MAJOR ASPECTS OF THE ENERGY SYSTEM DESIGN OF THE ALSTONVALE NET-ZERO ENERGY HOUSE

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ABSTRACT

This paper discusses the selection of some of the main components of the Alstonvale Net Zero House (ANZH), one of the winning designs of the CMHC EQuilibrium demonstration program, with the focus primarily on the energy system design. These components include the framing system of the BIPV/T, the air-to-water heat exchanger, the solar hot water collector, the thermal storage tank, the heat pumps and the backup system. The selection of this equipment required modifications of the previous conceptual design of the ANZH. The rationale for these changes and the final design are presented in this paper. Additional simulation results are presented and discussed.

INTRODUCTION

In 2007, the Canada Mortgage and Housing Corporation (CMHC) announced the 12 winners of its *EQuilibrium Initiative*, a design competition aimed at generating net zero energy demonstration homes throughout Canada. The ANZH, designed by an interdisciplinary Montréal team, was one of those selected (see Fig. 1).

Figure 1. Alstonvale Net Zero House

The goal of the ANZH has evolved from the objective of becoming a net zero energy house, towards demonstrating the attainability of a more encompassing "net zero energy lifestyle". In other words, the ANZH aims to generate all the energy required for the household's domestic as well as local transportation energy needs. By incorporating a garden, it will facilitate on-site food production in order to displace agricultural imports as much as possible.

The ANZH was designed to take advantage of passive solar heating. Triple-glazed windows (providing solar heat gains and daylighting) form 43% of the south façade and complete an air-tight building envelope with high insulating value (5.6 RSI in the walls, 12 RSI in the ceiling and 4.6 RSI in the floor). An internal masonry wall and 6-inch thick concrete floors provide large thermal inertia to the building, dampening the temperature fluctuations and storing heat from solar radiation and the HVAC system. This house was also designed to make use of energy efficient appliances and lighting, and incorporates several measures for the sensible use of domestic hot water. The building integrated photovoltaic/thermal system (BIPV/T), located on its roof, constitutes the main energy supply system of the house (Candanedo et al., 2007).

Fig. 2 shows the essential elements of the *preliminary* conceptual design of the ANZH (Candanedo et al., 2007), as it was in early 2007. The basic elements of this design were:

- Forced air convection was used to recover heat from the 5.5 kW_P BIPV/T roof.
- An independent heat exchanger (HX) for the direct transfer of heat between the BIPV/T air and the reservoir. This HX could be by-passed by operating a damper.
- A 14 kW (3.5 Ton) air-to-water heat pump (HP) with an incorporated fan.
- An evacuated tube solar collector array located on the roof would be used for the domestic hot water (DHW) production.
- Heat delivery to the space via a radiant floor heating system.
- Alcohol (ethanol) burners operating as the backup heating system.

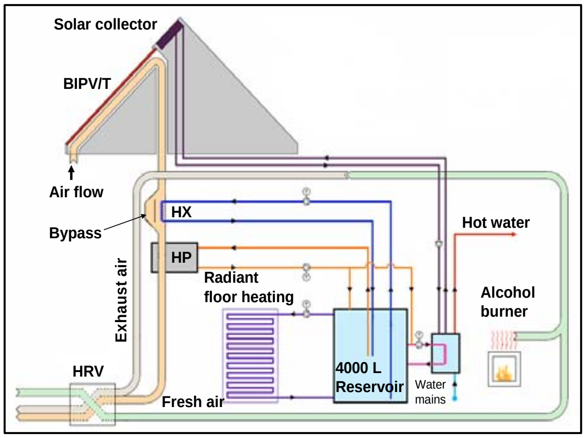


Figure 2. Preliminary design of the ANZH mechanical system.

The annual energy consumption of the ANZH was estimated to be 7000 kWh, of which about 2500 kWh was to be used for heating. Approximately 60-80% of the heating load was to be covered by the BIPV/T-HX-HP group, with the remainder being supplied by the backup system.

After the completion of the conceptual design, the next step was the selection of equipment and design of the final configuration of the house. This step proved challenging due to the lack of design guidelines for solar-optimised homes and commercial products specifically designed for BIPV/T installations.

MODIFIED FINAL DESIGN

BIPV/T Roof

The first important modification of the ANZH was the increase of the generating capacity of the PV panels from 5.5 kW_P to 7 kW_P. The additional 1.5 kW_P has been included to supply much of the power needed for a plug-in hybrid-electric vehicle. The consumption per charge of a hybrid-electric has been estimated to be 9 kWh, allowing the user to drive for 40 km (Moore, 2005). Assuming that three charges are required per week, about 1400 kWh are needed per year. A RETScreen (2007) calculation indicates that 1.5 kW_P at 45° generates approximately 1840 kWh of electricity per year in Montréal.

The main source of space heating of the ANZH is the roof, and choosing an adequate framing system for the BIPV/T and the glazing was a necessity. The main requirements included ease of installation, resistance to high temperatures (above 90°C), capacity to withstand thermal expansion, and reasonable cost.

Initially, an air-tight BIPV/T system with a single inlet at the soffit was considered in order to achieve high temperatures at the outlet. Curtain wall technology was evaluated to achieve this. However, air tightness was deemed not essential, as allowing some exterior air to enter along the BIPV/T channel enhances the overall thermal efficiency. It was finally decided that the framing system to be used would be Solrif (Solrif, 2007). This swiss product previously used at the Concordia Solar House in 2005 (Pasini and Athienitis, 2006), permits some degree of leakage at the joints between frames.

Solar Collector for DHW

A 12 m^2 flat plate collector was initially specified, with an estimated heat production of nearly 25,000 MJ/year. The initial location considered was the roof. In order to have a uniform construction on the roof and improved aesthetics, the solar collectors were moved to the overhangs of the south façade. They were also replaced with two evacuated tube solar collectors (AP-20), each with about 3 m^2 of gross area and 20 tubes. Fig. 3 shows the approximate solar fraction of the domestic water heating system according to a RETScreen simulation, assuming a usage of 130 L/day. It has also been assumed that the "Power-pipe", a heat exchanger that preheats the make-up water using grey water, contributes significantly to increasing the cold water temperature in the RETScreen simulation. The size of the DHW tank has also been increased from 300 to 400 L. The solar collector loop will have a heat dissipater to release the excess heat, mainly in the summer months. In addition, a motorized canopy will be used to cover the solar collector. This canopy can be extended over the edge of the overhangs to improve the shading of the south-facing windows in summer.

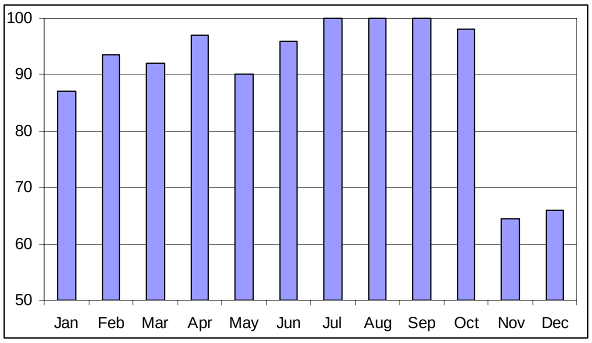


Figure 3. Estimated solar fraction with two evacuated tube collectors.

Heat Exchanger

The original BIPV/T air duct configuration included a bypass for the HX in order to reduce the pressure drop that the fan had to overcome, thus reducing energy expenditure. However, the expected pressure drops for the design flow rates were rather small. On the other hand, finding a satisfying air-to-water HP proved difficult. Finally, simulations indicated that using the HX and HP in series would seldom be required.

Considering the aforementioned factors, the ducting system coming from the BIPV/T roof was re-designed to use a single air-to-water HX for (a) direct heat transfer between the air and the water, and (b) use of BIPV/T air as a source for the heat pump. This design required a HX that had to operate in a wide range of flow and heat transfer rates. The water side (actually using a mixture of water and glycol) needed flow rates between 0.57 L/s (9 gpm) and 1.13 L/s (18 gpm); the air flow rates would be between 472 L/s (1000 cfm) and over 943 L/s (2000 cfm); the heat transfer rates would vary from 5 kW to more than 20 kW. Naturally, this heat exchanger would have a much larger total heat transfer area than most heat exchangers used in residential applications. The model chosen was the one suggested by a manufacturer (Madok), having 8-rows of coils, with 16 passes in total, 0.914 m (36 inches) by 1.27 m (50 inches), with a total face area of 1.16 m^2 (12.5 ft^2). The small rated value of the pressure drop on the air side, varying between 15 and 42 Pa, confirmed that a bypass duct is not needed.

The original location of the HX was the mechanical room in the basement. Considering its size, it will be located in the garage, where there is also room for smooth, rather than abrupt, duct transitions.

Heat Pump Configuration

The heat pump system is the most important piece of equipment of the ANZH. The heat pump chosen had to deliver the required peak heating load (estimated at 12-13 kW). It also had to operate at partial load under varying flow rates and temperatures, with a good COP (preferably above 5). It is important to have the lower temperature limit of operation at the source side as low as possible (preferably below 0 °C), in order to extend the range of the HP operating conditions, as this will reduce the need for the operation of the backup system.

The Tranquility^{TM} series (ClimateMaster, Inc., 2007), a water-to-air heat pump that can operate in reverse mode was an early good candidate; having two stages, an integrated fan and high COPs. However, it was decided not to use this device because it is not designed to work with air inlet temperatures near the freezing point, and most importantly, there was some uncertainty about its interaction with the supervisory control system.

Commercial heat pump water heaters were also evaluated. A technical report of the US Department of Energy (US DOE, 2000) refers to several products commercially available. However most of them are designed for warmer climates and the coldest air temperature they can handle is typically about 10 °C.

Products from Europe were considered: the air-to-water Vitocal^{TM} 350 AW manufactured by Viessmann (Germany) can work with temperatures as low as -15 °C (Viessmann, 2006), and Thermia Atria (Sweden) claim that their heat pumps operate with air temperatures as low as -20 °C (Thermia, n.d.). However, the lack of local availability of the product, service and refrigerant, made these choices inappropriate.

The use of CO_2 heat pumps was also investigated (Fry, 2007). Carbon dioxide has been used as a refrigerant for heat pump water heaters in Japan, which receive the name of EcoCute (Nihon ITOMIC, 2008; Kansai, 2006; Sanyo, n.d.). These CO_2 heat pump water heaters offer the advantage of working at very low temperatures at the source side (down to -20 °C), and delivering hot water at temperatures as high as 90 °C. Heat pumps using CO_2 have been proposed as an option for space heating, provided that the sink side inlet temperature is below approximately 30°C (Stene, 2005). Again, these products are not available in the local market.

After assessing the possibilities available in the local market, two configurations were evaluated: a single water-to-water Genesis GSW060, with a nominal output of 17.6 kW (60,000 BTU/hr), see Fig. 4, and two Genesis GSW036, each with a nominal output of 10.6 kW (36,000 BTU/hr), see Fig 5. The Genesis series is manufactured by ClimateMaster (2007). Both products operate under a wide range of conditions, but they have only one stage. Simulations using manufacturer's data, results of numerical calculations for the BIPV/T air temperatures, and an assumed effectiveness curve for the heat exchanger were carried out to compare the performance of both systems. Details of these simulations can be found in Candanedo and Athienitis (2008).

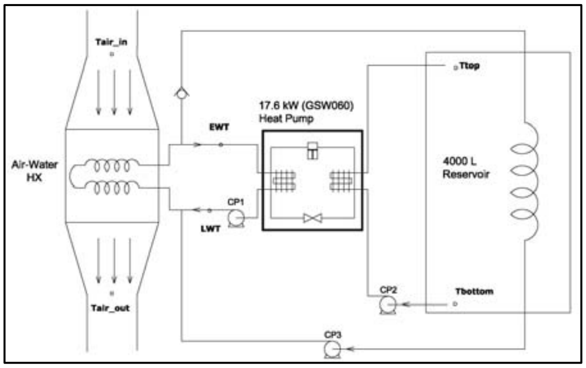


Figure 2. System configuration with one GSW060 heat pump.

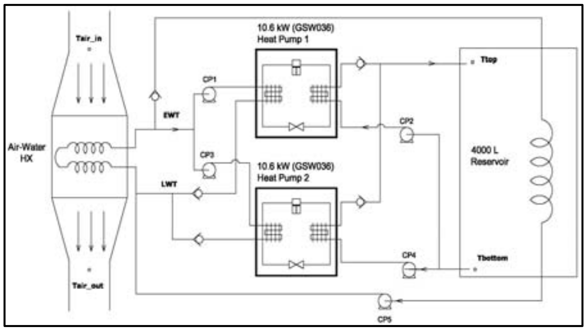


Figure 3. System configuration with two GSW036 heat pumps.

Fig. 6 shows a typical result: the COP of both GSW036 working in tandem. The simulations indicate that this system has better overall performance than the single GSW060, offering a greater heat output (above 22 kW) and better COP for the same air flow rate and temperature. The configuration with two heat pumps also offered other advantages. For instance, it is possible to work with very low flow rates and temperatures by operating only one heat pump, and still delivering 6 to 7 kW to the reservoir. The results shown in Fig. 6 are limited to temperatures between 10 and 40 °C, since this range guarantees the operation of the heat pumps for the air flow rates considered (between 472 and 850 L/s). For example, 450 L/s and 10°C, might not be adequate conditions for the operation of the heat pump. However, by maintaining higher flow rates, it is possible to work with BIPV/T air temperatures lower than 10 °C.

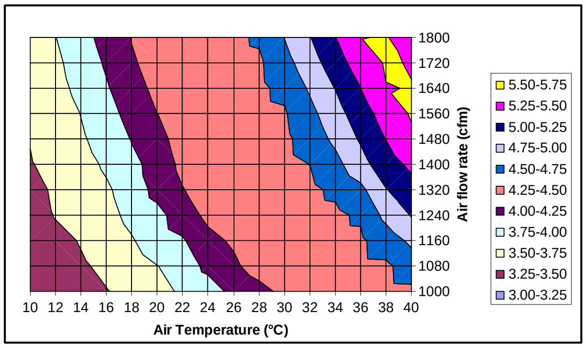


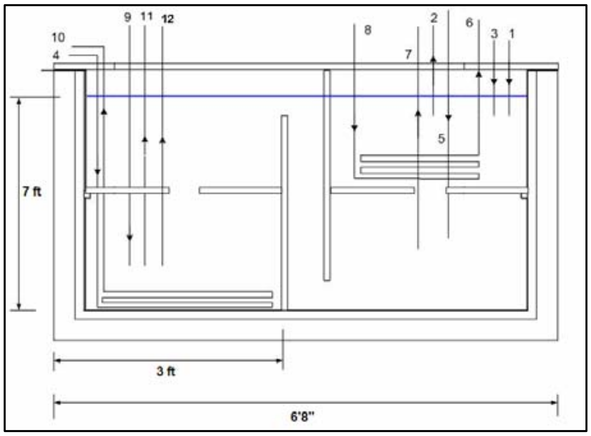
Figure 6. COP of two GSW036 operating in parallel under different conditions of air flow rate and temperature (reservoir temperature = 33 °C). Typical simulation results.

Thermal Storage Reservoir

The heat pumps operating in parallel will transfer heat to the bottom of the 4000-L thermal storage tank. As mentioned in Candanedo et al. (2007), the selection of the tank volume is not trivial: the final figure was chosen considering that similar tank sizes have been used in solar houses (Maine Solar House, 2007) and that this volume should allow one day worth of heat storage for a 6 kW heating load (close to the average) and a tank maximum temperature of 55 °C. Naturally, the storage capacity would last longer with lower heating loads. The size selected is not necessarily optimal: sizing procedures for thermal storage are needed for the operation of solar-based heating systems.

After circulating through the heat pump(s), the water will be deposited at the top of the reservoir. Because of the high flow rates required at the sink side (minimum 0.315 L/s per heat pump), the temperature rise is limited to 5-8 °C. This limits the thermal stratification capability of the tank. It is well-known that stratification facilitates heat exchange between a reservoir and its heat source(s) (solar collector, boiler, etc.), and sinks (air handling unit, hydronic coil, etc.). Measures have been taken to favour and maintain the thermal stratification, however small this may be.

Figure 7 shows the initial conceptual design of the tank. It includes movable perforated horizontal baffles and vertical divisions to enhance thermal stratification (Altuntop et al., 2005). Water from the tank could not be circulated directly through the air-to-water HX piping, since a water-glycol mixture is necessary to prevent freezing and bursting of pipes. A coil was added for this heat exchange. Other coils and inlets were added for heat exchange between the thermal storage tank, the DHW tank and the backup system (see Fig. 7). This design was later revised.



Number	Description	Number	Description	Number	Description
1	Pellet Boiler Inlet	5	DHW Inlet	9	Preheat Air Return
2	DHW Outlet	6	Floor Outlet	10	HX Coil Outlet
3	HP Inlet	7	Pre-heat Air Outlet	11	Pellet Boiler Outlet
4	HX Coil Inlet	8	Floor Return - Inlet	12	HP Outlet

Figure 7. Initial design of the thermal storage tank.

Backup System

The original backup system of the ANZH consisted of two ethanol burners, which also had an intrinsic aesthetic value (Ecosmart$^{\text{TM}}$, n.d.). However, concerns on their effect on indoor air quality encouraged the reconsideration of this design.

Keeping with the idea of using a renewable fuel, a wood pellet boiler, with some method of expelling combustion gases, was the next option considered. The smallest device available with the possibility of automatic control was the Harman PB105 pellet boiler (Harman Stoves, n.d.). Although its output was adjustable, the nominal power (33 kW) far exceeded the required capacity. Having such a large heating power offered the capability of responding fast to an emergency. The pellet boiler could also be used for heating the domestic hot water. However, the implementation of this backup system presented several challenges. In the first place, the pellet boiler works at much higher temperatures than those needed for the radiant floor heating system, and output temperature of the BIPV/T-HP group (25 to 60 °C). The interconnection of the pellet boiler with the rest of the mechanical system required a complex piping system. Guaranteeing the availability of the wood pellets, and the cost of the pellet boiler, were other shortcomings of this system.

Bearing in mind the disadvantages of the pellet boiler, the idea of using a biofuel as the backup system for cloudy days was abandoned in favour of an additional ground source loop (about 60 m long). The piping system was considerably simplified with a small change (the addition of a three way valve and a pump), and the usefulness of the heat pumps was extended by giving them an additional function. The wide range of temperatures that can be handled by the selected heat pumps facilitates the implementation of this dual-source system.

Revised Design of the Thermal Storage Reservoir

As mentioned above, the tank design was revised after the replacement of the backup system (see Fig. 8). A plate heat exchanger allows heat transfer between the radiant floor heating system and the reservoir. The tank also has one additional coil (permitting heat transfer between the reservoir and the DHW tank). The number of pipes entering and leaving the tank has been considerably reduced. The heat pumps will exchange heat directly with the water in the tank, taking it from the bottom (coldest), and delivering it at the top (hottest).

ADDITIONAL SIMULATIONS

The thermal network model in Mathcad used for the simulations described by Candanedo et al. (2007) has been reproduced in a MATLAB code. MATLAB allows for straightforward integration of subroutines, a feature that facilitates the development of independent models for the components of the mechanical system, and their incorporation into the main code. The following models were included in the fully explicit simulation: (a) 4 node model of the thermal energy storage reservoir, according to the method described by Duffie and Beckman (2006) to better describe the stratification of the tank; (b) The previously described heat pump model developed for comparing the performance of the system and (c) the BIPV/T model.

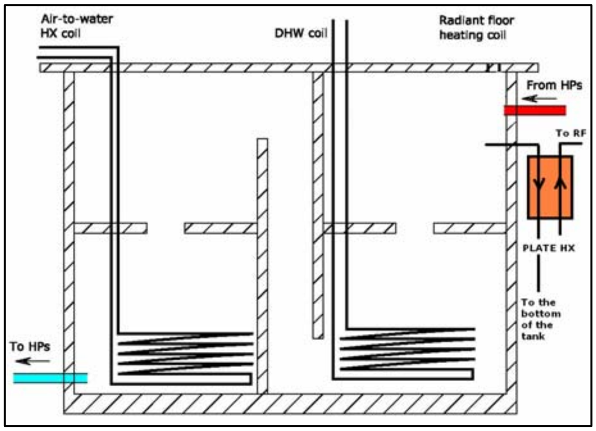


Figure 8. New tank design.

An adequate control strategy is essential for the coordination of the ANZH systems. The strategies presented below, of an exploratory nature, are intended to illustrate the effect of a predictive control strategy on the system's performance.

Two control strategies for the thermal energy storage tank were examined: (a) **keeping the tank fully charged** (i.e., the minimum temperature at the bottom was kept at 48.9 °C, which is the maximum tabulated temperature of the heat pumps sink side) by using the BIPV/T air; (b) **keeping the tank at a temperature which is a function of the solar radiation expected for the next day** (the tank temperature setpoint could be either 35, 40, 45 or 48.9 °C). While approach (a) is a simple control strategy that guarantees heat availability, approach (b) should save some electrical energy because the tank will not be charged unnecessarily, and the COP of the heat pumps will be higher for lower sink side (storage tank) temperatures.

The available heat in the BIPV/T air depends on the flow rate and the air temperature. In both control strategies discussed here, the air flow rate was kept constant at 755 L/s (1600 cfm). For **both** control strategies:

- When BIPV/T air temperature is greater or equal to 46 °C (near the technical operational limit of the heat pumps), the HX is used directly.
- Between 10 and 46 °C, both GSW036 heat pumps are used. Between 3 and 10 °C, since there is less heat available, only one GSW3036 heat pump is used (a different criterion could be established for deciding between the operation of either one or two heat pumps).
- If the BIPV/T air temperature is below 3°C, no heat is provided to the thermal storage reservoir unless the temperature at the bottom of the tank is below 30°C. If this occurs, the backup system (i.e., one heat pump with the ground source loop) is turned on.

The expected solar radiation for any given day is also used, **in both control strategies**, as an input of a simple anticipatory control scheme for controlling the position of the blinds/curtains. Regulating solar heat gains helps to control indoor temperature fluctuations of the house in order to avoid overheating. If despite these measures, the operative temperature of the house still exceeds 25°C (a possible problem during the shoulder seasons) fresh-air supply is increased.

The operative temperature setpoint was kept at 21°C, with a tolerance of 2 degrees; no mechanical cooling was used. For these simulations, no linkage was made between the DHW and the reservoir, although in practice it will exist. A typical meteorological year (TMY2 file) for Montréal was used. As a simplification, these simulations do not include the interaction with the solar collector for DHW.

Tables 1 and 2 show simulation results for the heating season for both control strategies.

Table 2. Heating energy (kWh). Control strategy 1.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Heat from ground loop	0	486	1580	1546	344	84	1
Heat directly (BIPV/T HX)	0	0	16	0	0	0	0
Heat from BIPV/T (one HP)	124	432	326	218	232	209	279
Heat from BIPV/T (two HPs)	158	634	850	928	1221	899	450
Heat given to reservoir	282	1552	2772	2692	1797	1192	730
Heat delivered to the space	134	1420	2729	2565	1659	1036	572
Percentage by BIPV/T	**100%**	**66%**	**40%**	**50%**	**78%**	**93%**	**100%**
HPs elect. Consumption	**89**	**361**	**544**	**548**	**443**	**315**	**227**

Table 1. Heating energy (kWh). Control strategy 2.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Heat from ground loop	0	547	1796	1796	221	301	41
Heat directly (BIPV/T HX)	0	0	0	0	0	0	2
Heat from BIPV/T (one HP)	73	331	300	197	671	192	242
Heat from BIPV/T (two HPs)	127	596	654	631	815	607	344
Heat given to reservoir	200	1474	2750	2624	1707	1100	629
Heat delivered to the space	135	1421	2730	2583	1661	1039	571
Percentage by BIPV/T	**100%**	**63%**	**35%**	**32%**	**87%**	**73%**	**93%**
HPs elect. Consumption	**54**	**344**	**597**	**597**	**399**	**255**	**156**

Savings are obtained by controlling the charge status of the tank (strategy 2). Of course, strategy 2 is not optimal and improvement is possible. In addition, the ground loop source is used more often with this strategy. It is also desirable to increase the usage of the heat exchanger for the direct recovery of heat, and to incorporate the solar radiation available at the current day in the calculation of the reservoir temperature setpoint. Other control strategies will be explored.

The temperature fluctuation for the 4 tank nodes, the operative temperature of the house and the BIPV/T exit temperature are shown in Fig. 9 and 10, for control strategies 1 and 2 respectively, for a period of 10 days in February. As expected, lower tank temperatures are maintained with the second control strategy. Both figures show the stratification of the tank.

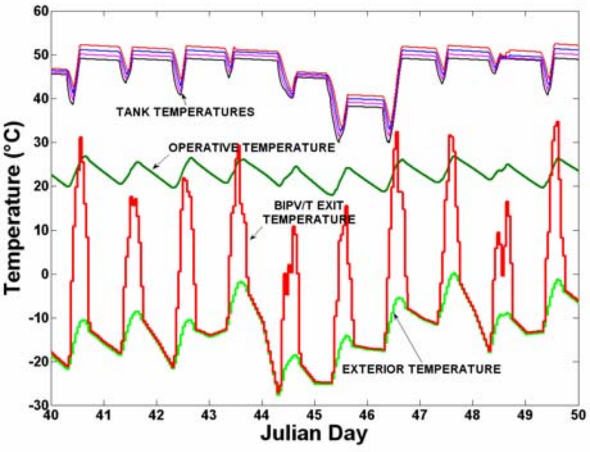


Figure 9. Tank temperatures (4 nodes), operative room temperature and BIPV/T exit temperatures for strategy 1.

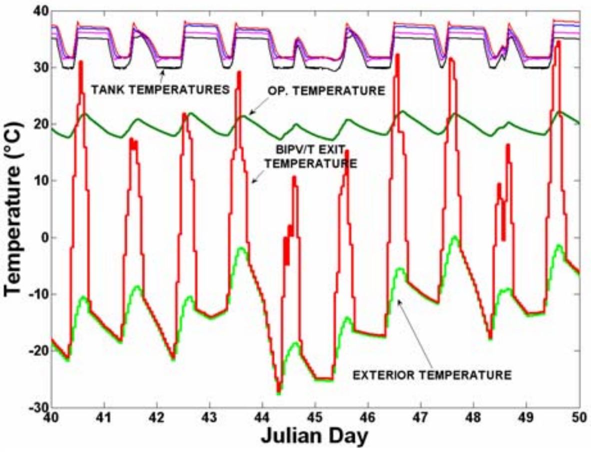


Figure 10. Tank temperatures (4 nodes), operative room temperature and BIPV/T exit temperatures for strategy 2.

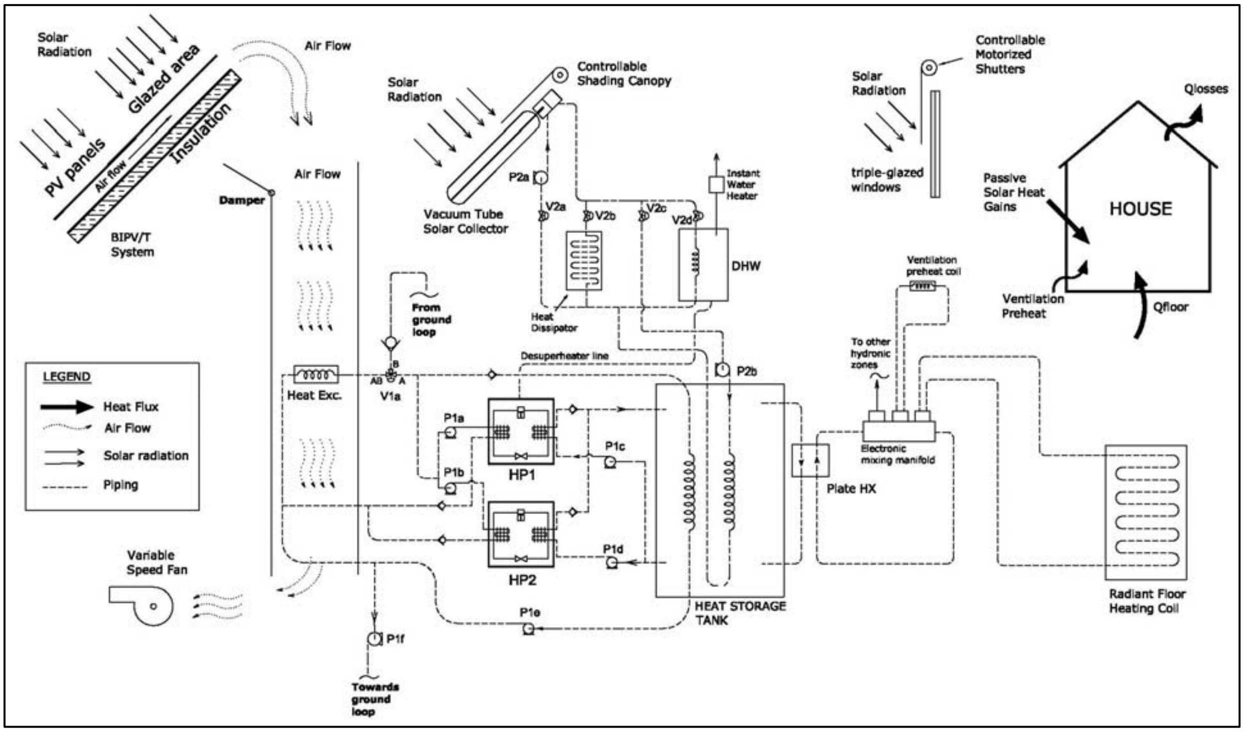


Figure 11. Final configuration of the ANZH.

FINAL DESIGN OF THE ANZH

Figure 11 shows the current status of the design of the ANZH. Apart from the aforementioned changes, the insulating panels planned for the south facing windows have been replaced by a motorized theater-type curtain. Another addition has been the connection of a HP desuperheater to the DHW tank. The approximate distribution of the energy consumption at the ANZH is given in Table 3:

Annual energy consumption	**kWh**
Heat pumps	2500
Fans and pumps	500
Domestic hot water	50
Ventilation	800
Lighting and appliances	3400
Electric plug-in vehicle	1400
TOTAL	**8650**
Energy generated by PV system	**8600**

CONCLUSIONS

Some of the considerations used in the design of the ANZH have been presented. The addition of 1.5 kW_P, and the installation of a ground source loop as a backup system are some of the most important changes. In its current state, the ANZH is approaching zero-emissions attributable to its operation, along with the ability to charge an electric vehicle to complete the net-zero lifestyle principle.

It is possible to build houses that rely solely on solar energy. To accomplish this goal, it is important to work in guidelines for the sizing and features of thermal storage systems, such as the maximum temperature achievable by the storage medium with the available heat sources, essential to reduce the required volume.

Although this house will make use of a ground source loop as a backup heat supply, a suitable custom-designed air source heat pump capable of using very low source temperatures could eliminate the need for a backup system. Progress can be made towards simplicity in future designs through accumulated research and experience.

Studies are under way to optimize the control of a house with so many interacting systems. Preliminary simulations have shown some of the benefits of anticipatory control in reducing energy consumption and maintaining comfortable conditions. The contribution of heat from the ground loop to the total heating energy supply, the tank temperature setpoint (which strongly affects the heat pump COP) and the air flow rate, are some of the important parameters that should be considered in a well-conceived control strategy.

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