To simulate the hot water withdrawal of a typical family, a set of flow control valves were opened during a given amount of time and according to a predetermined schedule in order to simulate the same flow rate as in typical events: shower, bath, dishwasher, hand washing, rinsing, etc. The same water withdrawal sequence was imposed simultaneously to each of the five electric water heating tanks. The flow control valves are shown on the Fig. 2, overhanging the hot water heaters.

The withdrawal profile was chosen to be typical of a family of four people: two adults, one teenager and a young child. During the weekdays, the family members are supposed to be outside the house during daytime: leaving the house before 8h00 in the morning and back by 17h00. The experimental data from another LTE's study concerning the energy consumption of electric water heating tank were exploited to establish this profile. This study, which involved real measurements in 75 homes, had revealed that the daily hot water use was lower than the ASHRAE Standard 90.2-2007 estimation for a four-member family (230 litres per day).

The hot water usage for our test was set to 208 litres per day, giving an average of 200 litres per day for the whole year if taking into account a two weeks vacation period during the summer, during which the hot water consumption is zero. Seasonal changes in hot water consumption, mainly due to varying mains water temperature, were not taken into account in this study.

3.5 Climatic conditions

The measurements covered two quasi-continuous periods: January to December 2008 and October 2009 to September 2010.

Solar input

The solar irradiance measurements along the two-year periods suffered from a slow drift of the sensibility of the pyranometers. Measurements as provided by an Environment Canada station in the area of Shawinigan (latitude 46,5°) indicate yearly solar gains close to the normal from 2008 to 2010. However, important differences between the monthly solar gains of the two testing years are worth noticing.

Temperature

For the two periods covered by the test, the yearly average ambient temperature was higher than the normal temperature of 4,5 °C for the town of Shawinigan: 4,7 °C for 2008 and 6,9 °C for October 2009 to September 2010 period.

Snow

2008 has been particularly snowy (5 meters in the area of Shawinigan). At several occasions, the solar panels were covered with snow or ice (Fig. 4). In most cases, all the collectors were soon free of snow after a small snowfall, but a heavy fall had the impact of covering the collectors completely for several days (note: system B with evacuated tubes was covered by snow to a much lesser degree), despite the 60° stiff angle (tilt). As a result, several days with a good solar potential have been nullified, impacting the annual solar gains. However, a long sunny period following a snowstorm always enabled the complete clearance of the collectors without human intervention. For the 2009-2010 period, the winter has been much less snowy and the periods where the collectors were covered with snow much less frequent.

Fig. 4: Real winter conditions: solar panels covered with snow

Particular conditions
The 2008 results were found disappointing, and our questioning led to the removal of the flowmeters on the calorific fluid piping, which were restricting the flow. This was identified as the only technical condition distinguishing our test facility with a real domestic solar system and susceptible to affect our results. Thus, the flow of the calorific fluid was higher during the 2009-2010 period as compared to 2008. Also, only two of the four systems were monitored during the 2009-2010 period, two systems (A and C) being used for another project. Hot water use was decreased to 200 litres per day, and no vacation period was simulated.

4. Experimental results

4.1 Impact on energy consumption

Over the whole of 2008, the solar systems saved 33% to 38% of the 4 510 kWh consumed by the reference water heating tank for a hot water usage of the fictive family of four people. It is worth noting that the four solar systems, with different areas and designs, and with different storage tank capacity, had a similar impact in terms of energy savings.

The 2009-2010 experimental period gave similar results. One system had a somewhat better performance, while the other had a poorer performance compared to 2008. The average energy saving for the two systems was 35% (1 530 kWh saved over 4 380 kWh as measured at the reference water heating tank).

It is interesting to note that the annual energy savings by the solar systems globally represents around 20% of the total solar energy incident to the surface of the collectors.

4.2 Impact on the average power demand during winter critical hours

In Quebec, chilly winter periods of January and February (less than -25 °C) often occur simultaneously with clear sky and very sunny conditions. Since year 2000, utility peak power demand periods coinciding with sunny clear sky periods occurred more than two times out of three.

Experimental results demonstrated that the solar systems contribute positively to lower the DWH average power demand during the winter critical hours (6h00 to 10h00 and 16h00 to 20h00): the reduction of the average power demand during these periods was as high as 60%. However, when the chilly period lasted several days, a single cloudy day drained completely the thermal storage tank.

It is worth mentioning that depending on the heat transfer apparatus, the positive impact of solar systems on the average power demand of the electric water heating tank is not occurring at the same moment. When the heat exchange between the calorific fluid and the water inside the storage tank is done with an external apparatus and based on the thermosyphon principle (systems A and D), the temperature stratification inside the tank is important: the very hot water at the top of the tank lowers the average power demand of the water heating tank during the evening peak period (16h00 to 20h00). However, the very next morning, the hot water supply from the storage tank has reached a much lower temperature and the impact on the morning peak power demand (6h00 to 10h00) is low. On the contrary, when the heat exchanger (coil tubing) is inside and rather at the bottom of the storage tank (systems B and C), the temperature is more evenly distributed along the height of the storage tank. Thus, the hot water demand during the evening drains less stored heat, and the following morning, the impact on the power demand is more significant. Figure 5 is illustrating this phenomenon by showing the temperature at the top of the storage tank along a chilly week.

Important note
The daily water withdrawal was set to a constant value, without consideration for the season. However, in Canada, the temperature of the water mains is much lower during the winter as compared to summer time: in Montreal, this temperature can vary from 3 °C to 23 °C. Consequently, the energy necessary to heat up the same amount of water to the desired level (55 °C to 60 °C) has to be higher. Moreover, as the temperature of the water for the showers, baths and hand washing is controlled by the user by adjusting the flow rates of the cold and hot water, more hot water is necessary to compensate for the colder water from the mains. However, in this study, the winter water flow rates were not decreased during the summer, as it would be in reality. A lower hot water use during the summer would have helped the energy coverage, but would have worsened the saturation of the storage tank during the hot season.

Also, the temperature of the water delivered to the solar systems of our test facility was not as low as it is in reality, especially during winter time. If it had been, the energy demand of all the water heating tanks would have been higher. Thus, the energy coverage during the winter would have been lower.

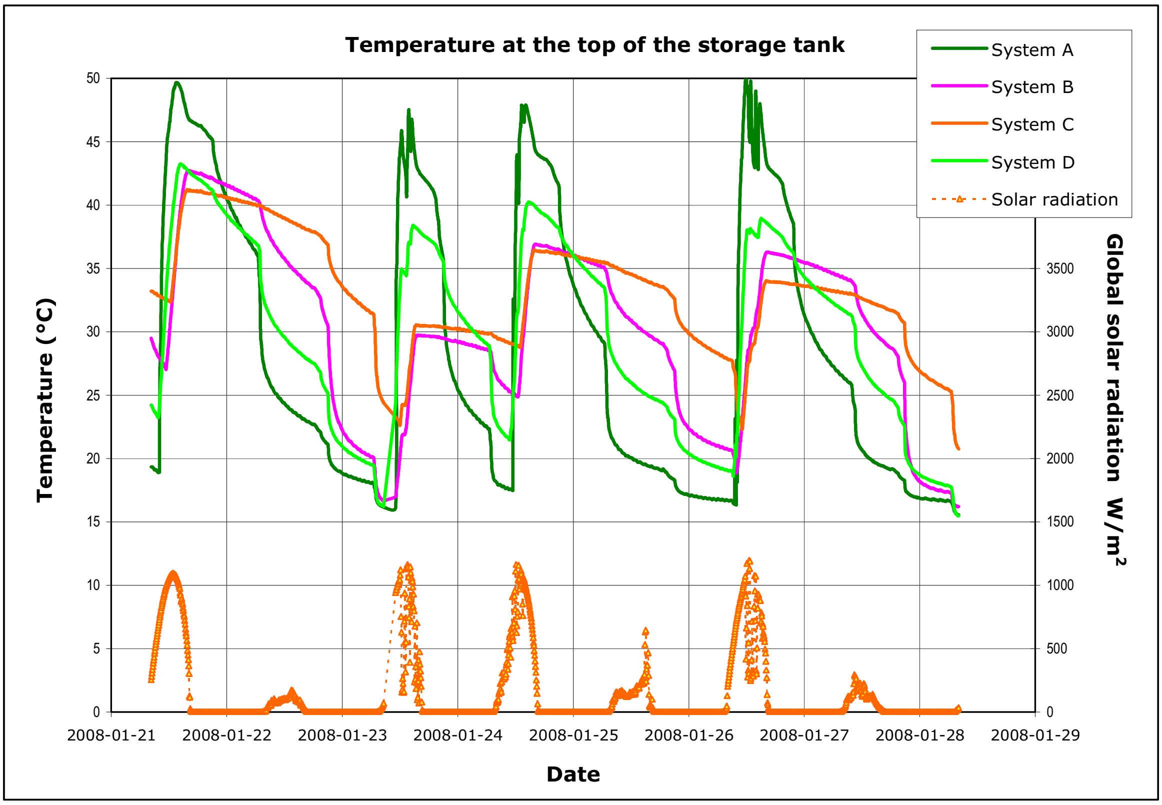

Fig. 5: Temperature at the top of the storage tank: impact of the type of heat transfer device

4.3 Losses

During high solar input periods, the losses along the calorific fluid tubing were evaluated to be more than 10% of the solar heat gain by the collectors in summer and up to 25% during a very cold winter day.

Also, it was estimated that during the winter, the losses by the back of the flat panels can represent more than 20% of the solar heat gains by the panels. The mounting of the panels on a framework implies that the back of the panels are exposed to the wind.

Another source of losses is related to the saturation of the storage tanks during certain periods. Foremost, the simulation of a two weeks vacation period during the 2008 summer (no hot water withdrawal) induced the thermal saturation of all the storage tanks, which is set to 60 °C or 65 °C for all the systems. When this happens, the controller of the solar systems stops the pump from circulating the water-glycol fluid. This is causing the warming of the fluid in the panels up to a level where the glycol deteriorates. All systems suffered such glycol degradation, this being noticeable by the change of the pH value.

But even with normal hot water withdrawal, saturation also happened in September, with a favourable combination of the angle of incidence of beam irradiance, outside temperature and duration of the daytime.

With a tilt angle substantially lower than 60° (for example, solar panels back to a roof with a slope of 30°), saturation is expected to occur more often during summer time. Also, it has to be mentioned that outside the two-week vacation simulation, no other periods of absence (no hot water withdrawal) was simulated during the test. In real life, people often do leave the house for one or two days during summertime, especially when it is sunny outside, and these are the best conditions for thermal saturation of the storage tank.

5. Profitability

5.1 Profitability for the residential customer

At the end of 2007, a typical solar system on the Canadian market (two 4’ x 8’ panels, heat exchanger, calorific fluid pump, controller, etc.) cost close to 5 000 Canadian dollars, excluding taxes and installation. The storage tank recommended by the suppliers of the flat plate collectors systems was an 80 imperial gallons (364 litres) capacity, which cost more than double the cost of a standard 60 imperial gallons (273 litres) tank. The installation cost of a solar system in Quebec is generally between 2 000 and 3 000 dollars. Also, a code requirement in Canada is the installation of a non-return valve which adds around 1 000 dollars. Globally, the minimum cost for the installation of a solar system, including the taxes, is over 9 000 Canadian dollars (CAD).

Our experimental results show that one can hope for an economy of 1 700 kWh (38%) of a hot water energy consumption of 4 500 kWh for a typical family of two adults and two children. With a domestic electric rate currently at 0,07 CAD (0,05 €) per kWh, the customer can expect an annual saving of about 120 CAD.

Thus, the simple Return On Investment (ROI) period (acquisition cost / annual savings) is well over 50 years, without taking into account maintenance costs. This is a much longer period than the 30 years life expectancy of a solar system. It is interesting to note that many installers recommend the replacement of the water-glycol fluid on a yearly basis. This operation takes away completely the yearly electric energy savings.

It is worth noting that the replacement of the water-glycol fluid is not a bad advice, given that during a long period of absence of the family (for example, a two-weeks vacation during the summer time), the water-glycol calorific fluid overheats within the solar collector.

5.2 Potential contribution from the electric utility

The electricity savings due to the use of a solar system has a value for the electric utility, which is considering this value in regard to the higher costs of its hydro-electric future projects. The net present value (NPV) of a domestic solar water heating system for the utility was estimated to 650 CAD in 2009. If this value is transferred to the domestic customer, it represents less than 7% of the initial investment.

6. Discussions

The experimental project enabled us to confirm that preheating of water by commercial solar systems is saving an interesting amount of energy: at least one third of the annual electricity consumption associated with domestic water heating can be covered by such a system, for a typical family of four. Unfavourable conditions like the length of the calorific fluid tubing and installation on a frame may have somehow affected the performance of the systems tested at the LTE. However, it is difficult to believe that even in a better situation, the contribution from a solar system, in real Canadian climate conditions, could be better than 40% of the hot water needs for this typical family.

The providers of the solar systems had estimated the level of energy savings of their system, as sold, to be between 50% and 60%. It is also the estimation generally accepted by most in this field. The Agence de l’Efficacité Énergétique du Québec (AEE), who has been conducting a program encouraging the acquisition of solar systems during the recent years, is mentioning this value on their web site.

The presence of humidity inside the flat plate collectors could be a key factor for explaining the relatively lower results compared to what was expected. Sealing of these solar panels is not perfect, and water from rain penetrates the panel. This water evaporates when the solar collector is heated by sunshine and eventually condensate on the inside face of the protecting glass. The condensation and re-evaporation leaves a deposit on the glass which impairs its transparency. This has also been identified by a French study (Lair et al., 2004). In all likelihood, this phenomenon probably wears on all along the life of the solar panels.

On the contrary, evacuated tubes collectors do not suffer from this phenomenon. However, along the period of testing, several tubes lost their vacuum and had to be replaced. Overall performance of the evacuated tubes collector was also below the one expected.

Another explanation for the gap between our results and the expected performance of hot water solar systems is a faulty design or a bad operation of the test facility. To enhance the degree of confidence in his findings, the LTE is currently collaborating to a test campaign on the performance of several solar systems set up in real houses located in different areas on the territory of the province of Quebec. This project is sponsored by the Agence de l'Efficacité Énergétique du Québec. This campaign will enable to confirm or revise the results obtained with the LTE's test facility. It will also allow the assessment of the relative impact of several parameters such as orientation and tilt of the solar collectors, area and climate and mounting on a structure or flat on the roof.

It is relevant to mention that a vast test campaign was performed in France (Buscarlet and Caccavelli 2006) by the Centre Scientifique et Technique du Bâtiment (CSTB) for the Agence de Développement et de Maîtrise de l'Énergie (ADEME). To have an estimation of the real-life performance of hot water solar systems, close to 120 solar residential installations were equipped with measurement devices, and continuous acquisition of the different measurements was done over a full year period. The solar systems were located in different areas in France.

In terms of annual energy savings, these were evaluated to be between 200 to 250 kWh/m^2/year (Alsace area to Provence-Alpes-Côte-d'Azur area, with an average hot water daily draw of 120 litres). It is interesting to compare these values with the LTE's results, between 260 and 360 kWh/m^2/year: despite a harsher winter time and a lower average temperature in Quebec, yearly global irradiation and net energy savings is good even compared to the south of France. Similarly to LTE's findings, the CSTB concluded from their results that "solar productivity around 200 kWh/m^2/year is widely inferior to the values usually assumed (400 kWh/m^2/year for example) by study firms and contractors". However, it should be mentioned that this value of 200 kWh/m^2/year is an average: among houses consuming the same volume of hot water as in the LTE's experiment (200 litres per day), the solar productivities found in the French study are very similar to LTE's. It is worth mentioning that the main factor determining the solar productivity is, according to the French study, not the area where the solar system is located (thus not the amount of yearly global irradiation), but the water withdrawal. Clearly, when hot water usage is low, saturation does occur and this reduces the energy savings. In Quebec, where summer hot water needs are substantially lower than winter needs, a better balance between solar gains during the two seasons has clearly to be looked for.

7. Conclusions

The experimental results from a test over two full years in real conditions at the LTE shows a performance lower than expected by the industry and the government agencies. From the point of view of the residential customer, it is easy to see that electricity savings cannot, at this moment, justify the acquisition of a hot water solar system, even when considering an eventual grant from the electric utility in Quebec. A strong increase of the cost of electricity and a substantial reduction of the purchase and installation costs of the solar systems are sine qua non conditions for the implementation of the technology in Quebec.

Generally speaking, the solar systems are well designed and relatively well adapted to a northern climate. However, a better thermal insulation at the back of the panels would be useful, especially when the panels are mounted on a framework and not backed to the roof of the house.

Also, two major problems were identified.

. Real-life conditions and inspection of the solar panels showed that the sealing of the flat plate solar collectors is not as tight as it should be: this ends up with a deposit on the glass which impairs transparency.
. None of the suppliers of solar systems had a sound solution to the overheating and degradation of the glycol in the solar collectors when there is no hot water demand and a lot of solar gains.

In Quebec, it is reasonable to think that most of the solar systems installed back to a roof are experiencing thermal saturation of the hot water storage during summertime. Also, winter solar gains are lower than what one should hope for (at least from the point of view of the electric utility). This is mainly due to the low tilt angle, and this is worsened by the fact that summer hot water needs are substantially lower than winter hot water needs, this being due to the mains water temperature difference between summer and winter. Ultimately, a better balance between solar gains during the summer and the winter is desirable.

8. Perspective: vertical installation ?

The results of the study led to cogitation on the relevance of the general practice to install solar panels backed to the roof of the houses. Most of the houses in Quebec have a roof with a relatively low slope. The said practice has disadvantages: snow accumulation on the panels that may stick there for a long period of time and high angle of incidence of beam irradiance during the winter. This means that the contribution from a solar system is particularly low during the winter season, when electric energy demand related to hot water use is higher and when it would be the most useful for the electric utility, which is facing peak network demand. During the summer, the angle of incidence of the beam irradiance is very favourable, and saturation of the storage tank will occur, even with 'normal' withdrawal of hot water, leading to the degradation of the glycol in the calorific fluid. The said practice of low tilt angle of the solar panels may also lead to an aggravation of the problem of infiltration of water and the related evaporation deposits on the inner face of the glass, impairing the performance of the flat plate solar collectors.

The installation on the roof itself, backed to the roof or on a framework, means reduced and risky accessibility for the owner. Also, the asphalt shingle and the plywood have to be perforated: in Quebec, such an operation has to be performed by a specialist with a licence. This installation also increases the length of the piping between the solar panels on the roof and the hot water tank, located in the basement leading to non-negligible losses. When the solar collectors are mounted on a framework to increase the tilt angle, this has, apart from the obvious aesthetic drawback, the practical inconvenience that the panels are exposed to the winds which increases the thermal losses from the back of the panels and also means that the attachment to the roof has to be very solid.

All of these inconveniences led to consider installing the solar collectors in a vertical position, on an external wall, at the level of the first floor.

The advantages of a vertical installation would be multiple:

. much less snow accumulation;
. less rain infiltration and less evaporation deposits inside the flat plate collectors;
. better match between the winter's higher hot water demand and solar contribution;
. almost maximal contribution during the winter, opening the possibility for a more generous grant from the electric utility to account for peak power reduction;
. less contribution during the summer, but no storage tank saturation, reducing the risk of glycol degradation;
. use of a standard 60 gallons storage tank, much less costly than a 80 gallons or a custom solar storage tank;
. easier and safer access to the solar collectors;
. possibility to cover the solar panels during a prolonged absence of the households;
. much lower thermal losses by the back of the solar panels because of the wind;
. less costly installation and less manual intervention (snow, leafs)

Of course, the global annual irradiation from the sun is theoretically lower in a vertical installation. However, the amount of time where snow is covering the solar collectors when these are backed to the roof is substantial. Also, in a vertical set-up, the snow on the ground reflects some solar irradiance to the collectors and contributes to increase their total solar radiation input.

Overall, the 'vertical' approach could be better adapted to the Canadian climate and houses and could better contribute to the electric energy and power demand specificity of the Quebec electric utility.

9. References

ANSI/ASHRAE Standard 90.2-2007.

Buscarlet, C., Caccavelli, D., 2006. Suivi et évaluation énergétique du Plan Soleil, Étude réalisée pour le compte de l'ADEME, d'EDF et de GDF par le CSTB (in French).

Lair, J., Laporthe, S., Marechal, J.C., Richard, P., 2004. Fiabilité et durabilité des systèmes solaires, Rapport du CSTB en collaboration avec l'ADEME et Enerplan (in French).