DOMESTIC HOT WATER HEATING IN ZERO NET ENERGY HOMES

Affouda-Léon Biaou, Michel Bernier
Département de Génie Mécanique
École Polytechnique de Montréal
Montréal, Québec
affouda-leon.biaou@polymtl.ca michel.bernier@polymtl.ca

ABSTRACT

The objective of this paper is to examine different means of producing domestic hot water (DHW) in Zero net energy homes (ZNEH). Four alternatives are examined : i) a regular electric hot water tank; ii) the desuperheater of a ground-source heat pump with electric backup; iii) thermal solar collectors with electric backup; iv) a heat pump water heater (HPWH) indirectly coupled to a space conditioning ground-source heat pump.

Energy simulations, using TRNSYS as the simulation engine, are performed to evaluate each alternative. The house simulated has 156 m^2 of conditioned space and is located in a northern climate (Montréal, Canada). On site electrical production is accomplished using efficient photovoltaic (PV) modules generating 197.3 kWh/m^2-year. Space conditioning is accomplished using an Energy Star 2.5 tons ground-source heat pump (GSHP).

Results indicate that the alternative that uses thermal solar collectors is the best solution as it requires only 8.05 kW of peak PV power (compared to 8.75 kW for the next best solution). The total house energy requirements are around 11000 kWh. This amount of electricity has to be produced by the PV modules in order to achieve the ZNEH target.

INTRODUCTION

ZNEH are energy-efficient grid-connected buildings with on-site electrical production from renewable energy sources (in most cases through photovoltaic (PV) panels). ZNEH send electricity to the utility when there is a surplus and draw from the same grid in the case of on-site energy production shortage. The “net-zero” concept implies that, on an annual basis, the excess energy sent to the utility balances the amount received from the grid.

ZNEH have been the subjects of many investigations which have been summarized by Biaou (2004) and Biaou et al. (2004). A more recent publication by Christian (2005) examined four ultra-low energy residences in Tennessee, USA. Even though these homes are strictly not ZNEH, they show that a judicious mix of energy-efficient measures and solar generated electricity can reduce the total energy cost to under $1US/day.

As far as domestic hot water heating is concerned, the article by Merrigan et al. (1990) is noteworthy even though it does not involve ZNEH. Much like the present investigation, they compared four alternative water heating technologies: standard electric water heating; heat pump water heaters; solar hot water systems; and heat pump desuperheaters. Each of the four systems was monitored in twenty single family residences. After two years of monitoring, the authors concluded that the solar hot water systems are the most efficient, followed by heat pump water heaters, desuperheaters and electric resistance water heaters. The solar hot water systems had the greatest electric peak demand reduction. The heat pump water heaters had approximately half the peak demand of electric water heaters in the winter but were unable to reduce summer peak demand by any significant amount. With the same peak demand reduction in winter and in summer, desuperheaters provided less peak demand reduction than the two other alternative technologies.

The present study is based on an earlier study by Biaou et al. (2004) who performed simulations on an energy-efficient (R-2000) home located in Montréal and equipped with a photovoltaic array and a 2.5 tons ground-source heat pump. Results indicated that the ground-source heat pump reduced energy consumption significantly and that it is possible to achieve a net-zero energy balance with an annual PV production of 13550 kWh. The electrical peak demand and the electrical consumption are respectively 59% and 44% lower than that required by an all-electric house. Biaou et al. (2004) also showed that about one third of the annual electricity requirement is used for space heating/cooling. Another third is used by electrical and lighting appliances. Finally, domestic hot water heating requires the other third. In other words, domestic hot water production requires as much energy as space heating/cooling. Clearly, if one wants to reduce the annual electricity needs and the associated capital cost of the PV system, then the efficiency of DHW production has to be improved. The objective of this paper is to examine the most efficient way of producing domestic hot water in ZNEH.

DESCRIPTION OF THE ZNEH

Generalities. The ZNEH studied in this paper is presented schematically in Figure 1. The four alternatives for DHW production, which will be presented shortly, use this basic house configuration. It consists of a well-insulated two-story 156 m^2 residence with an unheated half-basement. It is equipped with a PV array whose size will depend on several factors including how DHW is produced.
The direct current (DC) electricity generated by the PV array is converted to alternating current using an inverter. Then, the solar electricity is either used in the house or sent to the grid in the event of a surplus. When solar electricity production is insufficient, the house draws the necessary power from the grid.
One key element of this ZNEH is the closed-loop water-to-air ground-source heat pump (GSHP) which is used for space heating and cooling. As shown in Figure 1, a fluid is pumped from the GSHP to a ground heat exchanger which acts either as a source (heating) or as a sink (cooling). On the air side, the heat pump distributes cool or warm air in the house for space conditioning. With its relatively high COP in both heating and cooling, the GSHP enables an efficient use of solar electricity.

Appliances (including lights) require electricity which influences the size of the PV array. Also, electricity fed to appliances will ultimately be converted to heat. If this heat is released in the conditioned space, then it will decrease the heating load in winter and increase the cooling load in summer.

The four alternatives for DHW production will now be examined.

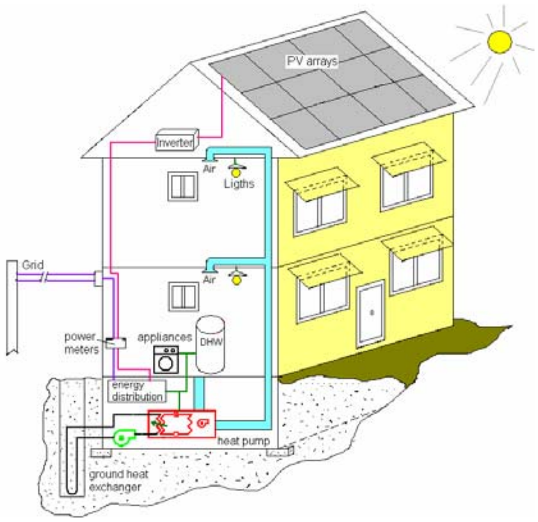

Figure 1: Schematic representation of the ZNEH studied here

Alternative 1: Electric water heater. The first system studied is a conventional electric hot water tank (Figure 2). Two electric resistances provide the power to heat the water from the mains temperature to the set point temperature. They operate in master/slave mode, with the highest priority assigned to the top element.

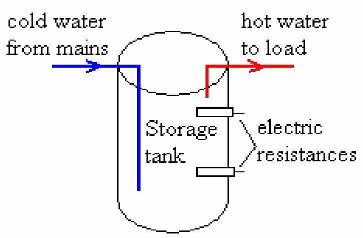

Figure 2: Electric water heating (Alternative 1)

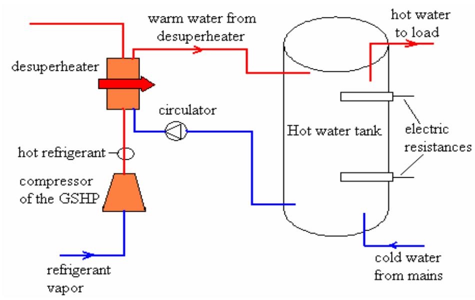

Figure 3: Domestic hot water heating using a desuperheater (Alternative 2)

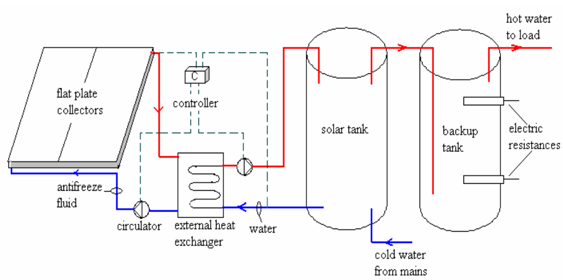

Figure 4: Solar domestic water heating system (Alternative 3)

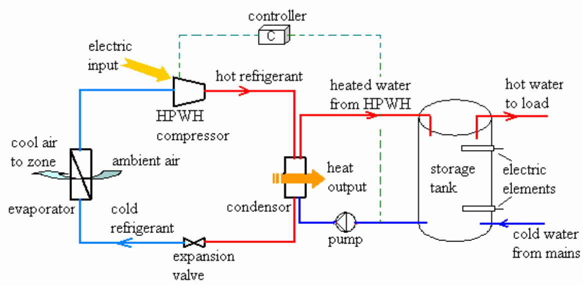

Figure 5: Heat pump water heater system (Alternative 4)

Alternative 2: Desuperheater. The second water heating system under consideration uses a GSHP desuperheater combined with a regular electric hot water tank. As shown in Figure 3, a desuperheater is a refrigerant-to-water heat exchanger located between the compressor and the condenser. Heat exchange is only possible when the GSHP is providing space heating or cooling. When the heat pump is activated, a circulator draws cold water from the tank bottom, passes it through the heat exchanger and returns it to the top of the hot water tank. When the GSHP is in cooling mode, there is a "free" heat exchange in the desuperheater which reduces the load on the condenser and, consequently, the amount of heat rejected to the ground. In heating mode, the heat recovered in the desuperheater translates into a loss of space heating capacity normally provided by the condenser of the GSHP. Thus, the GSHP has to operate for a longer period to meet the space heating requirements. In this case, the hot water produced is not "free" but nonetheless obtained with a relatively high COP.

Alternative 3: Solar water heating. The third alternative is a thermal solar system. The configuration chosen (Figure 4) is typical for a cold climate where freezing is a concern. As shown in Figure 4, the system is composed of flat plate solar collectors, an external heat exchanger (EHX), a solar water storage tank and a regular electric backup water tank, two circulators and a temperature controller. The solar tank is connected to a regular hot water tank equipped with two electric resistances which provide auxiliary heating if necessary. The solar system is operated by a differential thermostat. Two temperature sensors give the fluid temperature at the outlet of the solar collectors and at the bottom of the solar water tank. Whenever the heat exchanger hot side inlet temperature is higher than the temperature of the water at the bottom of the tank by more than 5°C, the two pumps are switched on. The pumps are turned off whenever this difference is lower than 1°C.

Alternative 4: Heat pump water heater. The last water heating system studied here is a heat pump water heater (HPWH) (DOE, 1995). As shown on Figure 5, a HPWH uses air as its energy source to heat water. In doing so, it cools the air. The cooled air can then be exhausted into the house (ambient-air HPWH) or exhausted outside the house (exhaust-air HPWH). In the first configuration, used here, the cooled air increases the house heating load in the winter whereas it decreases the cooling load in the summer. The water is circulated from the tank to the HPWH condenser where the hot refrigerant transfers its heat to the water. The heated water then returns to the storage tank where electric elements provide the supplementary heat if required. The operation of the HPWH is regulated by a controller which turns on the compressor whenever the temperature of the water at the bottom of the storage tank is lower than 50°C. The system is turned off when this temperature reaches 55°C. When combined with a space-conditioning ground-source heat pump in heating mode, the utilization of an ambient-air HPWH consists in fact in a transfer of energy from the ground to the air and then to the water. The efficiency of this two step heating process is a function of the COP of the GSHP and of the HPWH. For example, if both COP are equal to 3, then the ratio of hot water production over purchased energy (which will be referred to later as the Energy Factor) is 1.84 indicating that this hot water system produces 1.84 kW of hot water for every 1 kW of electricity sent to the GSHP and HPWH. In cooling mode, the HPWH reduces the house cooling load seen by the GSHP.

HOT WATER CONSUMPTION

The domestic hot water consumption profile used in the present study is given in Figure 6. It is based on a study by Perlman and Mills (1985).

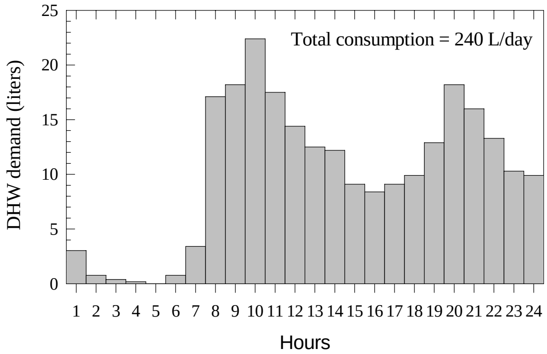

Figure 6: Hourly domestic hot water consumption

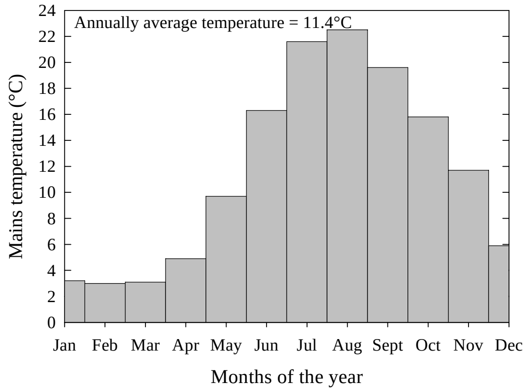

Figure 7: Mains monthly average temperature for Montreal

Figure 7 presents the mains monthly average water temperature for Montréal. These data were collected by Dumas (1994). As it can be seen, the mains temperature varies from a low of 3°C in February to a high of 23 °C in August. In all cases presented here, water was heated from these monthly temperatures to a set point temperature of 55 °C giving required water temperature rises of 52°C in February and 32°C in August. Thus, the summer and winter water heating loads are significantly different.

SIMULATION-MODELS

Generalities. The ZNEH is simulated using TRSNYS 15.3 with the IISIBAT 3.0 interface (Klein, et al, 2000). Most components are modeled using TRNSYS's standard library or the TESS library (TESS, 2001). Following is a description of the main components used. The reader is referred to an earlier work for a more complete description (Biaou et al., 2004). Annual simulations are performed using a one-hour time-step. The WYEC2 weather (ASHRAE, 1997) for Montréal is employed.

House. The house studied is a two-story 156 m^2 residence with an unheated half-basement. The house characteristics are given in Table 1. The overall UA-value of the building envelope is approximately 85 W/°C including windows. The thermostat set-point temperatures are 20 and 25°C in winter and in summer, respectively.

Table 1: House characteristics

Dimensions	
Conditioned area	156m^2 (6m×13m×2 floors)
Conditioned volume	468m^3(6m×13m×3m×2 floors)
	88.4 m^2/64.35m^2
Roof area (south/north)	187.2m^3
Attic volume	1.5m/117m^3
Basement (height/volume)	38.4m^2
Window area	3.6/27.3/3.6/3.9 m^2
East/south/west/north	
Envelope	
Window	Triple pane, low-e U=0.4 W/m^2°C, SHGC=0.408
Conditioned space walls	U=0.21 W/m^2°C
Conditioned space floor	U=0.27 W/m^2°C
Conditioned space ceiling	U=0.112 W/m^2°C
Basement wall	U=0.28 W/m^2°C
Roof	PV arrays on the south Tilted at 45°

As shown in Table 1, most of the window area is located on the south side of the house to take advantage of passive solar gains in winter. The window selected has a low U-value in order to reduce heat losses at night. Finally, as shown in Figure 1, overhangs are used on the south side to avoid overheating in mid-seasons and in summer.

The house is modeled using TRNSYS's TYPE 56 (In the TRNSYS terminology, a model is referred to a TYPE) as three distinct thermal zones: living quarters, attic and basement. The last two zones are unconditioned and, therefore, the temperatures in these spaces are free-floating. The living zone and the attic are modeled in Prebid (TRNSYS's building input description pre-processor) while basement heat losses are handled with a model developed in-house (Biaou et al. 2004). TYPE 34 is used to model the overhangs. House infiltration is calculated using a technique presented by ASHRAE (1981) which is detailed in the previous investigation by Biaou et al. (2004). It is assumed that the house is occupied by a family of four persons who perform light work.

The hourly electrical power demand profile from the electrical appliances (including lights) is based on the work of Gunes et al. (2003). When cumulated over a year, the annual electricity consumption for appliances is 4659 kWh (Biaou et al., 2004). It is assumed that the entire electrical load is instantly converted into heat and thus becomes a heat gain.

Geothermal system. The geothermal system includes the GSHP and the ground heat exchanger (GHE). Originally developed by TESS (TESS, 2001), the GSHP model used here was modified by Lemire (1999) to account for the time of operation of the heat pump during a simulation time step. A thermostat TYPE, also written by Lemire (1999), controls the operation of the heat pump. It calculates the time of operation required, during a simulation time step, to maintain the heating and cooling set point temperatures. These set point temperatures are 20°C in heating and 25°C in cooling (with a deadband of 1°C).

The modeled ground-source heat pump is a high performance Energy Star model (ClimateMaster, 2003). It has a nominal cooling capacity of 8.75 kW (2.5 tons) and a COP ranging from 3 to 6. The performance of this GSHP is modeled using coefficients generated by curve-fitting the manufacturer's data (Biaou et al. 2004).

The GHE consists of a closed-loop U-tube made of high density Polyethylene. The so-called DST model of Hellström et al. (1996) was used to model the GHE. Based on preliminary simulations, a 100 m borehole length was chosen. This length was sufficient to keep the fluid temperature at the GSHP inlet above -3.5^{o}C, the lower limit recommended by the manufacturer.

Photovoltaic system. Solar electricity is generated by a photovoltaic system composed of PV modules and an inverter. No on-site electrical storage is provided. The PV array is modeled using TRNSYS's TYPE 94. TYPE 94 uses a so-called "four parameter" model which treats a PV array as an irradiance and temperature dependent current source connected in parallel with a diode and in series with a resistor and the load. The model was largely discussed by Fry (1998), Biaou et al. (2004) and Biaou (2004). The module used here is a 1.22 m^2 mono-crystalline silicon panel with a peak power of 175 Watts at standard test conditions (irradiance=1000 W/m^2; cell temperature=25°C; AM=1.5). The module nominal efficiency is 13.3% which is about 16% higher than the one previously used by Biaou et al. (2004). It should be noted that PV cells are more efficient in colder temperature. In fact, the efficiency increases by about 0.5% for each ^{o}C below 25^{o}C.

Electric water heater (Alternative 1). The hot water tank is modeled using TYPE 60 of TRNSYS. The model simulates a stratified storage tank by performing an energy balance on fully mixing nodes to evaluate the fluid temperature, the energy transferred to the water, the required heating rate and tank heat losses. The simulated tank has the following geometry: 0.21 m³, height of 1.5 m and a diameter of 0.42 m. It is equipped with two 0.75 kW electric resistance heaters located at a height of 0.35 and 1 m from the bottom of the tank.

Desuperheater (Alternative 2). As shown in Figure 3, the warm water produced by the desuperheater is fed to a regular 0.21 m³ hot water tank equipped with two backup electrical resistance heaters. The cold water is drawn from the tank bottom and hot water is fed to the top of the tank in order to improve heat transfer in the desuperheater and to avoid destratification. A small circulator pumps the water from the tank to the desuperheater. The original TRNSYS water-to-air GSHP model developed by TESS (2001) was modified to simulate the heat transfer from the desuperheater to the water (Biaou et al., 2004).

Solar water heating (Alternative 3).
Alternative 3 consists of a typical solar water heating system. It is presented schematically in Figure 4 and the key features are summarized in Table 2. All components used in this system are modeled using standard TRNSYS 15 models. The flat plate solar collector model performs an energy balance to obtain the amount of heat transferred to the fluid. The model uses the characteristics of the collector (area, fin efficiency, loss coefficient, emittance and absorptance of the absorber plate), the weather conditions (irradiances, ambient temperature, and wind speed) and the installation features (collector slope, heat transfer fluid specific heat). The collector and storage loops are separated by an external heat exchanger (EHX) which is modeled here by assuming a constant UA value. Both tanks are modeled using TYPE 60 of TRNSYS.

Table 2: Solar water heating system characteristics

Flat plate solar collector	
Collectors area	6m^2 (2panels)
Slope of collector	45° southern roof
Absorber (selective surface)	absorptance=94%; emittance=5%
Collector fin efficiency	0.8
Bottom and edge losses coefficient	U=0.48 W/m^2°C
Heat transfer fluid	Mix of water and propylene glycol (30%); Cp=4 kJ/kg°C
Heat exchanger	
Overall heat transfer coefficient	380 W/°C
Cold side flow rate	50 kg/h
Hot side flow rate	150 kg/h
Pumps(2)	20 Watt nominal power
Solar storage tank	
Capacity	0.21 m³
Insulation	R=2.8 m^2°C/W
Backup water tank	
Capacity	0.21 m³
Insulation	R=2.8 m^2°C/W
Electric resistances (2)	0.75 kW each

Heat pump water heater (Alternative 4). Due to the unavailability of HPWH models and because of the lack of detailed performance data, a simple HPWH model was created to simulate the behavior of Alternative 4. Since the evaporator (house) and condenser (tank) sides of a HPWH operate at two relatively constant temperatures, the model assumes a constant COP. This value is equal to 2.4 based on existing HPWH (ECR International, 2003). Given this value and using other typical characteristics (Table 3) such as the nominal heating capacity, the model performs simple energy balances to obtain the electric input and the amount of energy removed from the ambient air. This energy is considered as a heat loss in the house model. The HPWH is coupled with a regular water storage tank which is simulated, like the other three systems, with TYPE 60.

Table 3: Characteristics of the HPWH

Heat pump water heater	
Nominal heating capacity	1500 W
COP	2.4
Air flow rate	900 kg/h
Water flow rate	100 kg/h
Storage tank	
Capacity	0.210 m³
Insulation	R=2.8 m^2°C/W
Electric resistances (two)	0.75 kW each

SIMULATION-RESULTS

Loads. Results presented in this section are based on the house described in Table 1. Figure 8 shows the hourly space conditioning loads. As shown, the peak heating and cooling loads are approximately 8.5 and 4 kW, respectively. Annually, space heating and cooling energy requirements are 11340 and 2031 kWh, respectively. Compared to a previous work performed on a similar house (Biaou et al., 2004), the annual heating needs are reduced by 18% while the annual cooling needs are increased by 16.5%. However, since cooling requirements are relatively small, the total space conditioning needs are reduced by about 14.5%. This is achieved by using high performance windows and overhangs and multiplying the south-side-window area by 3.5. Therefore, in winter, the heating load is reduced by passive solar gains.

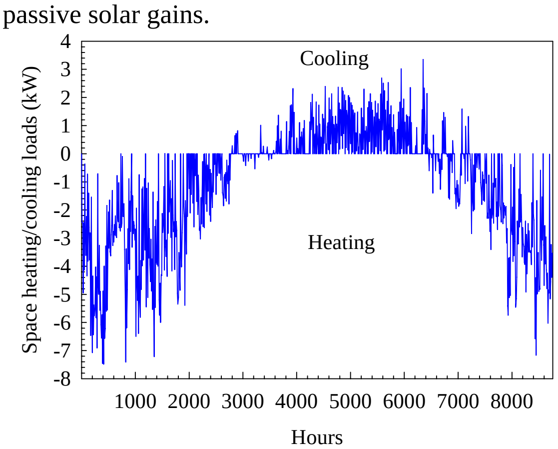

Figure 8: Hourly space heating and cooling loads

In summer, although the solar gains contribute to the cooling loads, only a small part of the solar radiation reaches the house due to the shading effects of the overhangs.

The annual energy needs for domestic water heating are 4605 kWh while appliances require 4659 kWh. Overall, if one assumes that the house is electrically heated (space and water) and cooled with an electrically-driven air-conditioning with a COP of 3, then the amount of electricity needed by the house is 21280 kWh (with 12017 kWh for space conditioning).

Equipment performance. The annual performance of two key technologies, i.e. the GSHP and the PV array, are presented in Figures 9 and 10. Figure 9 shows the hourly average coefficient of performance of the GSHP and the corresponding entering fluid temperature in the GSHP (= exit temperature from the ground heat exchanger). As shown on this figure, the COP ranges from a minimum of 3 in winter to a maximum of 6 at the beginning of the spring season. In the former case, the minimum is reached when the entering fluid temperature is at its lowest. In the later case, the high COP can be explained by the fact that the entering fluid temperature is relatively cold at the end of the winter season due to the amount of energy collected in the ground for heating purposes. As spring and summer progresses the COP decreases due to an increase in fluid temperature.

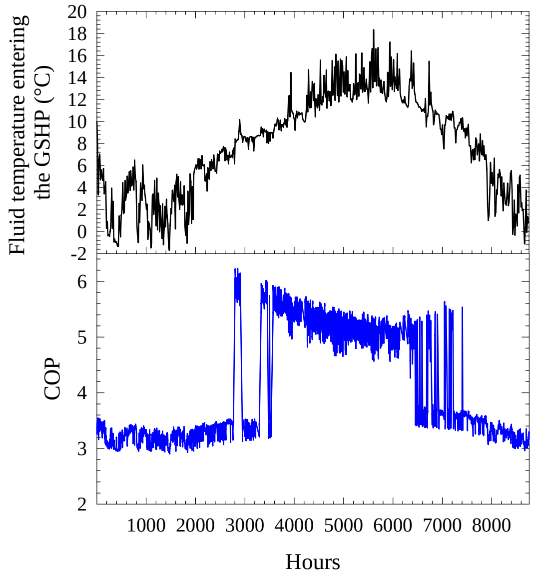

Figure 9: Hourly values of fluid temperature entering the GSHP and corresponding COP.

With such high efficiency in both heating and cooling it is not surprising that the space conditioning needs are reduced to 4222 kWh with a corresponding reduction of the annual electricity needs to 13914 kWh (compared to 21280 kWh for the base case). Consequently, space conditioning now represents only about 1/3 of the overall energy consumption of the house. The other two thirds are spilt about equally between domestic hot water heating (4605 kWh) and appliance requirements (4659 kWh). Thus, as indicated earlier, domestic hot water heating becomes as important as space conditioning in a ZNEH equipped with a GSHP. Figure 10 presents the hourly efficiency of the solar photovoltaic array. As shown on Figure 10, the efficiency of the PV modules varies from a minimum of 10% to a maximum of 16%. The highest efficiencies occur in winter. As indicated earlier, this is due to a negative temperature coefficient which causes an increase in cell efficiency in cold weather. The annual average efficiency is 13.27% and the yearly solar electricity produced is 197.3 kWh/m^2.

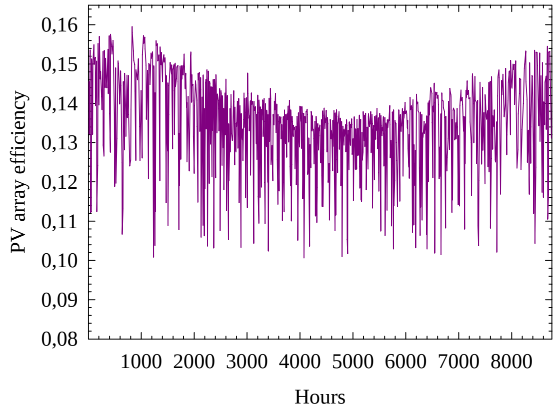

Figure 10: PV arrays efficiency

Comparison of the four alternatives. A comparison of the four alternatives of providing domestic hot water in a ZNEH is presented in Tables 4 and 5. As shown in the second column of Table 4, the domestic hot water loads are larger in winter than in summer. As indicated earlier, this is because the water mains temperature is lower in winter. The total annual water heating load is 4367 kWh (excluding tank heat losses). However, the amount of electricity required to deliver that amount of heat will vary with each alternative.

In Alternative 1, a total of 4605 kWh of electricity are required to meet the load.

When a desuperheater is used (Alternative 2), 2895 kWh are needed. The amount of “free” energy supplied by the desuperheater is high in winter but low in summer. For example, in January, the desuperheater supplies 73% of the needs while only 11.5% of the load is met in June. This behaviour is linked to the fact that the desuperheater only works when space conditioning is required. Since the space cooling load is small in the summer, the heat pump and the desuperheater are most often not operating. Overall the annual contribution of the desuperheater to water heating is about 40%. Solar thermal heating appears to be an attractive way to produce hot water as only 1410 kWh of electricity are required. The annual solar contribution is about 73%. Alternative 4 which uses a HPWH ranks reasonably well with a required electric input of 2116 kWh.

Table 5 presents detailed results on each alternative. In this Table, the energy required by circulators is accounted for as well as the impact of domestic hot water heating on the energy requirements of the GSHP. The heat output is the actual heat transferred to the water including the energy required to compensate for tank heat losses. The overall electric input is the total electric consumption including the requirements of the tank, the circulators (alternatives 2, 3 and 4) and the GSPH supplemental consumption attributable to the water heating systems (alternatives 2 and 4). In the case of Alternative 2, the GSHP requires 490 kWh to heat the water via the desuperheater. For Alternative 4, the use of an ambient-air HPWH increases the annual heating load by 1585 kWh and decreases the cooling load by 534 kWh. The end result, as shown in Table 5, is that the GSHP needs 392 kWh to supply supplemental space conditioning used by the HPWH.

In Table 5, the four alternatives are compared using a benchmark, the "energy factor" (EF) borrowed from domestic hot water tank testing terminology. The EF is defined as the ratio of heat output over electric input. Alternative 3 has the best EF at 3.11 followed by Alternative 4 at 1.85.

Table 4: Monthly energy requirements for water heating (kWh)

Months	Loads	**Alternative 1** Electric heating	**Alternative 2** Desuperheater		**Alternative 3** Solar heating		**Alternative 4** HPWH	
			Electric backup	Desuper heater	Electric backup	Solar energy	heat output	electric input
Jan	443	470	135	375	259	212	493.5	220
Feb	404	420	144	307	148	274	438	188
Mar	446	464	244	244	136	354	484.5	211
Apr	416	435	345	99	95	381	448.5	198
May	382	403	394	11	56	406	420	189
Jun	316	335	298	39	29	394	360	152
Jul	283	304	219	85	10	422	325.5	139
Aug	277	297	216	80	18	383	325.5	138
Sep	291	310	255	55	48	351	322.5	152
Oct	330	351	295	64	120	260	381	161
Nov	358	378	224	174	221	156	405	171
Dec	421	438	127	345	270	158	465	197
Total	4367	4605	2895	1877	1410	3751	4879	2116

Table 5: The energy factor for the four alternatives

	ZNEH with one of these alternatives			
	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Heat output (kWh)	4367	4501	4825	4705
Tank loss (kWh)	238	271	359	221
Circulators (kWh)	0	45	127	31
Effect on GSHP (kWh)	0	490	15	392
System electric consumption (kWh)	4605	2895	1410	2116
Overall electric input (kWh)	4605	3430	1552	2539
Energy factor	0.95	1.31	3.11	1.85

Impact on the PV array size. As indicated in Table 6, the type of domestic hot water system will have an impact on the overall energy consumption of the ZNEH and on the size of the required PV arrays. The fourth line of Table 6 presents the total annual energy needs preceded in the first three lines by a breakdown between space conditioning needs, domestic hot water and appliance requirements. As shown in this table, the lowest electrical needs are for Alternative 3 with a total of 10864 kWh. This amount of energy can be produced by 46 PV panels whose total installed peak capacity is 8.05 kW. The house using the HPWH shows the second lowest PV size, followed by the desuperheater configuration. When the best and worst solutions (Alternatives 1 and 3) are compared, there is approximately a 20% difference in PV array size.

Table 6: ZNEH PV system size

	ZNEH with one of these alternatives			
	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Space Conditioning (GSHP) (kWh)	4222	4712	4237	4614
Domestic hot water (kWh)	4605	2940	1537	2147
Appliances (kWh)	4659	4659	4659	4659
Total electrical needs (kWh)	13914	12792	10864	11873
Number and area(m²) of PV modules	60/73.2	54/65.9	46/56.1	50/61
Required installed power (kW)	10.5	9.45	8.05	8.75
PV production (kWh)	14368	12932	11016	11974
% above ZNEH	3.3%	1.1%	1.4%	1%

The energy flows in a ZNEH equipped with alternative 3 are shown in Figure 11. The quantities in normal character represent thermal energy while the quantities in bold and underlined represent electricity flows.

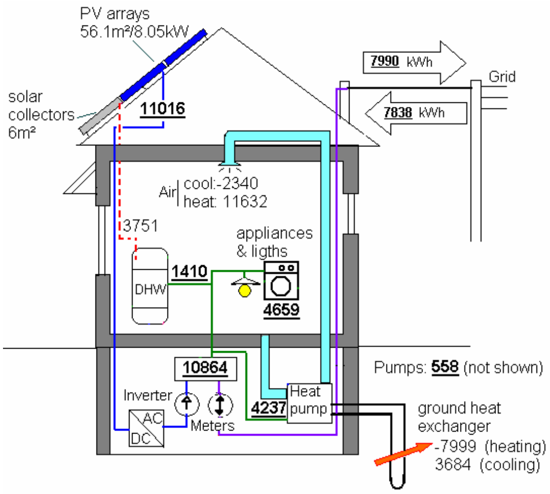

Figure 11: Energy flow of the ZNEH with solar collectors

It is interesting to note that the GSHP draws annually 7999 kWh from the ground while in heating mode and rejects 3684 kWh in cooling mode. Pumps (three in Alternative 3) require a total of 558 kWh. On the electrical side, the house sends annually 7990 kWh to the grid and takes from the same grid 7838 kWh giving essentially a zero net energy home.

CONCLUSION

This paper examined different means of producing domestic hot water in zero net energy homes equipped with PV modules for on-site electrical production. Four alternatives are examined : i) a regular electric hot water tank; ii) the desuperheater of a ground-source heat pump with electric backup; iii) thermal solar collectors with electric backup; iv) a heat pump water heater (HPWH) indirectly coupled to a space conditioning ground-source heat pump. The house simulated has 156m^2 of conditioned space and is located in Montréal (Canada).

Results indicate that the alternative that uses thermal solar collectors is the best solution as it requires only 8.05 kW of peak PV power (compared to 8.75 kW for the next best solution). When this alternative is combined with an Energy Star 2.5 tons ground-source heat pump for space conditioning, the total house energy requirements are around 11000 kWh. This amount of electricity has to be produced by the PV modules in order to achieve the ZNEH target.

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