Design, Analysis and Control of Solar Heating System with Seasonal Thermal Energy Storage

Presented By
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Presentation Overview:

Chap 1. Introduction and Literature Review
Chap. 2. Design and Analysis of Solar Water Heating System With Seasonal Storage
Chap 3. Design and Analysis of House Heating System with Storage Using Solar Electric Modules
Chap 4. Mathematical Modelling and Simulation of Solar Water Heating Systems
Chap 5. Remote control of house thermal energy storage system
Chap 6. Conclusion and Future Research
Acknowledgements
Publications and References
Questions and Answer
Chap 1. **Introduction** and Literature Review

### Energy consumption

#### Natural Resource Canada (NRCan)

- 6 million tons of CO$_2$ to Canada's GHG every year
- Residential consumers are consuming about 16%
- In 2020, solar electricity production is nearly 1% of the total electricity generation and almost 6300 MW.
- Canada plans to reduce its GHG emissions by 30% below 2005 levels by 2030[2].

#### Table 1: Space heating by fuel.

<table>
<thead>
<tr>
<th>Sectors</th>
<th>Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Heating</td>
<td>67%</td>
</tr>
<tr>
<td>Appliances</td>
<td>15%</td>
</tr>
<tr>
<td>Water Heating</td>
<td>15%</td>
</tr>
<tr>
<td>Lighting</td>
<td>3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel types</th>
<th>DHW</th>
<th>Space heating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>68%</td>
<td>50%</td>
</tr>
<tr>
<td>Electricity</td>
<td>29%</td>
<td>25%</td>
</tr>
<tr>
<td>Heating oil</td>
<td>2%</td>
<td>7%</td>
</tr>
<tr>
<td>Wood</td>
<td>1%</td>
<td>17%</td>
</tr>
<tr>
<td>Other</td>
<td>2%</td>
<td>1%</td>
</tr>
</tbody>
</table>

#### Energy consumption categories:
- Space heating
- Water heating
- Appliances
- Lighting
In 2020, solar electricity production is nearly 1% of the total electricity generation and almost 6300 MW.

The average annual solar irradiance in Newfoundland province is around 1000 kWh/kW/yr.

The average per capita electricity consumption in Newfoundland province was 1294 kWh in 2019.

NL province received an F rating that means a 5 kW photovoltaic system able to produce around 4,713 kWh per year,
Chap 1. Introduction and Literature Review

5/58 Solar Instruments

PV Array, Efficiency: 14~18%

Fig. 3 Flat plat collector (water-based)

Hybrid PVT Collector

Panel type | Energy efficiency | Exergy efficiency
---|---|---
Unglazed PVT-air [36] | 45% | 10.75
Single glazed PVT-air [37] | 55% | 13.5%
Single glazed PVT-air [38] | 55%–66% | 12%–15%
Double glazed T-air [39] | — | 7.4%
PVT-air [40] | 33%–45% | 11.3%–16%
PVT-water [41] | — | 3%–15%

PVT: photovoltaic thermal; T: thermal.
Domestic Water Heater Types

- Tankless Water Heater
- Integrated Water Heaters
- Heat Pump Water Heaters
- Solar Water Heaters

TES: Thermal Energy Storage Systems
STES: Solar TES
SSTES: Sessional Solar TES
Thermal Collector:

Solar Thermal Collector

- Concentration
- Non-concentrating/Stationary

1. Low grade heat (<110°F, 140~180°F)
   2. Use of glazed flat-plate collectors (air or liquid as heat transfer instrument, or concentrator collector)
   3. Applications: Mainly domestic hot water heating.

1. Medium grade heat (>110°F, 140~180°F)
   2. Use of glazed flat-plate collectors
   3. High heat (>180°F)
   4. Application: Independent power station

1. High temperature (>180°F)
   2. Examples: Parabolic dish or trough collectors
   3. Application: Independent power station

1. Collector area & absorber area are equal
   2. Examples: Flat-plate or Evacuated tube collector
   3. Applications: Building heating

Tracking
- Single axis
  - Fixed mirror solar concentrator
  - Cylindrical parabolic conc.
  - Linear Fresnel lens/reflector
- Two axis
  - Paraboloidal dish concentrator
  - Central tower receiver
  - Circular Fresnel lens
  - Hemispherical bowl mirror

Non-tracking
- Flat receiver with booster mirror
- Tabor-Zeimer circular cylinder
- Compound parabolic conc.
- V-trough

Temperature
- Low
- Medium
- High

Concentration
- Non-concentrating/Staionary
- Medium (Parabolic cylinder)
- High concentrating

Applications:
- Solar thermal power plants
- Parabolic trough
- Parabolic dish
- Satellite dish field
- Heliostat field

Tracking the sun on a single axis
- Fluid temp up to 750°F

Satellite dish type
- Concentrated to a focal point
- Fluid temp up to 500°F

Tracking mirrors & solar tower
- Fluid temp up to 3700°F
Chap 1. Introduction and Literature Review

Energy Storage Systems

- **Thermal**
  - ICE storage air conditioning
  - Solar pond

- **Physical processes**
  - Latent heat
  - Sensible heat

- **Chemical processes**
  - Thermochemical pipeline
  - Chemical heat pump

- **Mechanical**
  - Compressed air
  - Flywheels
  - Pump
  - Hydroelectric
  - Hydraulic accumulator
  - Heat of reaction
  - Fireless locomotive

- **Chemical**
  - Hydrogen
  - Methanol
  - Liquid hydrocarbon

- **Biological**
  - Starch
  - Glycogen

- **Magnetic**
  - Superconducting magnetic energy storage (SMES)

- **Electrical**
  - Electric double layer capacitor (EDLC)
  - Supercapacitor
  - High power supercapacitors

- **Phase change material**
  - Organic PCMs
  - Inorganic PCMs
  - Hygroscopic Materials
  - Solid-solid PCM

- **Closed**
  - Absorption
  - Salt hydrates
  - Two phase systems (solid-gas)

- **Open**
  - Adsorption
  - Silica gel
  - Zeolite
  - Three phase system (solid-liquid-gaseous)

- **Ice**
  - Liquid air energy storage (LAES)

- **Cryogenic energy storage**
  - Cryogenic energy storage

- **Power to Gas**
  - Electrochemical
  - Advanced battery energy storage systems (ABESSs)
  - Chemical heat pump (CHPs)

- **Flow batteries**
  - Flow batteries

- **Fuel cells**
  - NaS Battery
  - Advanced lead acid battery
  - Li-ion battery

- **Direct fired**
  - Metal hydrides
  - Low-hysteresis intermetallic
  - Solid-gas
  - Liquid gas

- **Indirect fired**
  - Organic inorganic

- **Direct methanol fuel cells (DMFC)**
  - Proton exchange membrane fuel cells (PEMFC)

- **Solid oxide fuel cells (SOFC)**
  - Phosphoric acid fuel cells (PAFC)

- **Molten carbonate fuel cells (MCFC)**
  - Alkaline fuel cells (AFC)

- **Chemical heat pump (CHPs)**
  - Thermal storage

- **Biological**
  - Organic PCMs
  - Inorganic PCMs
  - Hygroscopic Materials
  - Solid-solid PCM
Chap 1. Introduction and Literature Review

Solar Collector Market

- Liquid Glazed
- Air
- Liquid Unglazed
- Combined

Annual collector sales (sq. m) in Canada

Year
2001 2003 2005 2007 2009 2011 2013 2015 2017

Sales:
- Liquid Glazed: 53571, 139159, 199491, 57688, 36173
- Air: 4236, 61759, 114018, 114018, 24953
- Liquid Unglazed: 0, 0, 0, 0, 0
- Combined: 0, 0, 0, 0, 0

Values are in thousands of square meters.
Reference Projects

» Drack Landing project, AB in 2007.
» TES systems in BC for a fish firm.
» UOIT Developed a BTES Systems in 1990.
» Carleton University developed Low-temperature based TES.
» University of Alberta Built a BTES ES in 2015.
» Ahmed Aisa and Tariq Iqbal designed a sessional STES systems for a residential house in 2018.
» K & P contracting Ltd. built up a net-zero energy home in St. John's, Newfoundland

» Many more project around the world.
Research steps:

✓ Software Parts:

House parameters analysis using BEopt software.
» Components sizing in Mathematical calculations and Homer Software as well as weather.
» Design, simulation, and analysis of ES in PolySun software
» The TES system design and control using Matlab/Simulink software

✓ Hardware Parts:

Remote Control Implementation steps:
» The openHAB is used an IoT Platform (Home Server).
» Remote monitoring and control system has been developed using ESP 32Thing, MQTT and sensors.
The following assumptions are considered:

✓ The water flow has been considered under steady-state conditions.
✓ The tube flow has been assumed fully developed flow
✓ The collector's layer temperature has been neglected.
✓ All other parameters have been assumed temperature independent.
✓ There is no heat gain (or loss) when the water through the pumps and pipes.
✓ It is assumed that there is no shading and dust on the collector panel.
The required area of the solar collector is 16 m².
The optimal volume to collector area ratio should be 2 m³/m².
The optimal sessional tank volume is 30 m³.
The small tank for DWH is considered as 0.189 m³.
Finally, the sessional tank volume, \( V = \pi \times D^2 \times H / 4 \)
Where the tank height, \( H = 3 \) m and the volume, \( V = 30 \) m³. 

The calculated tank diameter is, \( D = 3.36 \) m. So, \( H/D = 3/3.36 = 0.89 \).
It showed a good agreement with literature.

Heat Pump COP = \( \frac{T_o}{T_o - T_i} = 3 \)

**ASHP/GSHP?**

Ground Temp: \( t_o = t_d + A_d \exp(-y[\Omega/(2a)]) \cos(\Omega \tau - y[\Omega/(2a)]) \)

Inlet and the outlet temp difference is small so, GSHP is unsuitable.

ASHP is considered.
Design, Analysis and Control of Solar Heating System with Seasonal Thermal Energy Storage

Chap. 2. Design and Analysis of TES Systems With Seasonal Storage

Weather Analysis

A typical winter (Jan)

A typical Summer (Jul)

Newfoundland and Labrador, Canada

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House Parameters Analysis

- **Monthly consumption (kWh):**
  - January: 2280
  - February: 2465
  - March: 1900
  - April: 2090
  - May: 1507
  - June: 607
  - July: 835
  - August: 607
  - September: 628
  - October: 1150
  - November: 1945

- **Monthly consumption (kWh) by Month:**
  - January: 15\%
  - February: 16\%
  - March: 17\%
  - April: 17\%
  - May: 12\%
  - June: 4\%
  - July: 2\%
  - August: 2\%
  - September: 2\%
  - October: 2\%
  - November: 1\%

- **Energy distribution (kWh/yr):**
  - Hot water: 19511 kWh
  - Heating: 4689 kWh
  - Lighting: 3421.26 kWh
  - Appliances: 2667 kWh
  - Ventilation fan: 2512 kWh

- **Energy rating index:**
  - Hot water: 62.9
  - Heating: 13.5
  - Lighting: 3.3
  - Appliances: 6.4

- **CO2 emission (tons/yr):**
  - Ventilation fan: 8.4 tons
  - Heating: 13.5 tons
  - Lighting: 1.4 tons
  - Appliances: 1.4 tons

- **Appliances consumption:**
  - Electrical appliances: 2667 kWh

- **Lighting consumption:**
  - Electrical appliances: 950.35 kWh

- **Water heating consumption:**
  - Electrical appliances: 3421.26 kWh

- **Space heating consumption:**
  - Electrical appliances: 11404.2 kWh

- **Space cooling consumption:**
  - Electrical appliances: 570.21 kWh

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**BEopt Software is used**

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Newfoundland and Labrador, Canada

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House Demand Analysis

- **Space Heating** (kWh) vs **Hot Water** (kWh) over **Time step (hr)**

- **Electrical load (kW)** over **Time step (hr)**

- **DHW** load over **Time step (hr)**

- **Space Heating load (kW)** over **Time step (kW)**
Existing House Simulation in PolySun

House simulation parameters: Chap. 2, Table 3

Simulation Results: Chap. 2, Table 4

- Grid energy (kWh)
- Appliances (kWh)
- Space heating (kWh)
- Hot water (kWh)
- Hot water Temp
- Radiator temp

House parameters:
- Grid
- Controller
- Demand
- Electric Boiler
- Hot water
- Cold water

Energy (lWh)
Temperature (°C)

Months

Grid energy (kWh)
Appliances (kWh)
Space heating (kWh)
Hot water (kWh)
Hot water Temp
Radiator temp
Chap. 2. Design and Analysis of TES Systems With Seasonal Storage

PolySun Software is used
Design and Analysis of TES Systems With Seasonal Storage

SSTES System Control

Solar collector to tank loop
- Controller Input: Tank bottom and collector outlet temperature
  - Is the pump running?
    - Yes: $T_{\text{collector outlet}} - T_{\text{tank bottom layer}} > 20 \degree C$?
      - Yes: Pump-ON
      - No: Reapet
    - No: $T_{\text{collector outlet}} - T_{\text{tank bottom layer}} > 10 \degree C$?
      - Yes: Pump-OFF
      - No: Reapet

Auxiliary heater controller
- Controller Input: Set and actual tank temperature
  - Is the heater running?
    - Yes: $T_{\text{actual}} - T_{\text{set}} > 5 \degree C$?
      - Yes: Heater-ON
      - No: Reapet
    - No: $T_{\text{actual}} - T_{\text{set}} < -5 \degree C$?
      - Yes: Heater-OFF
      - No: Reapet

Circulating pump controller
- Controller Input: Two tank upper temperatures and hot water settings
  - Is the circulating pump running?
    - Yes: $T_{\text{sessional tank upper}} \& T_{\text{diurnal tank upper}} > \text{settings (°C)}$?
      - Yes: Pump-ON
      - No: Reapet
    - No: $T_{\text{sessional tank upper}} \& T_{\text{diurnal tank upper}} < \text{settings (°C)}$?
      - Yes: Pump-OFF
      - No: Reapet

Space heating controller
- Change the mixing valve position
- Controller Input: Set and actual room temperature
  - Is the radiator pump running?
    - Yes: $T_{\text{actual}} - T_{\text{set}} > 1 \degree C$?
      - Yes: Pump-ON
      - No: Reapet
    - No: $T_{\text{actual}} - T_{\text{set}} < -1 \degree C$?
      - Yes: Pump-OFF
      - No: Reapet

**Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>10 m$^3$</th>
<th>15 m$^3$</th>
<th>20 m$^3$</th>
<th>25 m$^3$</th>
<th>30 m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel consumption (kWh)[HP]</td>
<td>4185</td>
<td>3621</td>
<td>3797</td>
<td>3960</td>
<td>4135</td>
</tr>
<tr>
<td>Energy to the system (kWh)</td>
<td>11769</td>
<td>10217</td>
<td>10721</td>
<td>11132</td>
<td>11685</td>
</tr>
<tr>
<td>Energy saving solar thermal (kWh)</td>
<td>4861</td>
<td>6791</td>
<td>6860</td>
<td>6904</td>
<td>6921</td>
</tr>
<tr>
<td>CO2 savings solar thermal (kg)</td>
<td>2608</td>
<td>3643</td>
<td>3680</td>
<td>3703</td>
<td>3712</td>
</tr>
<tr>
<td>Sessional storage tank heat loss (kWh)</td>
<td>2426</td>
<td>2839</td>
<td>3378</td>
<td>3809</td>
<td>4357</td>
</tr>
<tr>
<td>Tank top layer temperature (°C)</td>
<td>70.2</td>
<td>69.9</td>
<td>69.8</td>
<td>68.5</td>
<td>68.2</td>
</tr>
<tr>
<td>Tank top layer temperature (°C)</td>
<td>43.5</td>
<td>47.2</td>
<td>47</td>
<td>46.9</td>
<td>46.4</td>
</tr>
</tbody>
</table>
SSTES Simulation Results
Presentation Overview:

Chap. 2. Design and Analysis of TES Systems With Seasonal Storage
## Comparison of Ref and SSTES

<table>
<thead>
<tr>
<th>particulars</th>
<th>Reference systems (Grid + EH)</th>
<th>SSTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy demand (kWh)</td>
<td>12873</td>
<td>12573</td>
</tr>
<tr>
<td>Space heating temperature (°C)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Hot water temperature (°C)</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Collector size</td>
<td>N/A</td>
<td>16 m²</td>
</tr>
<tr>
<td>Main tsank size (m³)</td>
<td>0.189</td>
<td>30</td>
</tr>
<tr>
<td>Solar fraction to hot water (%)</td>
<td>0</td>
<td>61</td>
</tr>
<tr>
<td>Solar fraction to space heating (%)</td>
<td>0</td>
<td>61</td>
</tr>
<tr>
<td>Total thermal energy generation (kWh)</td>
<td>12873</td>
<td>12855</td>
</tr>
<tr>
<td>Solar energy production (kWh)</td>
<td>0</td>
<td>7837</td>
</tr>
<tr>
<td>Auxiliary heater production (kWh)</td>
<td>12873</td>
<td>5015</td>
</tr>
<tr>
<td>CO₂ emission (kg)</td>
<td>6224</td>
<td>3556</td>
</tr>
<tr>
<td>Electrical energy savings (%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Thermal energy savings (%)</td>
<td>0</td>
<td>61%</td>
</tr>
</tbody>
</table>
Chapter 3. Design and Analysis of Energy Storage Using Solar Electric Modules

Solar Collector Based Systems

Weather and house parameters remains same as mention in Chapter-2

Cold water temperature=10°C.
Storage hot water temperature= 55°C.
Per person hot water demand, DHW= 20 liter/day
Hot water demand in kitchen, HWD_k = 30 liter/day
Storage volume,

\[
V_{ST} = [(B \times 0 \times DHW) + HWD_k] \times 1.2
\]

= [(02 \times 02 \times 20) + 30] \times 1.2

= 132 liter=0.132 m³

Main Tank: 0.2 m³

Energy demand for hot water,

\[
Q_S = V_{ST} \times C_p \times \Delta T
\]

= 0.132 \times 1.16 \times 45 = 6.89 \text{ kWh/day.}

Coldwater temperature=10°C.
Storage hot water temperature= 55°C.
Per person hot water demand, DHW= 20 liter/day
Hot water demand in kitchen, HWD_k = 30 liter/day
Storage volume,

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Energy demand for hot water,

\[
Q_S = V_{ST} \times C_p \times \Delta T
\]

= 0.132 \times 1.16 \times 45 = 6.89 \text{ kWh/day.}
Solar Collector Based Systems

Collector yield,

\[ C_Y = S_R \times \eta_K \times \eta_{sys} \]

\[ = 2.9 \times 0.6 \times 0.8 = 1.392 \text{ kWh/m}^2. \]

Collector array, \( C_A = \frac{Q}{C_Y} = \frac{6.89 \text{ kWh}}{1.392 \text{ kWh/m}^2} = 4.95 \text{ m}^2 \)

The required number of collectors = \( \frac{\text{Daily requirement}}{\text{Collector output}} = 0.0223 \text{ (m}^2/\text{day)} \)

The total number of collectors = \( 0.02231 (\text{m}^2/\text{day}) \times 125.27 \text{ m}^2 = 2.7 \) per day.

The surface area of collector array = \( \text{No of collectors} \times \text{size of each collector in m}^2 \)

\[ = 2.7 \times 1.9 \text{ m}^2 = 5.13 \text{ m}^2 \]

AE-21 model solar collector dimension is considered

Total collector area for space heating and DHW = \( 10.08 \text{ m}^2 \cong 10 \text{ m}^2 \)
Chap 3. Design and Analysis of Energy Storage Using Solar Electric Modules

Collector Based TES Performance

![Graphs showing solar collector output and solar fraction for different months and models.](image)

- **Left Graph:**
  - Solar collector output (kWh) vs. Solar fraction (%)
  - Model 1 output, Model 2 output, Model 1 (S.F), Model 2 (S.F)
  - Months: Jan, Feb, Mar, Apr, May, Jun, July, Aug, Sep, Oct, Nov, Dec

- **Right Graph:**
  - Model 1 Oil consumption, Total energy consumption, Electricity consumption
  - Model 2 Total energy consumption, Electricity consumption
  - Consumption (kWh) vs. Time (Jan to Dec)

- **Bottom Graph:**
  - Oil burner input/output (kWh), Heat pump input/output (kWh)
  - Oil burner In, Oil burner Out, Heat pump In, Heat pump Out
  - JAN to DEC Whispering
## Collector based TES performance summary

<table>
<thead>
<tr>
<th>Basic sections</th>
<th>Particulars</th>
<th>Existing/ reference system</th>
<th>Model 1 (Oil Burner)</th>
<th>Model 2 (Heat pump)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solar collector</strong></td>
<td>Type</td>
<td>N/A</td>
<td>Flat plate</td>
<td>Flat plate</td>
</tr>
<tr>
<td></td>
<td>Number of collectors</td>
<td>N/A</td>
<td>05 (No tracking)</td>
<td>05 (No tracking)</td>
</tr>
<tr>
<td></td>
<td>Total gross area</td>
<td>N/A</td>
<td>10 m²</td>
<td>10 m²</td>
</tr>
<tr>
<td></td>
<td>Annual Output</td>
<td>N/A</td>
<td>4345 kWh</td>
<td>5161 kWh</td>
</tr>
<tr>
<td><strong>Storage tank</strong></td>
<td>Volume</td>
<td>181 Liter</td>
<td>(132+200) Liter</td>
<td>(132+200) Liter</td>
</tr>
<tr>
<td></td>
<td>Functions</td>
<td>DHW only</td>
<td>DHW and space heating</td>
<td>DHW and space heating</td>
</tr>
<tr>
<td><strong>Auxiliary burner</strong></td>
<td>Type, capacity</td>
<td>Electric resistance (4 kW)</td>
<td>Oil burner (3 kW)</td>
<td>Heat pump (3 kW)</td>
</tr>
<tr>
<td></td>
<td>Energy input/output</td>
<td>Same</td>
<td>1635/1091 kWh</td>
<td>354/882 kWh</td>
</tr>
<tr>
<td><strong>Annual energy consumption</strong></td>
<td>DHW and space heating</td>
<td>17009 kWh</td>
<td>9389.5 kWh + 159.2 L Oil</td>
<td>8320.5 kWh</td>
</tr>
<tr>
<td><strong>Annual consumer bill</strong></td>
<td>DHW and space heating</td>
<td>1690 CAD</td>
<td>1201 CAD</td>
<td>998.46 CAD</td>
</tr>
<tr>
<td></td>
<td>Savings</td>
<td>No</td>
<td>29%</td>
<td>44%</td>
</tr>
</tbody>
</table>
Sizing PV for Water Heating
Required load for water heating = 6.89 kWh/day (standard two rooms for 4 people)
Total PV panels energy needed = 6.89 kWh/day × 1.3 = 8.957 kWh/day.
Total Wp of PV panel capacity needed = 8957 Wh/day / 3.4 = 2634 Wp.
Number of PV module = 2634 Wp / 150 W = 17.56 modules ≈ 18 modules.
The area of PV panel = 0.93 × 0.675 m² = 0.6277 m²/per panel
The total area of PV panel = 11.3 m²

Sizing for Space Heating
Required load for space heating = 20.27 kWh/day [standard two rooms with 4 people]
Total PV panels energy needed = 20.27 kWh/day × 1.3 = 26.35 kWh/day.
Total Wp of PV panel capacity needed = 26350 Wh/day / 3.4 = 7750 Wp.
Number of PV module = 7750 Wp / 150 W = 51.66 modules ≈ 52 modules.
The area of PV panel = 0.93 × 0.675 m² = 0.6277 m²/per panel
The total area of PV panel = 0.6277 m² × 52 = 32.64 m²
The total number of a solar panel for water and space heating is 70 numbers, which are equal to 43.94 m².
Control Systems

Is the water level good?
Yes → Keep open the valve 2
No → Keep close the valve 2

Is it day time?
Yes → Connect three position switch in MCB 3 & heater coil 2 both, turn off the pump
No →

Is the sunshine available?
Yes → Switch on the auxiliary heater coil 1
No → Switch off the auxiliary heater coil 1

Is the water temperature >50?
Yes → Turn on the pump
No →

Is the water temperature <50?
Yes → Switch off the auxiliary heater coil 1
No →

Controller working principle
- Is the water level good?
  No →
  Yes → Keep open the valve 2
- Is it day time?
  No →
  Yes → Connect three position switch in MCB 3 & heater coil 2 both, turn off the pump
- Is the sunshine available?
  No →
  Yes → Switch on the auxiliary heater coil 1
- Is the water temperature >50?
  No →
  Yes → Turn on the pump
- Is the water temperature <50?
  No →
  Yes → Switch off the auxiliary heater coil 1

PV based TES Systems Design

Is the water level good?
Keep open the valve 2
Keep close the valve 2

Is it day time?
Connect three position switch in MCB 3 & heater coil 2 both, turn off the pump

Is the sunshine available?
Switch on the auxiliary heater coil 1
Switch off the auxiliary heater coil 1

Is the water temperature >50?
Turn on the pump

Is the water temperature <50?
Switch off the auxiliary heater coil 1
Switch on the auxiliary heater coil 1

Controller working principle
- Is the water level good?
  No →
  Yes → Keep open the valve 2
- Is it day time?
  No →
  Yes → Connect three position switch in MCB 3 & heater coil 2 both, turn off the pump
- Is the sunshine available?
  No →
  Yes → Switch on the auxiliary heater coil 1
- Is the water temperature >50?
  No →
  Yes → Turn on the pump
- Is the water temperature <50?
  No →
  Yes → Switch off the auxiliary heater coil 1

Room heater-1
Room heater-2

Pump
Valve 1
Hot water
Cold water
Heater coil-1
Level
Temp.
Sensors
Water boiler
Controller
Heater coil-2

MCB 1
Inverter

MCB 2
Auxiliary electric heater

MCB 3

Three position AC switch

Thermostat

PV panels

Inverter

Main switch box

LDR Sensor

Valve 1 → Hot water
Valve 2 → Cold water in
Valve 3 → Cold water out

PV panels

Sensors

Heater coil-1

Level Temp.

Controller

PV panels

Sensors

Heater coil-2
Design, Analysis and Control of Solar Heating System with Seasonal Thermal Energy Storage

Chap 3. Design and Analysis of Energy Storage Using Solar Electric Modules

**PV Basted TES Implementation Cost**

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>Sizing and Prices</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Panel cost</td>
<td>150$×70 no’s=10500 CAD.</td>
</tr>
<tr>
<td>Installation cost</td>
<td>10500×34%=2310 CAD.</td>
</tr>
<tr>
<td>450 L of Electric Water Tank with high insulation cost</td>
<td>3000 CAD</td>
</tr>
<tr>
<td>Combiner box (6 String, 250 V AC, 10 A each)</td>
<td>12×225 = 2700 CAD</td>
</tr>
<tr>
<td>MPPT installation</td>
<td>optional</td>
</tr>
<tr>
<td>Inverter cost (12000 W)</td>
<td>3000 CAD</td>
</tr>
<tr>
<td>Electrical components and fixing</td>
<td>10500×8%=840 CAD.</td>
</tr>
<tr>
<td>The total investment cost</td>
<td>22350 CAD</td>
</tr>
</tbody>
</table>

---

### Graphs

- **Output power (W) with no tracking**
- **House appliances consumption**
- **Heat Pump consumption**
- **Total consumption**

Months: 1 to 12

Consumption in kWh: 0 to 700

House appliances consumption: 0 to 600

Heat Pump consumption: 0 to 400

Total consumption: 0 to 700
### PV Basted TES System Comparison

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Reference system</th>
<th>Thermal Collector Based</th>
<th>PV Based</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Model 1</td>
<td>Model 2</td>
</tr>
<tr>
<td><strong>Energy generation from a renewable source</strong></td>
<td>0 kWh/year</td>
<td>4345 kWh/year</td>
<td>4345 kWh/year</td>
</tr>
<tr>
<td><strong>Energy is taken from the grid</strong></td>
<td>17009 kWh/year</td>
<td>9389.5 kWh + 159.2 L Oil</td>
<td>8320.5 kWh</td>
</tr>
<tr>
<td><strong>Annual energy savings</strong></td>
<td>0 kWh/year</td>
<td>7619.5 kWh/year</td>
<td>8688.5 kWh/year</td>
</tr>
<tr>
<td><strong>Surface requirement</strong></td>
<td>10 m²</td>
<td>10 m²</td>
<td>10 m²</td>
</tr>
<tr>
<td><strong>Storage tank size</strong></td>
<td>181 L</td>
<td>(132+200) Liter</td>
<td>(132+200) Liter</td>
</tr>
<tr>
<td><strong>Investment cost</strong></td>
<td>Nothing change</td>
<td>53,600 CAD</td>
<td>54,600 CAD</td>
</tr>
<tr>
<td><strong>Yearly savings</strong></td>
<td>0 CAD (0%)</td>
<td>914.34 CAD (29%)</td>
<td>1042.62 CAD (44%)</td>
</tr>
</tbody>
</table>
Assumptions:

1. The water flow has been considered under steady-state conditions.
2. The tube flow has been assumed fully developed flow.
3. The PVT and collectors layer temperature has been neglected.
4. All other parameters have been assumed; temperature independent.
5. There is no heat gain (or loss) when the water through the pumps and pipes.
6. It is assumed that there is no shading and dust on the PVT and collector panel.

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Mathematical Modelling of Solar Collector Based TES

Solar Collector:

\[
\frac{dT_{co}}{dt} = \frac{A_{c}n_{e}}{c} I_{c} - \frac{U_{1}A_{c}}{c} (T_{av} - T_{ca}) + \frac{v_{c}}{v_{c}} (T_{ci} - T_{co})
\]

Heat exchanger

\[
\frac{dT_{s}}{dt} = \frac{\dot{V}_{l}}{V_{s}} (T_{d} - T_{s}) + \frac{\dot{V}_{l}}{V_{s}} (T_{hco} - T_{s}) - \frac{A_{s}k_{s}}{\rho_{s}c_{s}V_{s}} (T_{s} - T_{sa})
\]

Mathematical Modelling of Solar Collector Based TES

The Simulink diagram of city cold water supply to the tank.

Circulating Pump
The flow rate in the collector to storage tank loop [13]:
\[
\dot{v}_c = \begin{cases} 
2.9 \times 10^{-5} \text{ m}^3 \text{ S}^{-1} & \text{when } T_{co} \geq T_s + 3 \\
0 & \text{when } T_{co} \leq T_s + 3 
\end{cases}
\]

The flow rate in the storage tank to the radiator loop:
\[
\dot{v}_c = \begin{cases} 
5.9 \times 10^{-5} \text{ m}^3 \text{ S}^{-1} & \text{when } T_{co} \geq T_s + 3 \\
0 & \text{when } T_{co} \leq T_s + 3 
\end{cases}
\]
Mathematical Modelling of Solar Collector Based TES

Radiator System Design Parameters: Chap. 4, Table 1

Thermostat (Matlab Programming)
Mathematical Modelling of Solar Collector Based TES

Details parameters: Chap. 4. Table 2
Mathematical Modelling of Solar Collector Based TES
Design, Analysis and Control of Solar Heating System with Seasonal Thermal Energy Storage

Chapter 4. Design and Simulation of Solar Water Heating Systems

Photovoltaic Thermal (PVT) Collector

- Flat Plate
- Concentrating
- Building integrated
- Un-covered
- Covered
- High concentration
- Low concentration
- Liquid based
- Heat pipe based
- PCM based
- Thermoelectric based
- Air-based

Solar Energy

Thermal Systems (Collector)

PVT Systems

PV Arrays

Heat Energy

Electrical Energy

Based on medium

Air, Water, Refrigerent, Flat Plate, Concentrating, Building Integrated

Based on Structure
The electrical efficiency of a glazed and unglazed PVT collector is about 11.5 and 13.4%.

Total efficiency of glazed and unglazed PVT collectors is 59.5% and 48.4%,

The thermal efficiency of a glazed and unglazed PVT collector is about 48% and 35%.

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The thermal efficiency of a glazed and unglazed PVT collector is about 48% and 35%.
Mathematical Modelling of PVT Based TES
# Available Technology in the Market

<table>
<thead>
<tr>
<th>Thermostat Name</th>
<th>Price</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Google Nest</td>
<td>$329</td>
<td>Smart way to control 3rd Gen are available</td>
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<td></td>
<td></td>
<td>Support multi-stage, multi-zone Local/Remote control</td>
<td></td>
</tr>
<tr>
<td>Honeywell</td>
<td>$149</td>
<td>Local/Remote control digital screen, the humidity, temperature, and thermostat settings options are available</td>
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<td>Compatible with temperature and humidity sensors Local/Remote control</td>
<td>it has only one temperature sensor and two occupancy sensors build in at Ecobee4 systems</td>
</tr>
</tbody>
</table>
Chap 5. Remote control of house thermal energy storage system

**System Architecture**

- **Demand**
- **Remote control and monitoring device**
- **Thermostat**
- **Appliances**
- **Home server**
- **Internet**
- **openHAB cloud**

**Solar thermal energy storage systems**

- Pre-heating Tank
- Main tank
- Collector
- A. H= Auxiliary heater

**Single family home**

- Cold water in
- Mobile device

**Configuration**

- Router with WLAN port
- Setup the HUB to work on user home network
- Login
- Create an account
- Enter IP Address
- Add Subnet Mask
- Select Interface
- Configuration
- End

- Already have an account?
- Yes
- No
- Yes
- No
- Yes
- No
- Yes
Overview of System Development

4.3 System Specifications and Requirements is mentioned

Components Description

5.1 openHAB Home Automation Local Server IoT Platform

5.2 DHT11 Digital Temperature Sensors

5.4 Wi-Fi Router (Communication Channel)

5.5 Digital Thermostat and Heater
Design, Analysis and Control of Solar Heating System with Seasonal Thermal Energy Storage

Chap 5. Remote control of house thermal energy storage system

Architecture and Connection of the ESP32 Thing board

SparkFun ESP32 Thing (DEV-13907)

The connection diagram
Available Technology in the Market

Model: Comfort Zone CZ523RBK

Thermostat settings

ESP32 Thing Microcontroller

Connection diagram of remote and ESP32 Thing

openHAB Setup and JAVA Programming
### openHAB Configuration

<table>
<thead>
<tr>
<th>openHAB components</th>
<th>Short descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add-ons</td>
<td>To communicate with connected devices</td>
</tr>
<tr>
<td>Things</td>
<td>Device representation in openHAB</td>
</tr>
<tr>
<td>Items</td>
<td>Things properties and capabilities</td>
</tr>
<tr>
<td>Groups</td>
<td>Items collections and categories</td>
</tr>
<tr>
<td>Sitemaps</td>
<td>User-defined interface to arrange groups, items, and so on.</td>
</tr>
<tr>
<td>Transformations</td>
<td>Functions to transform user data</td>
</tr>
<tr>
<td>Persistence</td>
<td>Store updated data service</td>
</tr>
<tr>
<td>Rules</td>
<td>It is used to automate the systems</td>
</tr>
<tr>
<td>Javascript</td>
<td>Define rule and other runtime objects using Java programming.</td>
</tr>
</tbody>
</table>

**openHAB and MQTT Configuration**
Chap 5. Remote control of house thermal energy storage system

Communication Mechanism

The relation between Things and Items.

openHAB home server and ESP32 Thing communication via MQTT broker
Table 2: The implementation methodologies

<table>
<thead>
<tr>
<th>Communication Mechanism</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>User 1</td>
<td>User 2</td>
<td>User 3</td>
</tr>
<tr>
<td>Remote Access (Log in ID/Password)</td>
<td>Publish/Subscribe</td>
<td>Publish/Subscribe</td>
</tr>
<tr>
<td>openHAB Cloud</td>
<td>openHAB</td>
<td>openHAB</td>
</tr>
<tr>
<td>Connection Through Wi-Fi</td>
<td>openHAB Home Server</td>
<td>ESP32 Thing microcontroller board</td>
</tr>
<tr>
<td>myopenhab.org</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2: The implementation methodologies

<table>
<thead>
<tr>
<th>Implementation Methodologies</th>
<th>Communication Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>openHAB Cloud</td>
<td>User 1</td>
</tr>
<tr>
<td>openHAB Home Server</td>
<td>User 2</td>
</tr>
<tr>
<td>Connection Through Wi-Fi</td>
<td>User 3</td>
</tr>
<tr>
<td>Publish/Subscribe</td>
<td>Remote Access</td>
</tr>
<tr>
<td>mosquitto (\text{TM})</td>
<td>Publish/Subscribe</td>
</tr>
<tr>
<td>Windows 10 MQTT</td>
<td>Publish/Subscribe</td>
</tr>
<tr>
<td>ESP32 Thing microcontroller board</td>
<td>Publish in: ON/OFF</td>
</tr>
<tr>
<td>DHT11 Sensor (Inside/Outside)</td>
<td>Publish in: Temperature</td>
</tr>
</tbody>
</table>
Experimental Setup

- DHT 11 Temperature sensors data
- 5 V USB
- Heater Remote
- ESP32 Thing Board
- Digital Thermostat
- Electrical Heater
- Control and Monitoring Dashboard
- Local Server
Chap 5. Remote control of house thermal energy storage system

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<table>
<thead>
<tr>
<th>Control Panel</th>
<th>HOME</th>
<th>LAB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Moon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance</td>
<td>2020-04-07 15:39</td>
<td></td>
</tr>
<tr>
<td>Parade</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Position</td>
<td>Azimuth: 196.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elevation: 21.35</td>
<td></td>
</tr>
<tr>
<td>Local Sun</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sunrise</td>
<td>2020-03-20 07:04</td>
<td></td>
</tr>
<tr>
<td>Sunset</td>
<td>2020-03-20 19:12</td>
<td></td>
</tr>
<tr>
<td>Noon</td>
<td>2020-03-20 13:10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Azimuth: 151.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elevation: 38.73</td>
<td></td>
</tr>
</tbody>
</table>

Control and Monitoring
- Relay Switch 1
- Relay Switch 2
- Relay Switch 3

Thermostat Settings
- Control
- Outdoor Temperature: -5.0 °C
- Indoor Temperature: 21.0 °C

Testing

Start

Sensors Read Data From Room Inside and Outside Environment
ESP32 Thing Receives Data From Sensors
ESP32 Displays Data on Serial Monitor
ESP32 Connects to the Local Wi-Fi Network
MQTT Broker Publishes/Subscribes
Post Data on openHAB Homer Local Server

IoT Server Acknowledges Data Receipt?
Yes
No

Is Relay Gets ON/OFF Signal?
Yes
No

Register at openHAB Cloud Console with UUID & Secret Number
Re-check C Drive for UUID/Secret Number
Yes
No

Do You Able to Access Dashboard Remotely?
Yes
No
Chap 5. Remote control of house thermal energy storage system

Main control and monitoring dashboards
Remote Control and Monitoring

https://myopenhab.org/login or openHAB App

Registered users, please log in.

mhrahaman@mun.ca

Forgot your password?

Sign in
## Proposed System Features

<table>
<thead>
<tr>
<th>S/N</th>
<th>Name of the components</th>
<th>QTY</th>
<th>Price (CA$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ESP32 Thing</td>
<td>1</td>
<td>31.90</td>
</tr>
<tr>
<td>2</td>
<td>TMP35 temperature sensors</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>DHT11 Temperature sensor</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Miscellaneous (Breadboard, Resistors, Wires, Boxes, etc.)</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Grad total:</td>
<td></td>
<td>45.9</td>
</tr>
</tbody>
</table>

### Available product features

<table>
<thead>
<tr>
<th>Thermostat Name</th>
<th>Price</th>
<th>Pros</th>
<th>Cons</th>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>S/N</th>
<th>Hardware</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ESP32 Thing</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>Breadboard (with Sensors, ESP32, Resistors, etc. connected)</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>Total:</td>
<td>3.8 W</td>
</tr>
</tbody>
</table>
Space heating and water heating is needed for approximately eight months in a year.

The major problem: grid overloading, GHG emission, high electricity bill and so on.

A single-family residential house has been analyzed and energy demand is calculated.

Proposed four TES systems such as solar collector, solar photovoltaic, hybrid type solar photovoltaic thermal array and a sessional. All systems can save a major portion of electricity consumption.

The proposed TES systems implementation cost and their instrumentation has been discussed.

A sessional solar thermal energy storage system has been proposed, mathematically designed, simulated and analyzed.

All results have been compared with the annual energy demand and annual energy production.

Nobody proposed such a system before in such a way and with respect to the Canadian (NL province) weather condition.

Proposed a remote control and monitoring systems prototype which is low cost and low power consumption.

The user can monitor and control from locally or remotely anywhere in the world.
Future Research Scopes

- Proposed STES systems can be redesigned at residential community, commercial or industrial.
- Several parameters assumed constant or ignored, can be considered and re-design.
- The thermal and electrical efficiency can be further improved.
- A robust controller can be proposed in dynamic simulation.
- Proposed STES system can be re-designed for all cold climate zone.
- Detailed reliability analysis of IoT based systems can be done in future.
- The remote-control prototype can be made with other type of MCU board to reduce cost.
- Data encryption can be implemented to ensure the more security.
- Various open source IoT/SCADA systems can be developed.
Publications

Refereed journal Articles

Refereed Conference Publications

Regional Conference Publication
✓ Habibur Rahaman, M. Tariq Iqbal, Load analysis of RUET, ECE building and design of a rooftop PV system to meet all its energy needs, presented at the 28th Annual IEEE NECEC conference, St. John’s, November 19th, 2019.

Research Presentations
✓ Md Habibur Rahaman and M. Tariq Iqbal, "Design a Low-Cost Remote Monitoring and Control Systems for Thermal Energy Storage System,” Presented at the 3 MT thesis competition, 2019 held at the Memorial University of Newfoundland, St. john’s, NL, Canada. June 1, 2019 [Awarded 3rd Prize].
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✓ Family members, Research Group Members and Friends