Master’s Thesis Seminar

SOLAR WATER HEATING SYSTEMS WITH THERMAL STORAGE FOR APPLICATION IN NEWFOUNDLAND

Presented by

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Presentation outline

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Introduction

❑ The sun is a great source of renewable energy
❑ Photovoltaic cell can generate electricity (Indirectly)
❑ Solar collector can generate heat (directly)
❑ Energy source is intermittence
❑ Thermal energy storage (TES) system is introduced
❑ TES can be sensible, latent and thermochemical
❑ Sensible storage mediums are water, rocks, sand etc.
## Background study

<table>
<thead>
<tr>
<th>Researcher/Project</th>
<th>System</th>
<th>Output</th>
<th>Place</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinel et al. [1]</td>
<td>STES</td>
<td>Performance suffered from condensation</td>
<td>United States</td>
</tr>
<tr>
<td></td>
<td>$A=136 \ m^2$, $V=68 \ m^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antoniadis and Martinopoulus et al.[2]</td>
<td>STES</td>
<td>$52.3%$ space heating and full DHW demand met</td>
<td>Greece</td>
</tr>
<tr>
<td></td>
<td>$A=30 \ m^2$, $V=36 \ m^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kemery et al. [3]</td>
<td>Combi-system</td>
<td>$93%$ demand for SH and DHW met</td>
<td>Ottawa, Canada</td>
</tr>
<tr>
<td></td>
<td>$A=29 \ m^2$, $V=35 \ m^3$, $D=450 \ l$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Riverdale NetZero (CMHC) [4]</td>
<td>Combi-system</td>
<td>$83%$ DHW, $21%$ SH demand met</td>
<td>Edmonton, Alberta</td>
</tr>
<tr>
<td></td>
<td>$A=21 \ m^2$, $V=17 \ m^3$, $D=300 \ l$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colcough et al. [5]</td>
<td>Combi-system</td>
<td>SF was $93%$ and $56%$ for DHW and SH</td>
<td>Ireland</td>
</tr>
<tr>
<td></td>
<td>$A=10.8 \ m^2$, $V=22 \ m^3$, $D = 300 \ l$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Background study (con…)

Fig. 01: 35 m³ below grade STST at Carleton University, Ottawa [3]
Research objectives

- To do extensive literature review on solar water heating systems
- To do thermal modeling of a house for estimating the annual loads
- Design a solar space heating system
- Design a solar space heating and domestic hot water system
- Seasonal thermal energy storage
- Contribute to pay less electricity bill
- Reduce the GHG gas emissions
- Annual power consumption and heat loss analysis of a HRV
- Dynamic simulation of a solar space heating system
Problem statement [6]

- Pay more electricity bill
- GHG emissions can affect the environment

**Fig.02: Secondary energy consumption**

**Fig.03: GHG emissions**
Required software

- RETScreen: Solar resource data
- BEopt: Thermal modeling of the house
- PolySun: System-1 simulation
- SHW: System-2 simulation
- MATLAB/Simulink: Dynamic simulation of the space heating system
Solar resource data [7]

Fig. 04: Graphical representation of solar radiation

Fig. 05: Numerical value of solar radiation

- Selected area is St. John’s, NL, Canada, and latitude (47.56 °N) and longitude (52.71°W)
- The average daily solar irradiation is 3.06 kWh/m²-day
- Average air temperature 4.8 °C
- Average relative humidity 82%
- Average wind speed 6.6 m/s
Thermal modeling of the house

Load estimation:
- Need to know the total amount of space heating & domestic hot water load per year
- Dimension of the house (length: 45 feet and width: 30 feet)
- Put the correct values for all outside walls, windows, doors, roof, orientation, location, all major electrical appliances and their types

Fig. 06: Physical view of the designed house
Fig. 07: Geometry Screen of the house [8]
### Thermal modeling of the house (con.)

<table>
<thead>
<tr>
<th>House parameters</th>
<th>Particulars</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building</td>
<td>Orientation</td>
<td>Northeast</td>
</tr>
<tr>
<td>Wall</td>
<td>Wood Stud</td>
<td>R-15 fiberglass batt 2*4, 16 in o.c</td>
</tr>
<tr>
<td>Ceilings/ Roofs</td>
<td>Unfinished attic</td>
<td>Ceiling R-38 fiberglass, vented</td>
</tr>
<tr>
<td>Windows &amp; Doors</td>
<td>Window areas</td>
<td>A new input of window areas has inserted with clear, double, non-metal, air</td>
</tr>
<tr>
<td>Space conditioning</td>
<td>Electric baseboard</td>
<td>100 % efficiency</td>
</tr>
<tr>
<td></td>
<td>Ducts</td>
<td>7.5 % leakage, uninsulated</td>
</tr>
<tr>
<td>Airflow</td>
<td>Air leakage</td>
<td>4 ACH50</td>
</tr>
<tr>
<td></td>
<td>Mechanical ventilation</td>
<td>2010, HRV, 70%</td>
</tr>
<tr>
<td>Water Heating</td>
<td>Water heater</td>
<td>Electric standard</td>
</tr>
<tr>
<td></td>
<td>Distribution</td>
<td>Uninsulated, HomeRun, PEX</td>
</tr>
<tr>
<td>Lighting</td>
<td>Lighting</td>
<td>34% CFL hardwired, 34 % CFL plugin</td>
</tr>
<tr>
<td>Appliances and fixtures</td>
<td>Refrigerator</td>
<td>Top freezer, EF= 21.9</td>
</tr>
<tr>
<td></td>
<td>Cooking range</td>
<td>Electric</td>
</tr>
<tr>
<td></td>
<td>Dishwasher</td>
<td>290 rated kWh, 80% usage</td>
</tr>
<tr>
<td></td>
<td>Clothes washer</td>
<td>Energy star cold only</td>
</tr>
<tr>
<td></td>
<td>Clothes dryer</td>
<td>Electric</td>
</tr>
</tbody>
</table>

**Fig. 08: Selected input parameters for options screen**
Thermal modeling of the house (con..)

**Simulation result:**

- Total annual energy consumption 19511 kWh (BEopt) and 18494 kWh (NL power)
- Space heating 7887 kWh and 4689 kWh
- Highest energy consumption 2231 kWh in January (from BEopt)
- Highest energy consumption 2778 kWh in March (from NL power)
- Average hourly space heating and hot water demand 0.9 KW and 0.54 KW
Design-1 solar water space heating system

Fig. 11: Active solar space heating system [9]

Sizing of system’s components:

(a) Collector

- Collector area, \( A_1 = \frac{Q_{demand}}{Q_{solar1}} \) ..........................................................(1)
- \( Q_{solar2} = A_1 \times Q_{solar1} \) .................................................................(2)
- \( Q_{excess} = Q_{solar2} - Q_{demand} \) ..........................................................(3)
Collector efficiency, $\eta = 50\%$, standby loss $= 0.05 \text{ kWh/hr.}$ and circulation loss $= 5\%$

$$Q_{solar3} = \eta \cdot Q_{solar2} - \eta \cdot Q_{solar2} \cdot 0.05 - 0.05 \quad \text{(4)}$$

Collector area, $A_2 = \frac{Q_{demand}}{Q_{solar3}} \quad \text{(5)}$

- Selected collector area 16 $m^2$
- Flat plate collector

(b) **Storage tank:**

- Tank volume is determined by the amount of available solar energy in summer months
- May to September are considered the summer in St. John’s, NL, Canada
- Excess electrical energy, $E = m \cdot C_p \cdot \Delta T \quad \text{(6)}$
- Mass of water, $m = E / (C_p \cdot \Delta T) \quad \text{(7)}$
- Volume of water tank, $V = m / \rho \quad \text{(8)}$
- Tank Volume, $V = \pi \cdot D^2 / 4 \cdot H \quad \text{(9)}$
Design-1 (con…)

Mass of water, \( m = 47,000 \) liters
Volume of water tank, \( V = 47 \ m^3 \)
\( D=H= 3.91 \ m \)
Tank material is enameled steel
Insulation material is flexible polyurethane foam with thickness 100 mm

Fig. 12: Month vs. \( Q_{solar} \) and Month vs. \( Q_{demand} \) for storage tank design
Design-1 (con…)

Pumps:
- \( \text{Power}_1 = [44.6 \times \exp(0.0181 \times A_c)] \) ...................................................(10)
- \( \text{Power}_2 = [78.3 \times \exp(0.0156 \times A_c)] - \text{power}_1 \) ................................. (11)

Heat pump:
- Selected heat pump model: Belaria 5 KW, water to water with (COP) 3.5 and performance factor 2.96 heat pump

External heat exchanger:
- Heat transfer capacity 5000W/K, and the number of heat exchanger plates was 20

Radiator:
- Area 2.5 \( m^2 \)
- Power of 1000 W per heating element
- Nominal inlet and return temperature of the radiator were 45°C and 35°C
Simulation result-1 and analysis

Fig. 13: Annual demand and production of the proposed system

- Energy demand 6337 kWh and production 6932 kWh (October - April)

- Space heating demand 7887 kWh and production 12751 kWh including losses of all components

Fig. 14: Different layer temperatures of the storage tank

- Highest and lowest top layer temperature 60 °C and 25°C

- Highest and lowest bottom layer temperature 48 °C and 21°C
Simulation result-1 (con…)

➢ Highest temperature was over 23 °C in January 1
➢ Lowest temperature was near 21.5 °C
➢ October to April are considered for winter months

➢ COP of the heat pump was 3.5
➢ Production and consumption of the heat pump were 4812 kWh and 1623 kWh
➢ Heat pump supplied temperature was higher in winter than summer months
Simulation result-1 (con…)

- Room temperature was set at 18 ºC in winter periods
- Room temperature found over 18 ºC during the heating periods
- And reached at 23 ºC in summer months

- Overall solar fraction was 61.4%
- Overall solar irradiation on the collector was 93.8%

**Fig. 17:** Supplied heating energy and room temperature of the building

**Fig. 18:** Solar and irradiation fraction of the collector of the proposed system
Design- 2 solar water heating system for DHW and SH

Fig. 19: Space and domestic hot water system for residential application [11]

Sizing of collector and storage tank for DHW:
(a) Collector:

- Collector area, $A = \frac{\text{No. of days} \times \text{solar fraction} \times Q_{\text{DHW}}}{\text{Daily solar irradiation} \times \text{Average system efficiency}}$ \hspace{1cm} (12)

- $Q_{\text{DHW}} = \text{volume of daily DHW} \times C_w \times \Delta T$ \hspace{1cm} (13)

- $Q_{\text{DHW}} = 12.52 \text{KWh/day}$

- $A = 2.92 \text{ m}^2$
(b) Storage tank:

\[ V_{cyl} = \frac{2*Vn*P*(T_h-T_c)}{(T_{dhw}-T_c)} \] \hspace{1cm} (14)

\[ V_{cyl} = 426 \text{ L} \]

Sizing of collector and storage tank for SH:

(c) Collector:

- Discussed earlier in previous section, new assumptions are collector efficiency, \( \eta = 55\% \), standby loss= 0.05 kWh/hr. and circulation loss= 8%

- Collector area, \( A=15 \text{ m}^2 \) (Using equation 1-5)

(d) Storage tank:

- Tank volume to collector area ratio, \( V/A=2 \) ............................................(15)
- Storage tank volume, \( V= 2*15=30 \text{ m}^3 \)
- Volume, \( V = (\pi * D^2 * H)/4 \) ............................................(16)
Design-2 (con...)

- Total collector area, $A=15+2.92=18 \text{ m}^2$
- Total storage tank volume, $V=0.45+30=31 \text{ m}^3$
- Selected model: COBRALINO AK 2.2 V, manufacturer: SOLTOP Schuppiesser AG, test standard: North America [12]
- Flat plate collector
- Cylindrical buried storage tank
- Material: enameled steel
- Height, $H=3 \text{ m}$ and diameter, $D=3.36 \text{ m}$

**Boiler:**
4 kW, propane gas based Boiler
Simulation result-2 and analysis

Fig. 20: Heating energy demand and energy production

- Space heating demand was 7887 kWh
- Energy production 8002 kWh
- Solar coverage around 32%
- Heating coverage value was 4381 kWh

Fig. 21: Space heating storage max. temperature

- Highest temperature found around 60 °C in summer
- Higher solar irradiation and lower heating demand are the reasons
- But, in heating months, value was 45 °C
Simulation result-2 (con…)

Fig. 22: DHW energy demand and energy production

- Domestic hot water demand was 4689 kWh
- Energy production was 4776 kWh
- Percentage of solar coverage was 60%
- Electric heater covered around 40%

Fig. 23: DHW storage maximum temperature

- Highest temperature was over 60 °C
- In winter months, upper edge temperature found 55 °C
- DHW set temperature was 50°C
Simulation result-2 (con…)

Fig. 24: solar energy from the collector and to the storage tank

- Useful energy from the collector 8331 kWh
- Useful energy to storage for DHW and space heating 7645 kWh
- Highest energy found in July

Fig. 25: Supplied electrical and boiler energy

- Electrical supply energy was 1905 kWh
- Boiler supplied energy was 5504 kWh
- Due to seasonal storage, boiler supplied energy was higher
Energy consumption and heat loss of a HRV

- Maintains indoor air quality
- Provides thermal comfort
- Helps to make energy efficient and energy saving house

Fig. 26: A typical heat recovery unit [13]

Fig. 27: Experiment set up of HRV
Calculation of heat loss and power consumption:

- Heat loss through, $HRV = Q_v \times d \times C_p \times \Delta T$ ................................................. (17)

- Flow rate of air, $Q_v = A \times V$ .......................................................... (18)

- Electrical energy consumption = Power $\times 24 \times 273$ ................................. (19)

- Total HRV losses = HRV losses + electrical energy consumption .............. (20)
Energy consumption and heat loss of a HRV (con…)

Result analysis:

- Yearly heat loss 2508 kWh
- Highest value found 402 kWh in December
- Power consumption was 720 kWh
- Total HRV energy loss 3228 kWh per year
- Total cost $484 per year

- Heat recovery unit was turned off in the June, July and August
- Maximum value of heat loss found 1134 W in December
Dynamic simulation of a solar space heating system

- To study the transient response of the system components
- To select, optimize, and do precise models of various components

Fig. 31: Simulink design of the full system [14]
Dynamic simulation (con…)
Result analysis:

- Simulation step size was 50 hr
- Initial liquid temperature was 11 °C
- Highest temperature found 52 °C
- Fluctuates between (44 to 49) °C
Dynamic simulation (con…)

Result analysis:

- Result is an increasing function over the time of the simulation
- At the beginning, the temperature was below 15 °C
- Indoor average temperature was reached above 25 °C
- Expected temperature was 24 °C
- Outdoor temperature was ranged between 0°C to 10 °C

Fig. 34: Comparing the outdoor and indoor average temperature
Conclusion

✓ Selected model: Design- 2

✓ Total collector area, \( A = 18 \, m^2 \)

✓ Collector model: COBRALINO AK 2.2 V, Manufacturer: SOLTOP Schuppisser AG

✓ Number of collectors, \( N = 8 \), Flat plate collector

✓ Total storage tank volume, \( V = 31 \, m^3 \), Cylindrical buried tank

✓ Material: Enameled steel with insulation thickness 0.3 m

✓ Height, \( H = 3 \) m and diameter, \( D = 3.36 \) m
Future work

- A hybrid system can be designed without using boiler and heat pump
- Extensive cost analysis of the full system can be done as it is very essential part
- A study could be done about design of such system with a heat pump and check its effectiveness
- A dynamic simulation of the full system could be done for a few hours
- A simulation method or software needs to be identified that can simulate performance of such a system for a year
- An alternative technique with proper insulation can be used to reduce the energy losses
- No control system was proposed in this study. Design of a proper control system is essential that should be considered for further work
- Impact of snow on solar collectors and snow removal technique can be considered for further work
- A study can be done to know the installation issues of this kind of system
Acknowledgement

- Dr. M. Tariq Iqbal
- Natural Science and Engineering Research Council (NSERC)
- School of Graduate Studies (SGS) of Memorial University of Newfoundland
- Faculty of Engineering and Applied Science
- My family & friends
Publications

Journal papers

1. Rabbani Rasha and M. Tariq Iqbal, Design and analysis of a solar water heating system with thermal storage for residential applications, submitted with Journal of sustainable Energy, September 2019 (under review)


Conference papers

1. Rabbani Rasha, Habibur Rahaman, Tariq Iqbal, Sizing, modeling and analysis of a solar seasonal energy storage for space heating in Newfoundland, presented at CSME-CFDSC 2019

Publications (con…)

Non-refereed local IEEE conference papers

1. Rabbani Rasha, Debobrata Gupta and Mohammad Tariq Iqbal, Design and modeling of a solar water heating system for a house in Bangladesh, presented at 27th IEEE NECEC St. John's, Nov.13, 2018

2. Debobrata Gupta, Rabbani Rasha and Mohammad Tariq Iqbal, Energy Analysis and PV System Design for a House in Bangladesh, presented at 27th IEEE NECEC St. John's, Nov.13, 2018

3. Rabbani Rasha and Mohammad Tariq Iqbal, Experimental investigation of yearly energy loss through a heat recovery ventilator unit in Newfoundland, presented at 28th IEEE NECEC St. John's, Nov.19, 2019 (will be presented)

Poster presentation

1. Rabbani Rasha and M. Tariq Iqbal, Sizing, modeling and analysis of a solar seasonal energy storage for space heating in Newfoundland, Presented in poster session at Ryerson University, Toronto, ON, during NESTNet 3rd annual technical conference, June 17-19, 2019
References


3. https://curve.carleton.ca/7128b9f8-df4f-4517-a032-93d334518e6c


References (con…)

Thank you!