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IMPACT OF GREY WATER HEAT RECOVERY ON THE ELECTRICAL DEMAND OF DOMESTIC HOT WATER HEATERS

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ABSTRACT

Grey water heat exchangers (GWHE) are used to recuperate part of the energy contained in grey waters. The configuration used in this study recuperates part of the energy contained in the grey water from showers to pre-heat domestic hot water. Previous simulations studies have shown that this configuration can recuperate part of the energy that would otherwise be lost and allow the use of smaller electric domestic hot water (DHW) tanks. This paper focuses on the impact that GWHE have on peak electrical demand from electric DHW tanks. Simulations are performed using TRNSYS with a standard DHW tank model and a special GWHE model.

A total of ten different yearly water draw profiles are statistically generated at 1 minute intervals. This small time step is required in order to capture the transient effects in the GWHE. It is shown that the aggregated effect of these profiles corresponds to the electrical consumption measurements performed on 600 residential electric DHW tanks.

Simulation results show that GWHE have an impact on the peak electrical demand with reductions of 119.4 Watts (10.4% reduction) at 8:00 and 184.0 Watts (21.5% reduction) at 22:00. On an annual basis, the energy required for DHW heating is 4501 and 5299 kW-hr with and without a GWHE, respectively.

INTRODUCTION

The energy associated with DHW heating can represent a significant portion of the total energy consumption of a typical residence. In terms of electrical demand, electric DHW tanks have morning and evening peaks which are not necessarily welcomed by electric utilities. While there have been a number of studies indicating that GWHE have the potential to save energy, there are apparently no reported works on its potential for peak electrical demand reduction.

Figure 1 presents the configuration used in the present study. It consists of an electric DHW tank and a GWHE. The GWHE recuperates heat from the shower drain to preheat DHW water. GWHE are usually inserted into the regular plumbing system of a residence replacing a section of drain pipe. The shower drain flows inside the main pipe of the GWHE and adheres to the wall while incoming cold water from the city mains circulates in a spiral coil in close contact with the main pipe. Both the main pipe and the coil are usually made of copper to enhance heat transfer. The nature of this installation implies that there must be simultaneous water flow in the drain and in the coil in order to maximize heat recovery. In a residence, this occurs mostly when showers are used.

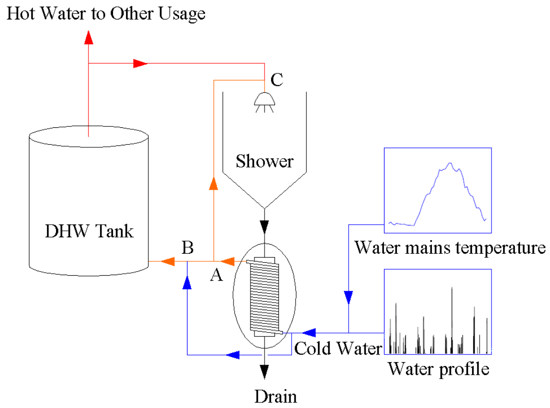

Figure 1. Schematic presentation of DHW system

Different studies reported significant energy savings using GWHE. According to one early study conducted in England by Smith (1975), the overall fuel savings for water heating were 31.7%. Proskiw (1998) classified different grey water heat recovery systems and concluded that they can provide between 30% and 55% of the DHW load. In 2001, the US Department of Energy tested three different GWHE configurations. It was shown that energy savings were of the order of 51%, 41%, and 35% depending on whether: i) the shower water was all preheated; ii) only the cold water was preheated; iii) only the hot water was preheated. Zaloum et al. (2007) tested five different GWHE units from three manufacturers to determine the energy savings of the GWHE units. They found that all the units could save a significant amount of energy with an average savings of 16% of the total DHW load.

Various GWHE configurations were modeled in TRNSYS by Picard et al. (2006) and results indicated that they can recuperate up to 49% of the energy required to heat the water for showers. Picard et al. (2006, 2007) also developed a GWHE model in TRNSYS. This model, which will be used in this study, accounts for transient heating and cooling of the GWHE. Picard and Bernier (2008) are also at the origin of a study showing that the storage tank volume can be reduced when a GWHE is installed.

Bouthillier and Bernier (1995) showed that various off-peak DHW heating scenarios such as shutting off the bottom heating element for a specific time can reduce and/or displace the peak electrical demand.

The performance of GWHE is a function of the entering grey water flow rate which depends on the flow pattern consumption. Various researchers have studied residential DHW consumption profiles. According to Fairey and Parker (2004), hourly average flow profiles were proposed by Perlman and Mills (1985), ANSI/ASHRAE Standard 90.2 (1993), Becker and Stogsdill (1990), and Bouchelle and Parker (2000). Finally, according to Stevenson (1983), Jordan and Vajen (2000), and Lowenstein and Hiller (1996) about 40% of DHW load can be classified as simultaneous flows (drain and cold water) with shower usage representing the vast majority of these flows.

OBJECTIVE

The main objective of this study is to quantify the impact of GWHE on peak electrical demand. As a minor objective the effect of the entering water temperature on the electrical energy consumption is also examined.

METHODOLOGY

Two configurations are examined in this study. The first one, shown in Figure 1, uses a GWHE. As shown on this figure, the water mains flow rate is split in two at point A: Part of the pre-heated water is going to the cold faucet of the shower and the other directly to the electric DHW tank. The second configuration does not use a GWHE and the cold water from the water mains goes directly to the DHW tank.

DHW profiles

Hourly DHW consumption profiles are mostly used in performance analysis of residential DHW systems but are inadequate to capture the effects occurring in showers which last only a few minutes. Therefore, water flow consumption patterns at the one-minute level are desirable. In this study, the DHW-Calc software (Jordan and Vajen ,2003a) is used to generate realistic profiles. These profiles are generated in two main categories: showers and other flow rates. Table 1 presents the daily flow rate in each category. The total daily flow rate of 240 L/day corresponds to the daily profile suggested by Perlman and Mills (1985) for an average family.

Table 1. Mean daily shower, other hot water usage, and total hot water draw profiles

Shower l/day	Other Usage l/day	Total DHW l/day
163*	144	240

*Represents the total daily shower flow rate. Daily hot water shower draw is 96 l/day at 60ºC.

In this study, 10 different DHW profiles are generated using DHW-calc (Jordan and Vajen, 2003b). A complete description of how these profiles are generated is outside the scope of this paper. Readers are referred to the work of Picard et al. (2006) for more details.

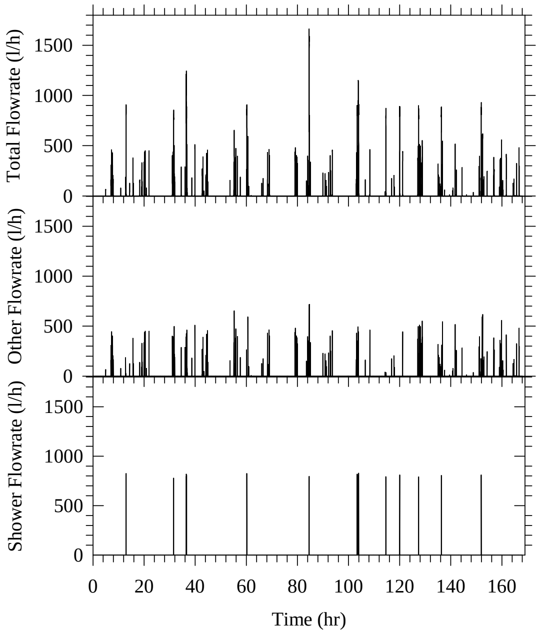

Figure 2: First week flow patterns for the shower, other flow rates, and total flow rates for one of the generated profiles

The daily percentage of hot water for each draw category, mean flow rate per draw, draw duration, standard deviation of each category and daily total hot water are the same for the 10 profiles. However, the DHW draw occurrence probabilities during the day and the time of occurrence of each draw are different for each profile. This enables the generation of different profiles, which as will be shown later, mimic the behaviour of a DHW population. An example of one of the ten profiles is shown in Figure 2. This figure shows the shower flow rates and the other flow rates for the first week of the year. As can be seen, the shower flow rates and their duration are not constant as is the case in practice.

The Perlman and Mills (1985) daily profile is compared to the yearly average of the 10 generated profiles in Figure 3. Even though the daily consumption is the same, there are some differences between the two profiles particularly in the morning were the average of the 10 profiles is significantly higher than the Perlman and Mills profile. Despite this discrepancy, it was decided to keep the 10 profiles as they match, as will be shown shortly, experimental measurements.

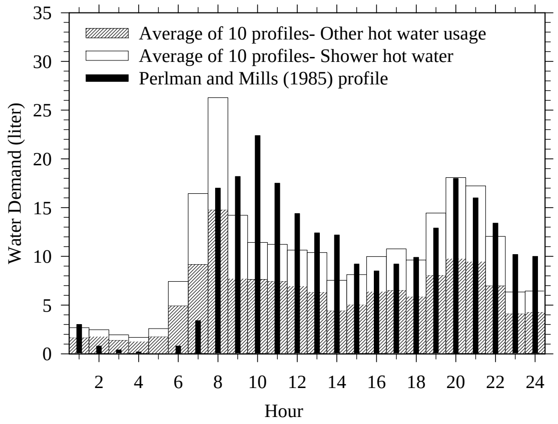

Figure 3: Comparison between the hourly average of the 10 profiles used in this study and Perlman and Mills (1985) profile

Each of the 10 profiles is generated once and read as an independent input file in TRNSYS.

Mains water temperature

In this study, the water mains daily temperature of Montréal is used. As shown in Figure 4, this temperature varies from a low of 1.8ºC in March to a high of 23.1 ºC in August. These measured data were compiled during 2003 (Marcoux and Dumas, 2004). They are read as an input file in TRNSYS.

Hot water tanks

The electric DHW tanks are modeled using type 4e of TRNSYS. A schematic representation of these tanks is shown in Figure 5. Typically, the volume of residential hot water tanks ranges from 175 L (40 gal) to 270 L (60 gal). They have two heating elements with power ratings from 3 to 6 kW. In this study 175 L tanks are used.

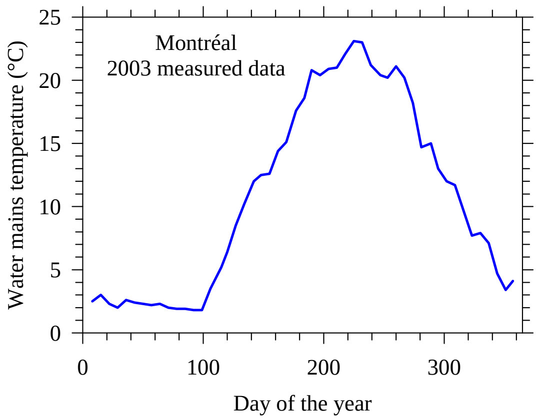

Figure 4: Water mains temperature variations for Montréal

Each tank is equipped with two 3 kW heating elements which operate in flip-flop mode with the highest priority assigned to the top element. The tanks are divided in 10 nodes each with a height of 0.108 m. The upper and lower elements along with their controlling thermostats are located in nodes 2 and 9, respectively. The heat loss coefficient from tanks is set to 2.89 kJ h^{-1} m^{-2} K^{-1} in accordance with current insulation practice for DHW tanks.

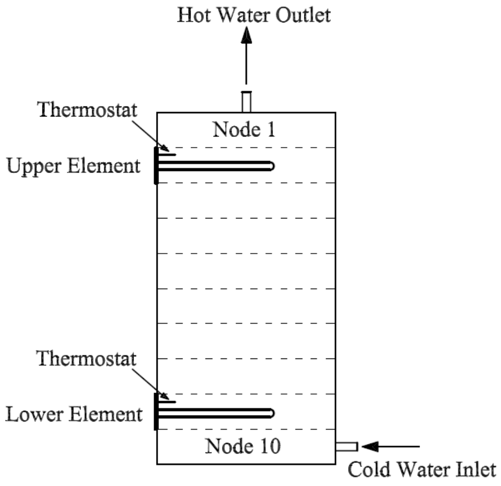

Figure 5: Schematic presentation of a residential hot water tank

The initial hot water tank temperature is 60ºC and thermostats are set to 60ºC with a dead band of 2ºC. The ambient temperature is assumed to be 25ºC.

Shower

The shower is simulated using a mixer TYPE in TRNSYS. This component mixes the amount of hot and cold water to provide a shower temperature of 40ºC. A 4ºC temperature drop between the shower head and the drain is assumed. This value is based on crude temperature measurements performed in a shower.

Grey water heat exchanger

As shown in Figure 1, warm grey water from the shower drain flows inside the drain pipe and at the same time cold mains water circulates inside the spiral coil. The TRNSYS model used in this work is based on the one developed by Picard (2007). It uses the concept of steady-state effectiveness combined with a damping factor. Using the nomenclature presented in Figure 6, the steady-state effectiveness is given by:

$$\varepsilon_{ss} = \frac{\dot{m}_{cold}\, c_p \left(T_{cold,out} - T_{cold,in}\right)}{\dot{m}_{\min}\, c_p \left(T_{drain,in} - T_{cold,in}\right)} \tag{1}$$

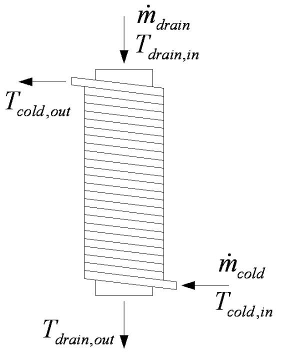

Figure 6: Nomenclature used in the GWHE model

Picard et al. (2006) introduced a damping factor, f , in order to represent the transient behaviour of the GWHE. With this approach, the steady-state equation is modified according to:

$$\varepsilon = f \times \varepsilon_{ss} \tag{2}$$

The value of f is given by:

$$f = 1 - e^{-(t/\tau_{op})}, \dot{m}_{drain} \neq 0$$

$$f = e^{-(t/\tau_{sb})}, \dot{m}_{drain} = 0$$

The time constants, τ_{op} and τ_{sb} , used when the GWHE is operating (op) and during standby (sb) operation are assumed equal to 30 and 300 seconds, respectively. Picard and Bernier (2008) have shown that the heat recovery performance is not significantly affected by the choice of the value assigned to τ_{op} and τ_{sb}. For example, the heat recovery changes by ±5% when τ_{op} changes by ±50%.

The GWHE used in this study is based on a commercially-available model (G3-60 from Waterfilm Energy Inc). The steady-state effectiveness data of the manufacturer has been used to obtain curve fitted values of the steady-state effectiveness (Picard, 2007).

RESULTS

The results section is divided into three parts. First, the simulated DHW electrical demand is compared against the average electrical demand of 600 electric water heaters located in the Montréal area (Couture, 1990). This data is used to establish the validity of the 10 water consumption profiles used in this study. The effect of the entering water mains temperature on the electrical consumption is examined in the second section. Finally, the electrical demand reduction resulting from the use of a GWHE is presented.

Combined effects of 10 different draw profiles

In this first set of results, the average hourly electrical demand resulting from 10 different draw profiles is examined and compared to measured experimental data. This comparison is performed in order to establish that the behaviour of a real set of electric DHW tanks (without GWHEs) can be simulated using only ten different profiles. The experimental data were obtained on 600 electric water heaters located in the Montréal area (Couture, 1990). This sample includes tanks of various sizes and electrical capacities. According to Bouthillier and Bernier (1995), the average water mains temperature was 5ºC during these tests.

The average hourly value of the electrical demand of these 600 electric DHW heaters is shown in Figure 7. This graph shows that these DHW tanks experience aggregated daily peaks of around 1.3 kW at 8:00 and 20:00. Also shown in Figure 7 are the results obtained for the 10 profiles presented earlier. Ten simulations (one for each profile) were performed using a one-minute time interval over the period from November to May where the average water temperature is 5ºC. These results were then averaged for each hour of the day.

The results obtained for the 10 different profiles give an hourly average electrical demand that is in good agreement with the measured data including both peaks. In contrast, the Perlman and Mills profile does not produce an average hourly electrical demand that is close to the measured data.

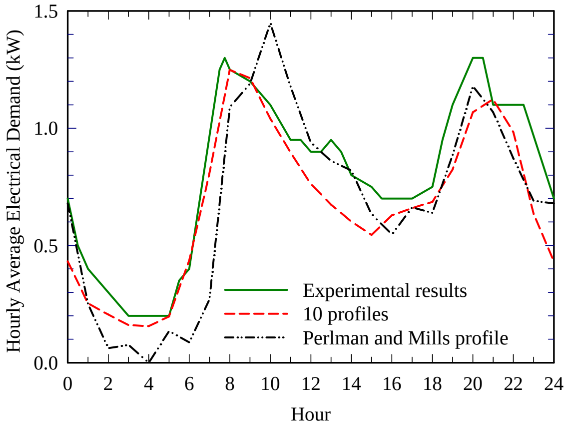

Figure 7. Comparison of hourly average electrical demand

Effect of water mains temperature

The effect of entering water mains temperature on electrical energy consumption of water heaters will now be examined. In this part, two different days (March 30th and September 1st) with almost identical hot water consumption are considered. Two showers with about 900 l/hr flow rate take place in both days and each shower is 5 min long. The DHW flow characteristics are summarized in Table 2.

Table 2. Total shower and other hot water usage flow characteristics of two different days

Day	**Total Shower Draw l/day**	**Other Hot Water Usage Draw l/day**	**Water Mains Temp.**
30 Mar.	148.5	131	1.8ºC
1 Sep.	148	134	20.6ºC

As shown in Table 2, the difference between the flow rates is small. What is different, however, is the water temperature which is 1.8ºC on March 30th and 20.6ºC on September 1st. These days are used to examine the impact of water mains temperature on electrical energy consumption.

The results presented in Figure 8 show that the hot water tank without the GWHE consumes 10.6 kW-hr for an inlet temperature of 20.6ºC whereas the same tank consumes 16.5 kW-hr for an inlet temperature of 1.8ºC. With a GWHE, the corresponding energy consumptions are 9.4 and 13.6 kW-hr, respectively. Thus, the amount of energy recuperated by the GWHE is greater for colder mains temperatures. In the case of Figure 8, 1.6 kW-hr more energy is recuperated by the GWHE on March 30th compared to September 1st. Thus, GWHE may not be a worthwhile investment in areas where the city mains temperatures are relatively high.

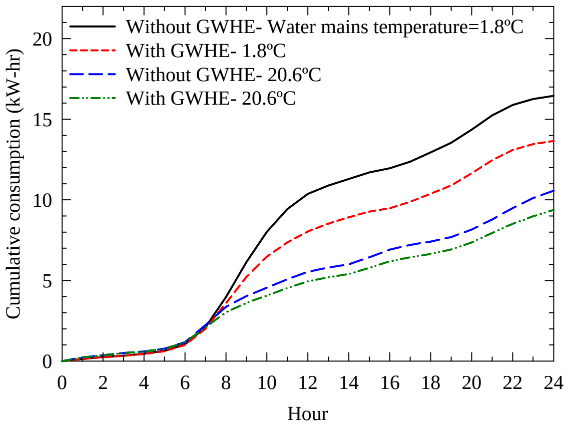

Figure 8. Daily cumulative energy consumption as a function of entering water temperature

Impact on peak electrical demand

In this section, the impact of a GWHE on peak electrical demand is quantified. The 10 profiles presented earlier are used with and without a GWHE. Thus, 20 simulations are performed for 8760 hr (one year) with 15 seconds time step. Once the average of the electrical demand of each time step is determined, an hourly average electrical demand for the whole year is calculated. The resulting averages are plotted in Figure 9.

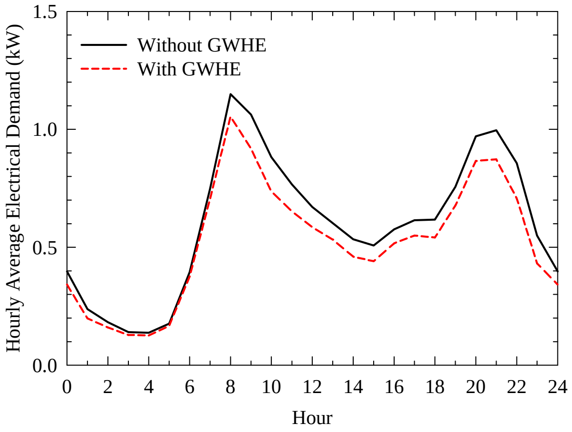

Figure 9. Yearly average of the hourly average electrical demand for DHW with and without a GWHE

As shown in Figure 9 and in Table 3, GWHE have an impact on the peak electrical demand with reductions of 119.4 Watts (10.4% reduction) at 8:00 and 184.0 Watts (21.5% reduction) at 22:00. On an annual basis, it can be shown that the energy required for DHW heating is 4501 and 5299 kW-hr with and without a GWHE, respectively. This represents a difference of 15% on the total energy required for DHW. This value agrees with the ones obtained in other studies presented earlier.

Attention will now be focused on the impact GWHE would have on an electric utility if they were widely used. For this purpose, the total electrical demand of a major utility where electric DHW tanks are widely used has been selected. This demand is shown in Figure 10. It represents the total electrical demand for Hydro-Québec on January 5th, 1989 (Couture, 1990).

The analysis will focus on the impact of using 1.2 million GWHE coupled to an equivalent number of 175 L hot water tanks. As there are approximately 2 million electric hot water tanks in the province of Québec, this represents a 60% coverage.

Table 3. Average electrical demand reduction obtained using a GWHE

Hour	**Electrical demand reduction (W)**	**Hour**	**Electrical demand reduction (W)**
1:00	48.8	13:00	86.0
2:00	27.1	14:00	93.1
3:00	14.6	15:00	80.3
4:00	14.5	16:00	71.9
5:00	10.0	17:00	80.6
6:00	20.0	18:00	94.5
7:00	51.4	19:00	97.3
8:00	119.4	20:00	128.9
9:00	180.4	21:00	154.2
10:00	180.4	22:00	184.0
11:00	137.8	23:00	142.3
12:00	104.1	24:00	66.0

The resulting drop in the total electrical demand shown in Figure 10 has been obtained using the profiles shown in Figure 9.

Results indicate that if 1.2 million electrical hot water tanks were equipped with GWHE, the two daily peaks would experience a reduction of 125 MW (at 12:00) and 155 MW (at 20:00).

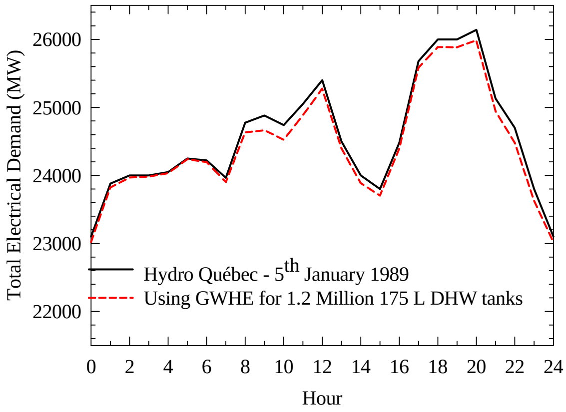

Figure 10. The impact of using GWHE for 1.2 million electric DHW tanks on total electrical demand

It is interesting to look at the economics of such a widespread use of GWHE for an electric utility. The current price of GWHE is approximately $500 CAN. Thus, if Hydro-Québec was to subsidize the installation of 1.2 millions GWHE, the cost would be 3870$CAN per kW of peak electricity reduction (based on the peak reduction at 20:00). This value can be compared to the projected cost of a planned hydroelectric plant (Hydro-Québec, 2008). It will have a 1550 MW capacity and will cost 6.5×10^9 $CAN. The resulting cost is 4200$CAN per kW of production. Thus, this simple analysis reveals that the cost per kW is almost the same for both scenarios.

CONCLUSION

This paper quantifies the impact of grey water heat exchangers on peak electrical demand. Simulations are performed using TRNSYS for different DHW profiles and the actual water mains temperature from Montréal.

In a first set of results, the effects of water mains temperature are examined. The results presented in Figure 8 show that the hot water tank without the GWHE consumes 10.6 kW-hr for an inlet temperature of 20.6ºC whereas the same tank consumes 16.5 kW-hr for an inlet temperature of 1.8ºC. With a GWHE, the corresponding energy consumption are 9.4 and 13.6 kW-hr, respectively.

As shown in Figure 9 and in Table 3, GWHE have an impact on the peak electrical demand with reductions of 119.4 Watts (10.4% reduction) at 8:00 and 184.0 Watts (21.5% reduction) at 22:00. On an annual basis, it can be shown that the energy required for DHW heating is 4501 and 5299 kW-hr with and without a GWHE, respectively.

Finally, results indicate that if 1.2 million electrical hot water tanks where equipped with GWHE, the two daily peaks experienced by Hydro-Québec would see a reduction of 125 MW (at 12:00) and 155 MW (at 20:00).

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