*Energies* **2012**, *5*, 3972-3985; doi:10.3390/en5103972

OPEN ACCESS

*energies*

**ISSN 1996-1073**

www.mdpi.com/journal/energies

*Article*

# Residential Solar-Based Seasonal Thermal Storage Systems in Cold Climates: Building Envelope and Thermal Storage

**Alexandre Hugo [1] and Radu Zmeureanu [2,*]**

[1] Halsall Associates, 2300 Yonge Street, Suite 2300 Toronto, Ontario M4P 1E4, Canada; E-Mail: ahugo@halsall.com

[2] Department of Building, Civil and Environmental Engineering, Faculty of Engineering and Computer Science, Concordia University, Montréal, Québec H3G 1M8, Canada

* Author to whom correspondence should be addressed; E-Mail: radu.zmeureanu@concordia.ca; Tel.: +1-514-848-2424 (ext. 3203); Fax: +1-514-848-7965.

*Received: 21 August 2012; in revised form: 26 September 2012 / Accepted: 8 October 2012 / Published: 16 October 2012*

---

**Abstract:** The reduction of electricity use for heating and domestic hot water in cold climates can be achieved by: (1) reducing the heating loads through the improvement of the thermal performance of house envelopes, and (2) using solar energy through a residential solar-based thermal storage system. First, this paper presents the life cycle energy and cost analysis of a typical one-storey detached house, located in Montreal, Canada. Simulation of annual energy use is performed using the TRNSYS software. Second, several design alternatives with improved thermal resistance for walls, ceiling and windows, increased overall air tightness, and increased window-to-wall ratio of South facing windows are evaluated with respect to the life cycle energy use, life cycle emissions and life cycle cost. The solution that minimizes the energy demand is chosen as a reference house for the study of long-term thermal storage. Third, the computer simulation of a solar heating system with solar thermal collectors and long-term thermal storage capacity is presented. Finally, the life cycle cost and life cycle energy use of the solar combisystem are estimated for flat-plate solar collectors and evacuated tube solar collectors, respectively, for the economic and climatic conditions of this study.

**Keywords:** combisystem; heating; solar energy; house; envelope; storage; energy; cost; life cycle

---

## 1. Introduction

One of the most comprehensive studies on solar combisystems was performed within the frame of IEA-Task 26 [1] by comparing 21 different configurations. The optimization of nine combisystems under the same climatic reference conditions was performed by computer simulation using the TRNSYS program. Several design strategies were recommended [2] such as: the use of low temperature heating systems like a radiant floor; the increase of the insulation thickness of the storage tank to minimize the heat losses; the use of energy efficient pumps to decrease the electricity demand; and the use of stratifying devices and external heat exchangers to maintain the stratification in the storage tank. A follow up project of the IEA-Task 26 was the European project ALTENER Solar Combisystems [3]. More than 200 solar combisystems in seven European countries were installed, documented and theoretically evaluated, and 39 of them were monitored. A detailed literature review of such solar combisystems and seasonal storage approaches was presented in [4]. This paper focuses on the life cycle analysis of a solar combisystem used for seasonal thermal storage.

First, this paper presents the life cycle energy, emissions and cost analysis of a typical one-storey detached house in Montreal, Canada, where the average annual number of heating degree-days (HDD) is about 4500 °C at 18 °C outdoor temperature baseline. Second, several design alternatives with improved thermal resistance for walls, ceiling and windows, increased overall air tightness, and increased window-to-wall ratio of South facing windows are evaluated with respect to the life cycle energy use, life cycle emissions and life cycle cost. The solution that minimizes the energy demand is chosen as a reference house for the study of long-term thermal storage. Third, the performance of a solar combisystem with a long-term thermal storage capacity is investigated. The system is designed to supply hot water for the radiant floor heating system and the preparation of domestic hot water, for one year, using exclusively the solar energy. Finally, the life cycle cost, life cycle emissions and life cycle energy use of the solar combisystem is estimated for flat-plate solar collectors and evacuated tube solar collectors, respectively, for the economic and climatic conditions of this study.

## 2. Life Cycle Performance of the Base Case House

### *2.1. Annual Energy Performance*

A one-storey detached house built in Montreal in the 1990s, with a total heated floor area of 186 $m^2$, was used as the starting point in the development of the base case study house [4]. The house was made of a wood-frame structure and brick veneer (Table 1). Conventional electric baseboard heaters and an electric heater, installed in the storage tank, were used to satisfy the space heating and domestic hot water requirements.

Four additional design alternatives of the house were developed by incremental changes to the original house, with the goal to reduce the heating energy use, before analyzing the impact of the solar combisystem. The energy use of the base case house, as estimated by TRNSYS 16 program [5], was compared with measured energy use of similar houses in the city. The simulated energy use was equal to 26,156 kWh (94,163 MJ) or 140.6 kWh/$m^2$ (506 MJ/$m^2$ of heated floor area). These values are comparable with 123.8 ± 29.0 kWh/$m^2$ of normalized annual energy use monitored by Zmeureanu *et al.* [6] in 10 houses built in Montreal between 1986 and 1993.

**Table 1.** Thermal resistance of the exterior envelope of the base case house.

| Component | Thermal resistance ($m^2$·C/W) |
|---|---|
| Ceiling/roof | 6.08 |
| Above-ground walls | 4.11 |
| Foundation walls | 1.09 |
| Basement floor | 0.99 |
| Garage door (Polystyrol) | 1.89 |
| Exterior wood doors | 0.47 |
| Double glazed windows filled with argon, with aluminum frame | 0.71 |
| Overall weighted thermal resistance of all components | 3.37 |

### *2.2. Life Cycle Analysis of the Base Case House*

#### 2.2.1. Life Cycle Energy Use

The life cycle energy use includes the total energy input over the entire life cycle of a building and its subsystems. The life cycle in this study was 30 years as recommended by [7]. Within the scope of this study, we evaluated the embodied energy due to the manufacturing of the building materials in the pre-operating phase, and the total energy use in the operating phase. The embodied energy of plumbing, electrical, and ventilation systems was not taken into account, as those systems were identical in the base case house and in the house with combisystem. The estimation did not consider the energy used for demolition.

The embodied primary energy that represents direct and indirect energy use to extract and transport raw materials, and fabrication of the final product was estimated using ATHENA [8]. The total embodied energy of the base case house was assessed at 566,907 MJ (Table 2), corresponding to 2697 MJ/$m^2$ of total floor area, and it was equivalent to approximately five years of operating energy use. For comparison purpose, the results of other studies are cited: Haines *et al.* [9] estimated the embodied energy of a single-family house, complying with the Ontario Provincial Building Code, at 520,000 MJ or 2600 MJ/$m^2$ of floor area, while Kassab [10] found a value of 707,883 MJ or 2286 MJ/$m^2$ of floor area for a duplex-apartment house built in year 2000 in Montreal. The exterior and foundation walls accounted for the highest embodied energy (1574 MJ/$m^2$ of wall area), followed by floors and roofs (637 MJ/$m^2$), foundations (355 MJ/$m^2$), and doors and windows (239 MJ/$m^2$).

The total operating primary energy use was calculated using the electricity mix of Quebec, where hydro-electricity accounted for 95.4% of the total electricity generated with the average power plant efficiency of 80%; the heavy fuel oil and nuclear accounted for 2% each with the power plant efficiency of 32.8% and 30%, respectively. Other sources such as natural gas, light fuel oil and wood had a negligible contribution, of only 0.6%, to the total power generation. The transmission and distribution losses were about 6%. The average annual efficiency of power generation plants was estimated at 73.1%, which was higher than for the conversion by using fossil fuels only. Assuming that the annual operating energy use would not change over the 30-year life span of the house, the total operating energy consumption was estimated at 3,864,000 MJ (Table 2), corresponding to 18,382 MJ/$m^2$ of floor area.

The life cycle energy use of the base case house, calculated as the sum of the embodied energy and the operating energy use over 30 years, was equal to 4,430,907 MJ (Table 2).

**Table 2.** Life cycle profile of the base case house.

| | | Construction phase | Operating phase | Life cycle |
|---|---|---|---|---|
| Life cycle energy use | (MJ) | 566,907 | 3,864,000 | 4,430,907 |
| | (%) | 13 | 87 | 100 |
| Life cycle emissions | (Equivalent tons $CO_2$) | 29.75 | 56.24 | 85.98 |
| | (%) | 35 | 65 | 100 |
| Life cycle cost | ($) | 204,576 | 46,193 | 250,769 |
| | (%) | 82 | 18 | 100 |

2.2.2. Life Cycle Emissions

The embodied emissions of the base case house were evaluated at 29.75 equivalent tons of $CO_2$, using the annual average values of emissions coefficients that are available with ATHENA program [8]. For detailed explanation of emissions factors, which is beyond the purpose of this paper, the reader might consult reference [8]. The exterior and foundation walls had the highest embodied energy (73 kg $CO_2/m^2$ of wall area), followed by doors and windows (38 kg $CO_2/m^2$), and floors and roofs (32 kg $CO_2/m^2$). The annual emissions due to the operating energy use were estimated at 1875 kg of equivalent $CO_2$, and 56.24 tons of equivalent $CO_2$ over 30 years. The life cycle emissions were estimated at 85.98 tons of equivalent $CO_2$ emissions (Table 2).

2.2.3. Life Cycle Cost

The initial cost of the base house was estimated using RSMeans [11], including the total cost of building materials, labor, contractor profit and overhead cost, at $204,576 or 973 $/m^2$ of floor area. All costs are listed in Canadian dollars. At the time of this study, the exchange rate between US and Canadian dollars was 1.01.

The operating costs included energy and maintenance costs during the life span of the building. The annual energy use was supposed to be constant during the life span of the building. The life cycle electricity cost was estimated at $46,193, calculated using the Present Worth method with the electricity rates of Hydro-Quebec [12], discount rate of 5.54%, inflation rate of 2.24% and inflation rate of electricity price of 2%. The life cycle cost of the base case house was estimated at $250,769 (Table 2).

## 3. Life Cycle Performance of Improved Houses

In this section, several design alternatives are proposed in order to quantify their potential effect on a life cycle perspective. The first two design alternatives were elaborated to comply with the minimum insulation levels according to references [7,13]; they were named Quebec and MNECCH, respectively (Table 3). Since the windows of the base case house were quite small, having a window-to-wall ratio (WWR) of 0.09, a third design alternative presenting the same insulation levels and materials as the MNECCH design, but with larger windows on the South façade (WWR of 0.20), was considered. This

design alternative is named MNECCH+. One last design alternative, called "best case", was proposed with higher insulation levels and "sustainable" materials.

**Table 3.** Summary of design alternatives of improved houses.

| **Building component** | **Design alternative** | | | | |
|---|---|---|---|---|---|
| | **Base case** | **Quebec** | **MNECCH** | **MNECCH+** | **"Best case"** |
| Air tightness (ach50) | 3.5 | 3.5 | 3.5 | 3.5 | 1.5 |
| WWR (South façade) | 0.09 | 0.09 | 0.09 | 0.20 | 0.20 |
| | **Thermal resistance ($m^2$·°C/W)** | | | | |
| Ceiling/Roof | 6.08 | 6.08 (5.3) | 7.61 (7.0) | 7.61 (7.0) | 7.61 |
| Exterior walls | 4.11 | 4.11 (3.4) | 4.11 (4.1) | 4.11 (4.1) | 6.49 |
| Foundation walls | 1.09 | 2.87 (2.2) | 3.56 (3.1) | 3.56 (3.1) | 4.74 |
| Basement floor | 0.99 | 1.36 (2.2) | 1.36 (1.1) | 1.36 (1.1) | 2.82 |
| Exterior doors | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 |
| Garage door | 1.89 | 1.89 | 1.89 | 1.89 | 1.89 |
| | ***U*-value (W/($m^2$·°C))** | | | | |
| Windows | 1.40 | 1.40 | 1.40 | 1.40 | 1.26 |
| Overall thermal resistance | 3.37 | 3.61 | 4.05 | 4.01 | 5.29 |

Note: the number between parentheses represents the minimum thermal resistance required by the code associated with the design alternative.

Windows were upgraded to the best double-glazed window available in TRNSYS library, corresponding to an average *U*-value of 1.26 W/($m^2$·°C) that accounts for the centre of glass, edge-of-glass and frame. The WWR was kept at a value of 0.20 for the South façade, identical to the MNECCH+ alternative.

The air infiltration rate was reduced from 3.5 air change per hour at 50 Pa pressure difference (ach50) to 1.5 ach50. The infiltration rate of 1.5 ach50, measured by the depressurization of the house using the blower door technique, is usually given as the reference for airtight houses. The natural air infiltration rate, usually at 4 Pa pressure difference, cannot be measured, and is estimated from the value at 50 Pa pressure difference; this value is used in simulations with TRNSYS. To achieve this low infiltration rate, sprayed applied polyisocyanurate (PIR) was assumed to be used to fill the gaps around windows and doors, at the junction of the main floor framing and the foundation, and at tops of exterior and partition walls.

Using the TRNSYS and ATHENA computer programs and the RSMeans database, the life cycle energy use, life cycle emissions and life cycle cost were estimated for each design alternative of the house. Table 4 shows a summary of results and reductions compared with the base case house. The "best case" design alternative was the most efficient choice, with the highest reductions in terms of the life cycle energy use (33.2%), life cycle emissions (24%) and life cycle cost (2.2%).

**Table 4.** Life cycle performance of improved houses compared with the base case house.

| Design alternative | Life cycle energy use (GJ) | Life cycle emissions (Tons $CO_2$ equivalent) | Life cycle cost ($) |
|---|---|---|---|
| Base case | 4,431 | 85.98 | 250,769 |
| Quebec | 4,132 | 81.75 | 250,644 |
| | (−7.2%) | (−5.2%) | (+0.0%) |
| MNECCH | 4,056 | 80.21 | 250,951 |
| | (−9.2%) | (−7.2%) | (+0.1%) |
| MNECCH+ | 4,033 | 80.35 | 252,239 |
| | (−9.9%) | (−7.0%) | (+0.6%) |
| "Best case" | 3,327 | 69.33 | 245,390 |
| | (−33.2%) | (−24.0%) | (−2.2%) |

Note: negative percentage value represents the decrease compared with the base case house.

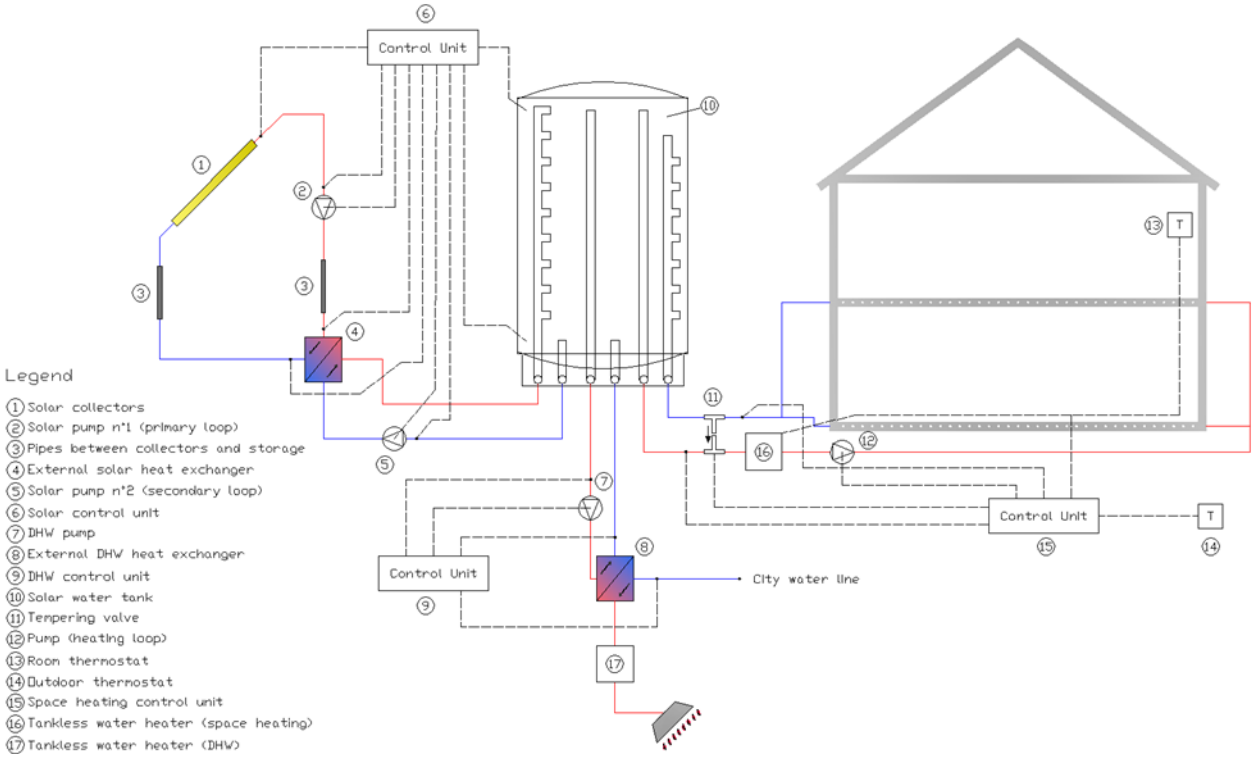
## 4. Solar Combisystem with Solar Thermal Collectors and Long-Term Thermal Storage

The solar combisystem was installed in the "best case" design alternative (Table 4). The long term thermal storage system was designed to supply hot water for the space heating and the preparation of domestic hot water (DHW), for one year, using only the solar energy, that is, without using the auxiliary heating elements.

### *4.1. Description of the Solar Combisystem*

The combisystem consisted of solar collectors (point 1 in Figure 1) of about 50 $m^2$ installed on the roof of the house, the heat transfer loop with antifreeze fluid and a pump (point 2), and the external heat exchanger (point 4) that transferred the heat from the primary loop into a secondary loop, which circulated the water. Hot water of the secondary loop, circulated by a pump (point 5), entered a large cylindrical storage tank (point 10) of 38,600 liters. A stratifier device improved the stratification by avoiding the mixing of water layers of different temperatures inside the tank. Hot water was supplied to radiant heating floors of the house by a variable speed pump (point 12) controlled by a thermostat installed on the first floor (point 13). Two electric tankless water heaters (points 16 and 17, Figure 5) are used to ensure a correct water temperature for space heating and domestic hot water. Such external devices are preferred to electric heating elements submerged in the storage tank as they heat water only when it is needed, which avoids standby heat loss through the tank and water pipes. An external heat exchanger (point 8) and a variable speed pump (point 7) enabled the control of domestic hot water at around 45 °C at the user-end. Detailed presentation of TRNSYS simulation was given in [14]. At the beginning of the first year of simulation, each layer of the storage tank is assumed at 60 °C. The first year of simulation is only used to remove the impact of initial guess values of water temperature. The results at the end of the first year of simulation are input as initial conditions for the simulation of the second year. The results from the second year of simulation represent the annual energy use of the first year of operation. In our study we assumed that the energy used during the first year of simulation does not change over the system life.

**Figure 1.** Solar combisystem with long-term thermal storage.




*4.2. Energy Performance of the Solar Combisystem*

The annual house electricity use was estimated by TRNSYS at 8300 kWh (29,880 MJ), or 45 kWh/m$^2$ of heated floor area (161 MJ/m$^2$). Compared to the annual electricity use of 18,830 kWh of the "best case" (without solar energy), this result represented a reduction of more than 50%. The ventilation had the highest contribution to the energy use as it accounted for 65.3% of the total value, followed by lighting with 14.7%, humidification with 9.2% and cooling with 8.9%. The space heating and domestic hot water production accounted for only 1.8% of the annual electricity use. The monthly electricity use of end-uses is shown in Table 5. The Heating and DHW part represents the electricity use by circulating pumps for the heating and domestic hot water systems. The ventilation system had the highest contribution to the electricity use in the winter months since the outdoor air was heated up to the temperature of 20 °C. During summer, the months of July and August presented higher electricity usage by the cooling system. The energy use by electric appliances was estimated by TRNSYS by using the user-defined installed power (in kW) and the corresponding hourly schedule of usage. The radiative and convective components of heat gains from those appliances were used in the heat balance of each thermal zone of the house. Figure 2 presents the variation of water temperature in storage tank during the first year of operation (second year of simulation).

**Figure 2.** Water temperature in the storage tank during the first year of operation (second year of simulation).

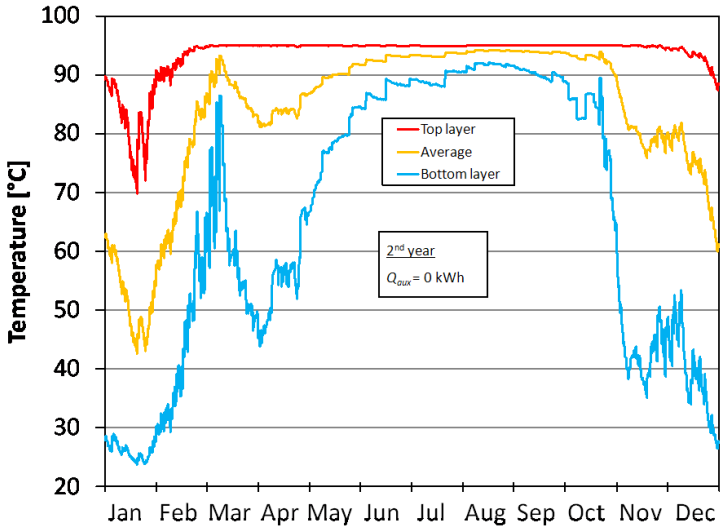



**Table 5.** Monthly electricity use (kWh) in the case of solar combisystem.

| End-uses | Month | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Tot |
| Heating & DHW | 24 | 24 | 29 | 20 | 4 | 2 | 1 | 2 | 1 | 4 | 18 | 21 | 150 |
| Humidification | 205 | 173 | 125 | 37 | 1 | - | - | - | - | 4 | 51 | 167 | 764 |
| Cooling | - | - | - | - | 7 | 146 | 310 | 231 | 47 | - | - | - | 740 |
| Lighting | 144 | 108 | 102 | 88 | 72 | 65 | 68 | 81 | 96 | 121 | 141 | 146 | 1220 |
| Ventilation | 670 | 593 | 590 | 469 | 347 | 285 | 294 | 294 | 285 | 429 | 523 | 642 | 5421 |
| Total | 1035 | 900 | 846 | 613 | 432 | 498 | 673 | 608 | 429 | 558 | 732 | 976 | 8300 |

### *4.3. Life Cycle Performance of Solar Combisystem*

This section presents the life cycle cost and life cycle energy use of two solar combisystems: the design alternative No.1 with evacuated tube solar collectors, and the design alternative No.2 with flat-plate solar collectors (Table 6). These two design alternatives had the solar fraction superior to 90%. The annual electricity use of the solar combisystem, required to provide for space heating and domestic hot water, was equal to 365 kWh (1.3 GJ) for design alternative No.1, and 567 kWh (2.0 GJ) for design alternative No.2.

**Table 6.** Design alternatives for solar collectors.

| Design alternative | Type of solar collector | Area ($m^2$) | Tank volume ($m^3$) | $\dot{m}_{solar}$ ($kg/(h \cdot m^2)$) | Tilt angle (deg) |
|---|---|---|---|---|---|
| 1 | Evacuated tube | 47.1 | 34.7 | 25 | 60.0 |
| 2 | Flat-plate | 53.0 | 38.6 | 27 | 67.5 |

4.3.1. Life Cycle Cost

Since the combisystem provided for the space heating and domestic hot water, the electric baseboard heaters and the water heater were not necessary. Therefore, both design alternatives are credited with the initial costs of these systems. The cost of cross-linked polyethylene pipes (PEX) integrated in the radiant heating floor was considered. Since the flat-plate collectors were integrated to the roof, the cost of asphalt shingles was reduced.

The initial cost of the solar combisystem was estimated at $58,162 for design alternative No.1 and $39,949 for design alternative No.2 (Table 7). The main cost difference came from the collectors where the price of evacuated tubes ($35,603) represented more than twice the price of flat-plate collectors ($17,238).

**Table 7.** Initial cost of the solar combisystem.

| System component | Design alternative 1 ($) | Design alternative 2 ($) |
|---|---|---|
| Storage tank | 12,031 | 13,023 |
| Tank insulation | 4,777 | 5,138 |
| Conventional storage tank | −1,053 | −1,053 |
| Electric baseboard heaters | −3,097 | −3,087 |
| Radiant floor (PEX pipes) | 2,502 | 2,502 |
| Solar collectors | 35,603 | 17,238 |
| Shingles (credit for integrated mounting) | - | −1,201 |
| Control unit | 2,280 | 2,280 |
| Pumps Stratos ECO | 1,328 | 1,328 |
| Pumps Stratos ECO-ST (Solar pump n$^{o}$1) | 474 | 474 |
| Tankless water heaters | 1,331 | 1,331 |
| Copper pipes | 1,784 | 1,784 |
| Piping insulation | 202 | 202 |
| Total | 58,162 | 39,949 |

The annual operating costs were estimated at $26 for design alternative No.1 (Table 8) and $40 for design alternative No.2, based on the electricity use of the solar combisystem and the electricity rates of Hydro-Quebec [12].

The life cycle cost was estimated at $58,799 for design alternative No.1, and $40,939 for alternative No.2. The simple payback period of the solar combisystem was calculated as the ratio of the initial cost ($) of the solar combisystem and the annual energy savings for space and water heating ($/year), which were obtained by the use of proposed design alternative during the first year of operation. The simple payback was estimated at 79.4 years for alternative No.1 and 55.6 years for alternative No.2 (Table 8).

**Table 8.** Simple payback period of design alternatives.

| Alternative | Electricity use (kWh) | Operating cost ($) | Solar savings ($) | Simple payback (years) |
|---|---|---|---|---|
| “Best case” | 10,704 | 759 | - | - |
| 1 | 365 | 26 | 733 | 79.4 |
| 2 | 567 | 40 | 719 | 55.6 |

Compared to the simple payback period, the improved payback is a much more realistic approach as it considers the time value of money. It is defined as the period required for the cumulative savings to equal the initial cost of the system. As shown in Figure 3, the solar combisystem was not able to payback its installation costs. Yet, 50% of the installation costs were recovered after 55 years for design alternative No.1 (evacuated tube), and 34 years for design alternative No.2 (flat-plate). If the inflation rate of electricity goes up from 2% to 4%, the curve of cumulative savings shows a different shape (Figure 4), and the payback period for design alternative No.1 is achieved after 38 years and after 26 years for design alternative No.2.

**Figure 3.** Cumulative savings of design alternatives and improved payback period (inflation rate of electricity of 2%).

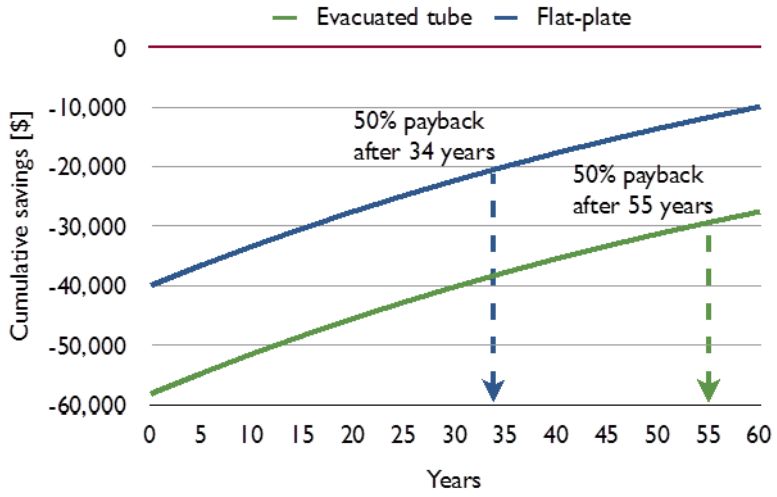
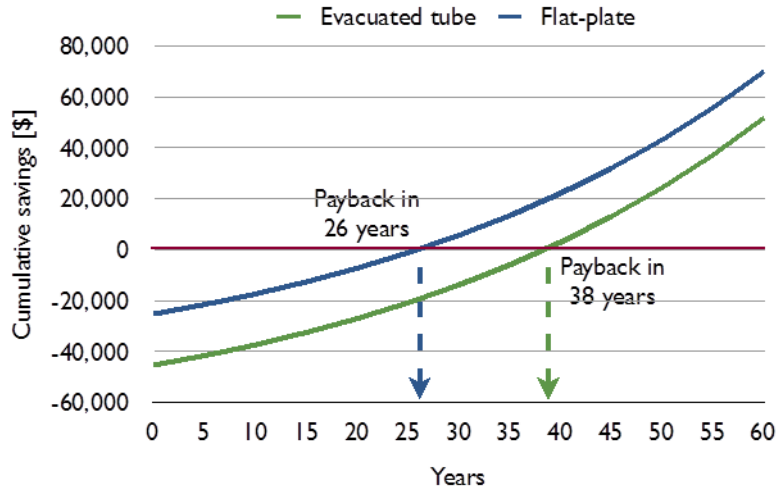



**Figure 4.** Cumulative savings of design alternatives and improved payback period (inflation rate of electricity of 4%).




The improved payback period of the seasonal storage system was quite long, from 55 to 38 years for design alternative No.1 (depending on the economic scenario), and from 34 to 26 years for design alternative No.2. The only way to obtain a payback period under the 30-years life span of the system is to benefit from substantial incentives. These results are seen as the direct consequence of the high

initial costs of the combisystem in the context of low rates of electricity in Quebec, compared to other Canadian provinces.

4.3.2. Life Cycle Energy Use

The embodied energy of the evacuated tube collectors was estimated at 1521 MJ/m$^2$ or 71,717 MJ for the total collector area of 47.1 m$^2$ based on reference [15]. The average value of the embodied energy of a flat-plate collector, of 1732 MJ/m$^2$, was estimated using data from several studies (Table 9). For the total collector area of 53 m$^2$, the embodied energy was calculated at 91,766 MJ. The storage tank was made of stainless steel (16.3 MJ/kg) and covered by 20 cm of mineral wool (15.6 MJ/kg). Copper pipes (48.7 MJ/kg) between the collectors and the storage tank had a diameter of 31.8 mm and were insulated with fiberglass (30.3 MJ/kg) over the length of 20 m. The heat exchangers were made of stainless steel (16.3 MJ/kg), and the pumps of stainless steel and grey cast iron (32.8 MJ/kg). The electric baseboard heaters previously used to heat the "best case" house were made of aluminum (58.5 MJ/kg). The embodied energy of baseboard heaters, water heaters (6155 MJ) and roof shingles (76.6 MJ/m$^2$) was deducted from the total embodied energy. The embodied energy of the PEX pipes (103.0 MJ/kg), installed in the radiant floor, was considered in the analysis.

**Table 9.** Embodied energy of flat-plate solar collectors.

| Collector area (m$^2$) | Embodied energy (MJ) | (MJ/ m$^2$) | Country | References |
|---|---|---|---|---|
| 2.13 | 3,513 | 1,649 | Italy | [16] |
| 1.35 | 2,663 | 1,973 | Cyprus | [17] |
| 5.00 | 6,408 | 1,282 | Germany | [18] |
| 5.00 | 8,633 | 1,727 | Germany | [18] |
| 6.15 | 11,450 | 1,862 | Germany | [15] |
| 5.76 | 9,790 | 1,700 | Germany | [15] |
| 2.00 | 3,604 | 1,802 | India | [15] |
| | Average | 1,732 | | |

The total embodied energy of the solar combisystem was approximated at 157,870 MJ for design alternative No.1 and 134,689 MJ for design alternative No.2. The total operating energy use over 30 years was calculated at 53.9 GJ for design alternative No.1 and 83.8 GJ for design alternative No.2.

The life cycle energy use of the seasonal storage system, the sum of the embodied energy of the combisystem and the operating energy use over 30 years, was estimated at 188.6 GJ (design alternative No.1) and 241.6 GJ (design alternative No.2).

The energy payback time (EPT) was defined as the time (in years) in which the primary energy used to manufacture the solar combisystem was compensated by the reduction of annual electricity use [19]. With the energy payback time value of 4.9 years for design alternative No.1 and 6.0 years for design alternative No.2, the results are higher than the typical energy payback times of solar combisystems (without long-term storage capacity) ranging from 2.0 to 4.3 years [20]. Yet, such

difference is easily explained by the higher overall efficiency of power plants in Quebec (73.1%) compared to Germany (35.0%).

The energy yield ratio (EYR) was defined as how many times the energy invested in the manufacturing of combisystem was returned by the system in its entire life span [20]. Higher ratio values show better performance. Contrary to the energy payback time, this indicator considered the life span of the solar combisystem and hence provided more meaningful results. The EYR for design alternative No.1 was calculated at 6.1, and 5.0 for design alternative No.2. It was quite lower than the values ranging from 7.5 to 12.6 calculated for typical combisystems (without long-term storage) installed in Germany [15]. As for the EPT, this difference should be credited to the higher overall efficiency of power plants in Quebec.

#### 4.3.3. Discussion

The life cycle cost analysis indicated that the use of proposed solar combisystem design alternatives does not result in an acceptable payback period, under the default economic conditions. However, with higher rates of inflation and with some financial incentives, the initial costs could be recovered in a shorter period of time.

The great potential of energy savings of the solar combisystem was very well demonstrated on the life cycle basis. Indeed, the energy payback time and energy yield ratio had acceptable values for such a large system. Compared to the second design alternative using flat-plate collectors, the first design alternative performed better in terms of energy payback time and energy yield ratio. Due to the higher efficiency of evacuated tube in cold climates, it required smaller solar collectors and storage tank. Therefore, less material was required for the same level of performance.

The design of solar combisystem was based on textbooks on solar systems, manufacturers' recommendations and design practice. We performed a sensitivity analysis with respect to storage tank volume, solar panel surface, tilt angle and insulation thickness, which was presented in references [4,14].

## 5. Conclusions

The improvement of the house envelope from the base case house to the "best case" had as a result the reduction of the life cycle cost by $4.9 per GJ of reduction of life cycle energy use. When the combisystem, design alternative No.1 was used along with the "best case" house, the life cycle cost increased by $18.7 per GJ of reduction of life cycle energy use; in the case of alternative No.2, the increase was $13.3 per GJ.

There are two main conclusions from this study: (1) the improvement of thermal performance of the envelope is more cost effective, and therefore should be the target before designing such complex solar combisystems; and (2) the use of a solar combisystem under the economic conditions presented in the paper is not cost effective yet. On the other hand, the energy payback shows a significant positive impact of using the solar combisystem, as the energy invested in the construction of the combisystem is recovered, through the annual operating savings, in a few years.

The results of this study are specific to the one-storey case study house in Montreal, and cannot be generalized to other buildings and locations, where the climatic conditions and energy and initial costs are different. Similar studies should be undertaken under different conditions.

The scope of this study was the development of a computer model of a complex solar combisystem to evaluate the performance in terms of life cycle cost and life cycle energy. Certainly, in the context of current low energy price of electricity in Quebec, there are not too many owners ready to invest in such a complex system with long payback period of the initial investment. However, the conclusion about long payback period was balanced by the short energy payback, which might reflect the true impact beyond the current prices of energy, material and labor.

## Acknowledgments

The authors acknowledge the financial support from Natural Sciences and Engineering Research Council of Canada and from the Faculty of Engineering and Computer Science, Concordia University.

## References

1. International Energy Agency, Solar Heating and Cooling. Available online: http://www.iea-shc.org (accessed on 8 March 2007).
2. Tepe, R.; Bales, C.; Bony, J.; Pittet, T.; Heimrath, R. *Elements and Examples of Dream Systems of Solar Combisystems*; Technical Report of Task 26; International Energy Agency, Solar Heating and Cooling: Graz, Austria, 2004.
3. Ellehauge, K. *Solar Combisystems*; Technical report for the European Altener Programme Project, 2003. Available online: http://www.elle-kilde.dk/altener-combi/ (accessed on 5 October 2008).
4. Hugo, A. Computer Simulation and Life Cycle Analysis of a Seasonal Thermal Storage System in a Residential Building. Master's Thesis, Concordia University, Montreal, Canada, 2008.
5. TRNSYS 16. A Transient Simulation Program; University of Wisconsin: Madison, WI, USA, 2006.
6. Zmeureanu, R.; Marceau, M.L.; Payer, J.; Derome, D. Evaluation of Energy Performance of Nine Identical Row Houses in MONTREAL. In *Proceedings of the Thermal Performance of the Exterior Envelopes of Buildings VII*, Clearwater Beach, FL, USA, December 1998.
7. *Model National Energy Code of Canada for Houses*. National Research Council of Canada, Canadian Commission on Buildings and Fire Codes: Ottawa, Canada, 1997.
8. ATHENA, Environmental Impact Estimator v3.0. Athena Sustainable Materials Institute: Ottawa, Canada, 2003.
9. Haines, G.; Org, M.; Barkan, A.; Pressnail, K.D. An Economic and Environmental Comparison of Standard *versus* Energy Efficient Homes in Toronto, Canada. In *Proceedings of ENHR Conference on Sustainable Urban Areas*, Rotterdam, The Netherlands, June 2007.
10. Kassab, M. Improving the Energy Performance of Houses in Montreal Using the Life-Cycle Analysis. Master's Thesis, Concordia University, Montreal, Canada, 2002.
11. RSMeans, Residential Cost Data, Volume 26. RSMeans Company: Kingston, MA, USA, 2007.
12. Hydro-Quebec. Available online: http://www.hydroquebec.com (accessed on 10 September 2008).

13. *Regulation Respecting Energy Conservation in New Buildings*; Publications du Quebec: Quebec, Canada, 1992.
14. Hugo, A.; Zmeureanu, R.; Rivard, H. Solar combisystem with seasonal thermal storage. *J. Build. Perform. Simul.* **2010**, *3*, 255–268.
15. Gurzenich, D.; Mathur, J. *Material and Energy Demand for Selected Renewable Energy Technologies*; Technical Report; DLR-International Bureau of the BMBF: Essen, Germany, 1998.
16. Ardente, F.; Beccali, G.; Cellura, M.; Lo Brano, V. Life cycle assessment of a solar thermal collector. *Renew. Energy* **2005**, *30*, 1031–1054.
17. Kalogirou, S. Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters. *Sol. Energy* **2009**, *83*, 39–48.
18. Streicher, E.; Heidemann, W.; Muller-Steinhagen, H. Energy Payback Time—A Key Number for the Assessment of Thermal Solar Systems. In *Proceedings of EuroSun2004*, Freiburg, Germany, 20–23 June 2004.
19. Richards, B.; Watt, M. Permanently dispelling a myth of photovoltaics via the adoption of a new net energy indicator. *Renew. Sustain. Energy Rev.* **2007**, *11*, 162–172.
20. Watt, M.E.; Johnson, A.J.; Ellis, M.; Outhred, H.R. Life-cycle air emissions from PV power systems. *Prog. Photovolt. Res. Appl.* **1998**, *6*, 127–136.