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

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

Background study (con…)

Fig. 01: 35 m^3 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]

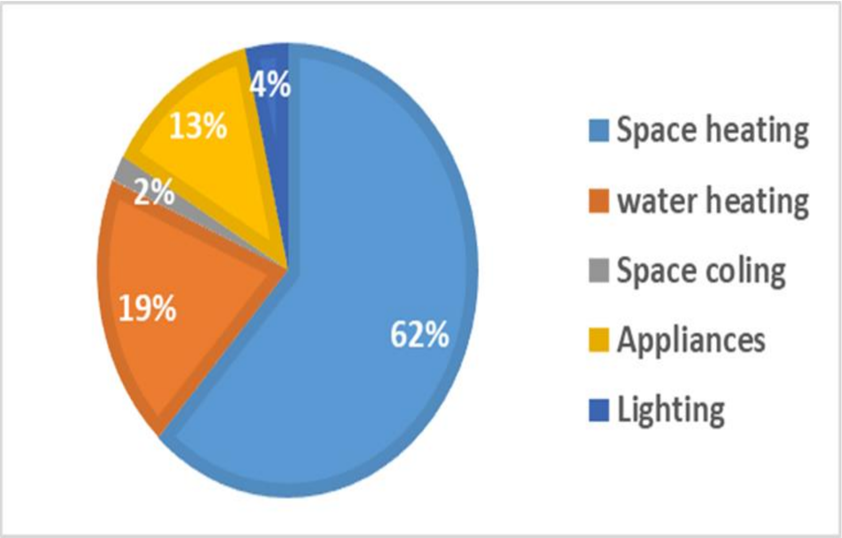

Fig.02: Secondary energy consumption

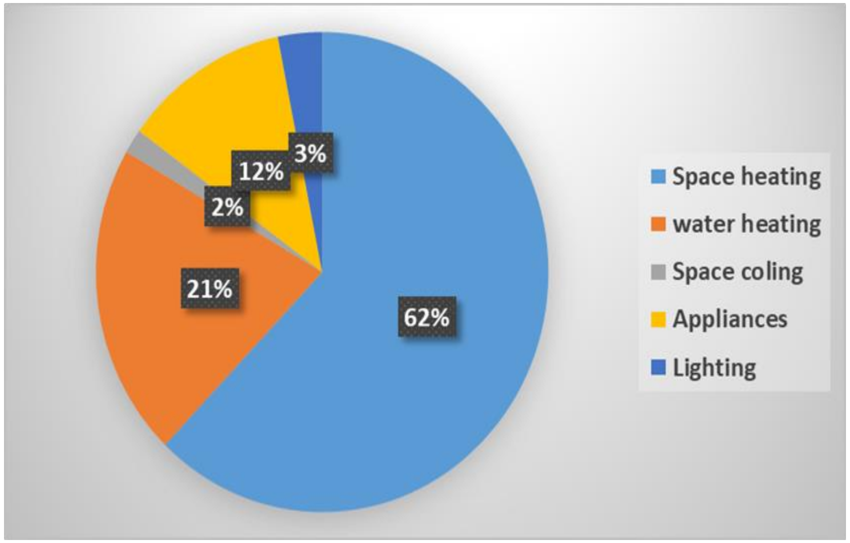

Fig.03: GHG emissions

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

Required software

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- ❑ 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]

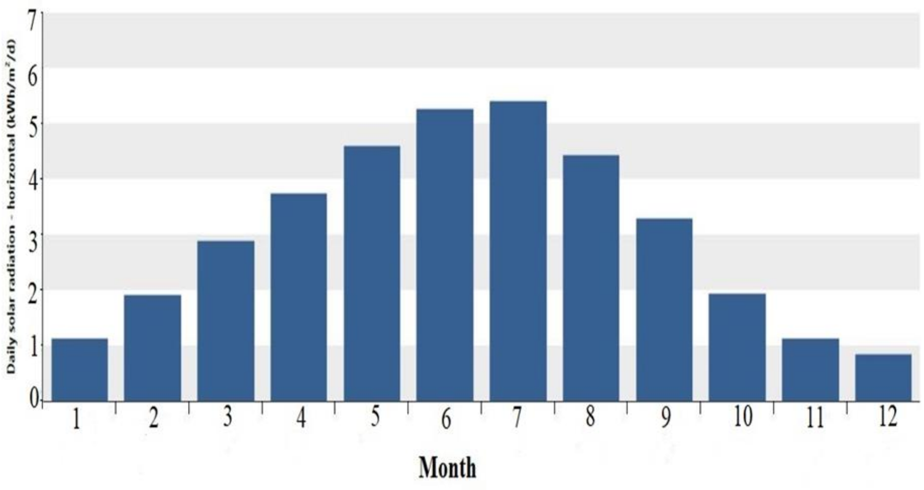

Fig. 04: Graphical representation of solar radiation

	Unit	Climate data location	Facility location	Source
Latitude		47.6	47.6	
Longitude		-52.7	-52.7	
Climate zone		6A - Cold - Humid		Ground+NASA
Elevation	m	141	94	Ground – Ground
Heating design temperature	°C	-13.5		Ground
Cooling design temperature	°C	23.0		Ground
Earth temperature amplitude	°C	7.2		NASA

Month	Air temperature	Relative humidity	Precipitation	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days 18 °C	Cooling degree-days 10 °C
	°C	%	mm	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January	-4.3	81.8%	132.19	1.14	99.0	7.8	0.5	691	0
February	-5.0	80.5%	99.16	1.92	99.1	7.5	-0.4	644	0
March	-2.5	80.8%	103.22	2.89	99.2	7.2	-0.1	636	0
April	1.3	82.1%	89.71	3.75	99.5	6.7	0.5	501	0
May	5.8	80.6%	79.22	4.59	99.8	6.1	2.1	378	0
June	10.9	81.5%	77.00	5.26	99.7	6.1	5.1	213	27
July	15.4	81.6%	90.57	5.40	99.8	5.8	9.9	81	167
August	15.3	81.7%	94.72	4.43	99.8	5.8	13.4	84	164
September	11.6	84.0%	109.92	3.30	99.8	5.8	12.5	192	48
October	7.0	83.9%	131.20	1.94	99.7	6.4	9.1	341	0
November	3.1	82.9%	131.97	1.14	99.5	7.0	5.3	447	0
December	-1.7	83.2%	140.55	0.85	99.2	7.5	2.3	611	0
Annual	**4.8**	**82.1%**	**1,279.43**	**3.06**	**99.5**	**6.6**	**5.0**	**4,818**	**407**
Source	Ground	Ground	NASA	Ground	Ground	Ground	NASA	Ground	Ground
Measured at					m	10	0		

Fig. 05: Numerical value of solar radiation

- Selected area is St. john's, NL, Canada, and latitude (47.56 ºN) 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

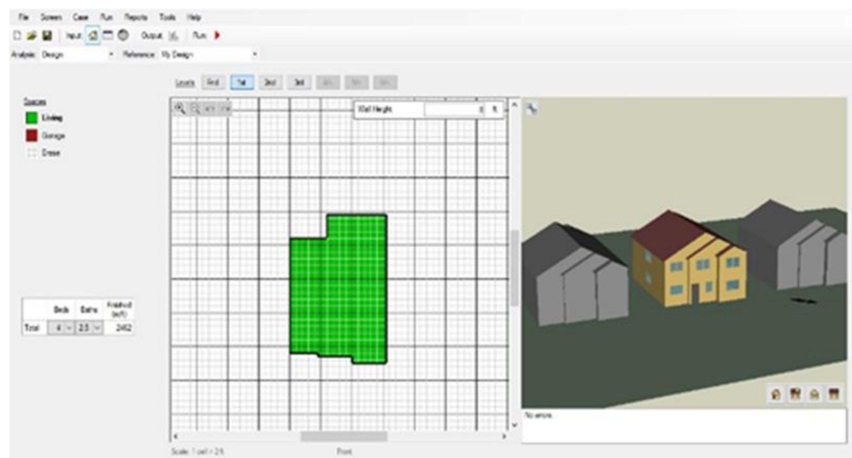

Fig. 07: Geometry Screen of the house [8]

Thermal modeling of the house(con..)

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

Fig. 08: Selected input parameters for options screen

Thermal modeling of the house (con..)

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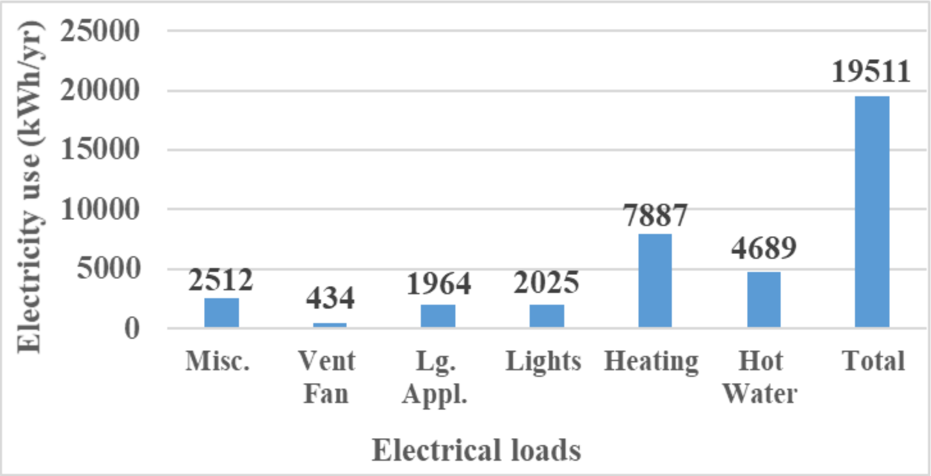

Fig. 09: Electricity consumption for one year

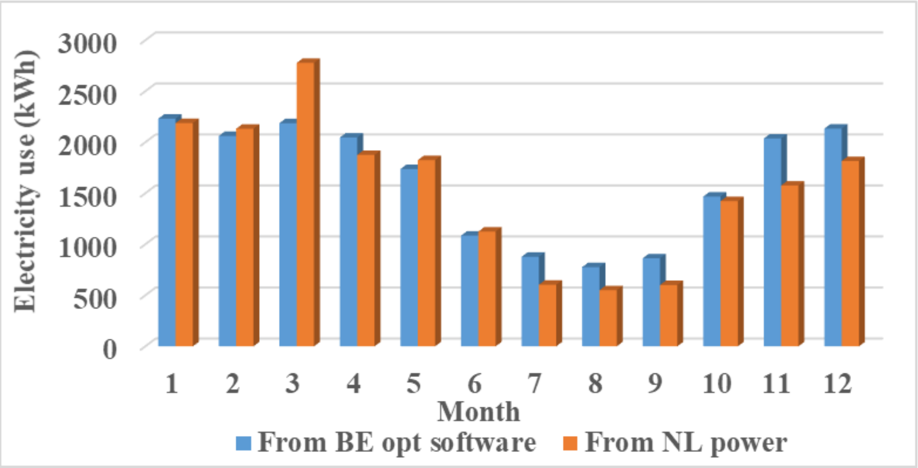

Fig.10: Electricity consumption from BE opt and NL power for one year

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

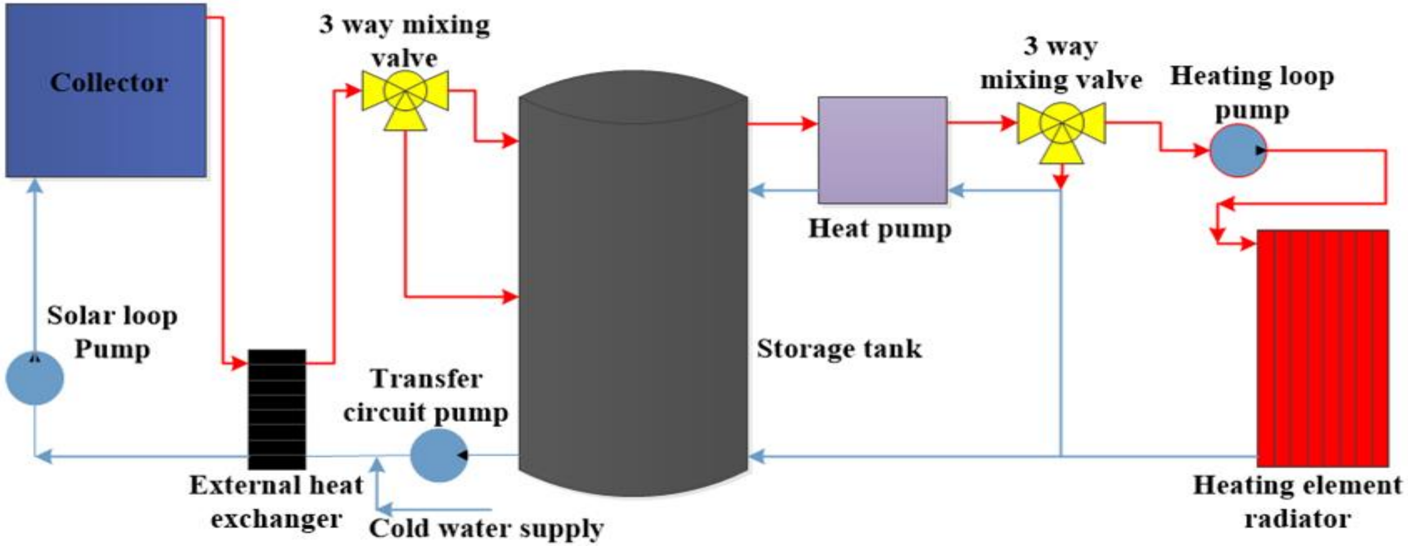

Fig. 11: Active solar space heating system [9]

Sizing of system's components:

(a) Collector

- Collector area, $A_1 = Q_{demand}/Q_{solar1}$ ……………………………………………(1)
- $Q_{solar2} = A_1 * Q_{solar1}$ ……………………………………………………………(2)
- $Q_{excess} = Q_{solar2} - Q_{demand}$ ………………………………………………………(3)

Design-1 (con…)

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- Collector efficiency, η= 50%, standby loss= 0.05 kWh/hr. and circulation loss= 5%
- Q_{solar3}=η* Q_{solar2} – η* Q_{solar2}* 0.05- 0.05 ……………………………….(4)
- Collector area, A_2=Q_{demand}/Q_{solar3}……………………... ……….............(5)

- Selected collector area 16 m^2
- Flat plate collector
- Model: Honeycomb collector HC1-A, manufacturer: TIGI Ltd, test standard: North America [10]

(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=$m * C_p * \Delta T$ ……………………. ……………...(6)
- ✓ Mass of water, m= $E/(C_p * \Delta T)$……………………………………………..(7)
- ✓ Volume of water tank, V=m/ρ………………………………………………..(8)
- ✓ Tank Volume, V= $\pi * D^2/4 * H$………………………………………………..(9)

Design-1 (con…)

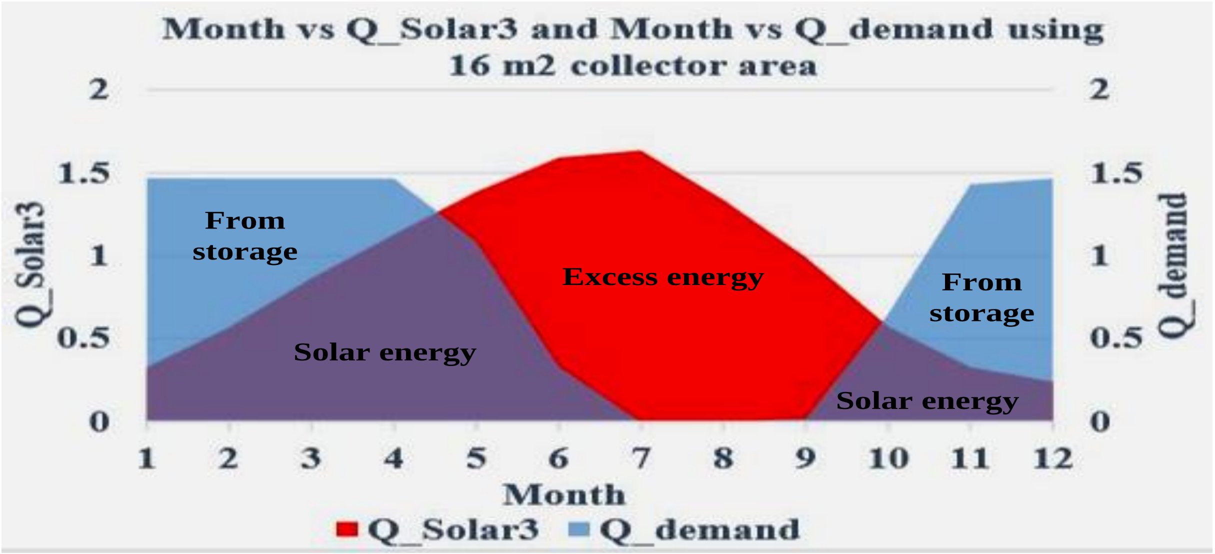

Fig. 12: Month vs. Q_{solar3} and Month vs. Q_{demand} for storage tank design

- 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

Design-1 (con…)

Pumps:

- $\text{Power1} = [44.6 * \exp(0.0181 * A_c)]$ ……………………………………..…(10)
- $\text{Power2} = [78.3 * \exp(0.0156 * A_c)] - \text{power1}$ ………………………… . (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 45ºC and 35ºC

Simulation result-1 and analysis

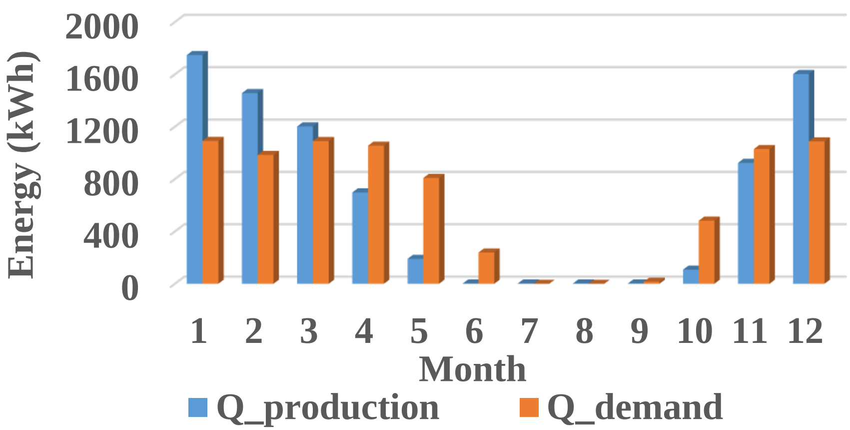

Fig. 13: Annual demand and production of the proposed system

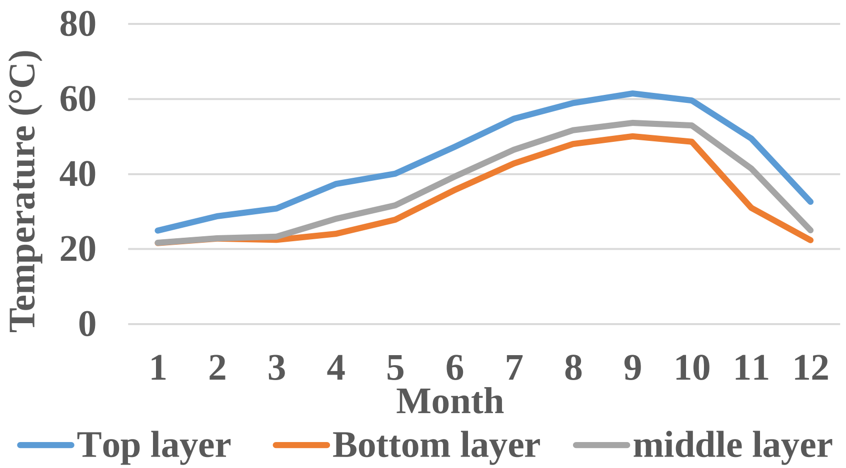

Fig.14: Different layer temperatures of the storage tank

- Energy demand 6337 kWh and production 6932 kWh (October -April)
- Space heating demand 7887 kWh and production 12751 kWh including losses of all components

- 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…)

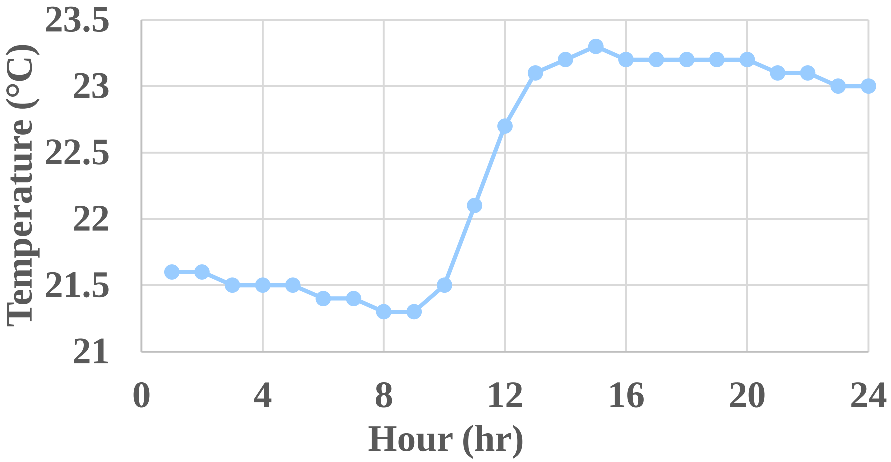

Fig. 15: Daily top layer temperature of the storage tank

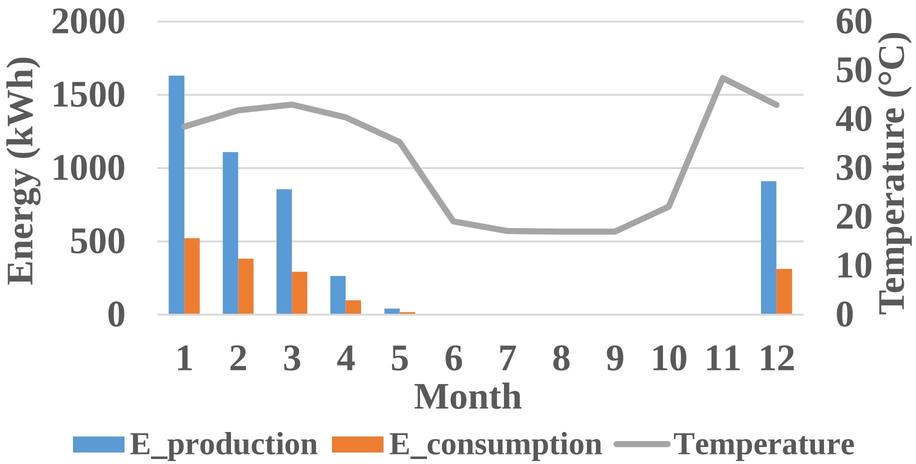

Fig.16: Electricity consumption and production with temperature of heat pump

- ➢ Highest temperature was over 23 °C in January 1
- ➢ Lowest temperature was near 21.5 ºC
- ➢ 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…)

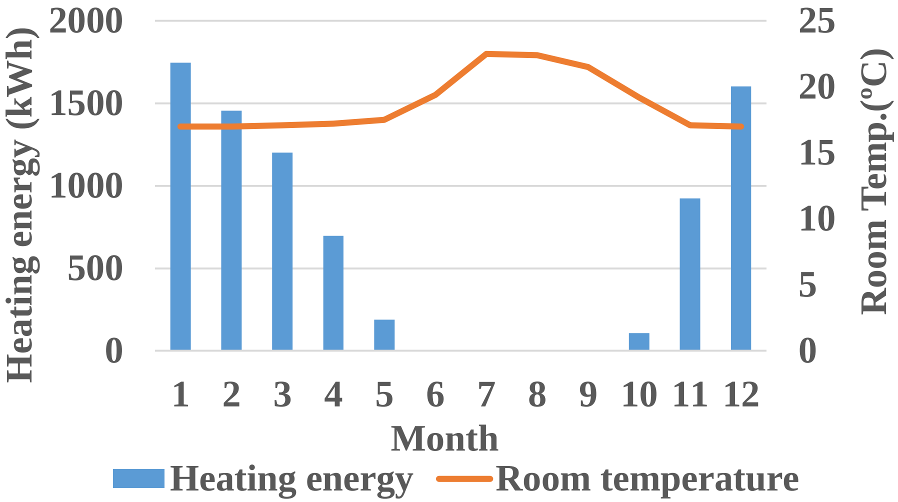

Fig.17: Supplied heating energy and room temperature of the building

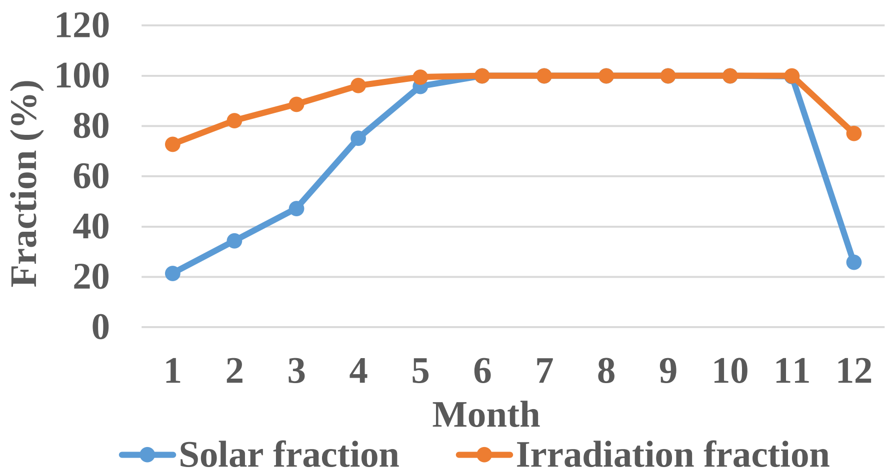

Fig.18: Solar and irradiation fraction of the collector of the proposed system

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

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

Design- 2 solar water heating system for DHW and SH

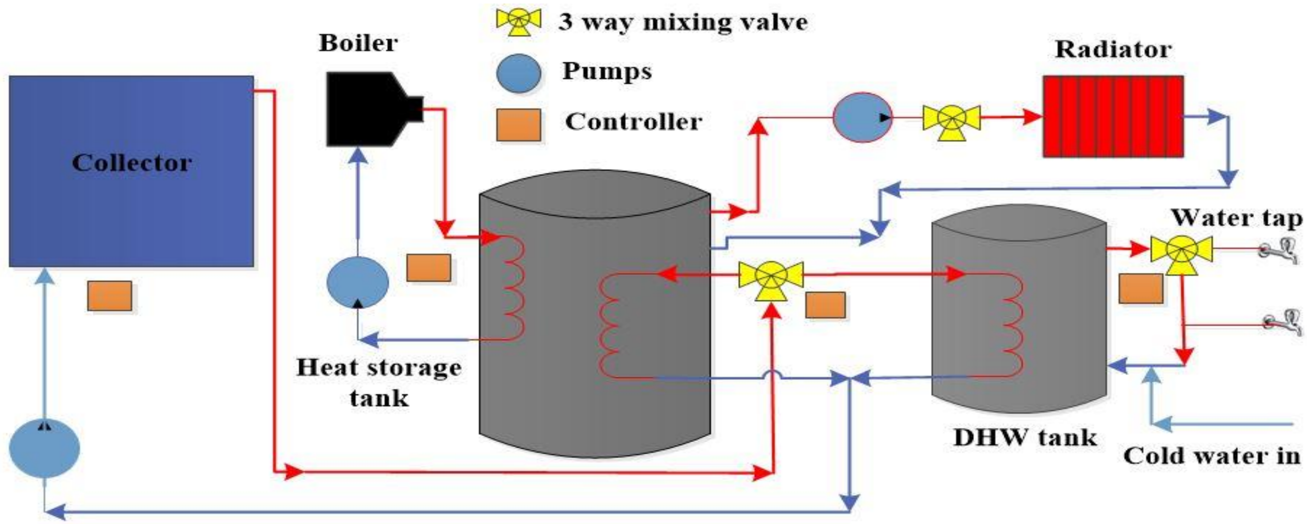

Fig. 19: Space and domestic hot water system for residential application [11]

Sizing of collector and storage tank for DHW:

(a) Collector:

❖ $Collector\ area, A = \frac{No.of\ days * solar\ fraction * Q_{DHW}}{Daily\ solar\ irradiation * Average\ system\ efficiency}$ ……………………….(12)

❖ $Q_{DHW} = volume\ of\ daily\ DHW * C_w * \Delta T$ …………………………………….(13)

❖ Q_{DHW}= 12.52 KWh/day

❖ A =2.92 m^2

Design-2 (con…)

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(b) **Storage tank:**

❖ $$V_{cyl} = \frac{2*Vn*P*(T_h - T_c)}{(T_{dhw} - T_c)}$$ …………………………… (14)

❖ $V_{cyl} = 426$ L

Sizing of collector and storage tank for SH:

(c) Collector:

- Discussed earlier in previous section, new assumptions are collector efficiency, η= 55%, standby loss= 0.05 kWh/hr. and circulation loss= 8%
- Collector area, A=15 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 m^3

✓ Volume, $V = (\pi * D^2 * H)/4$ ………………………………………..(16)

Design-2 (con…)

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

Boiler:

4 kW, propane gas based Boiler

Simulation result-2 and analysis

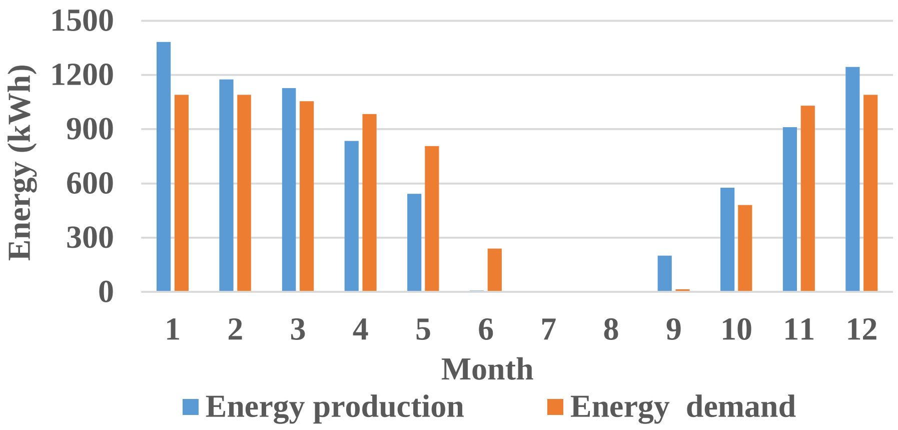

Fig. 20: Heating energy demand and energy production

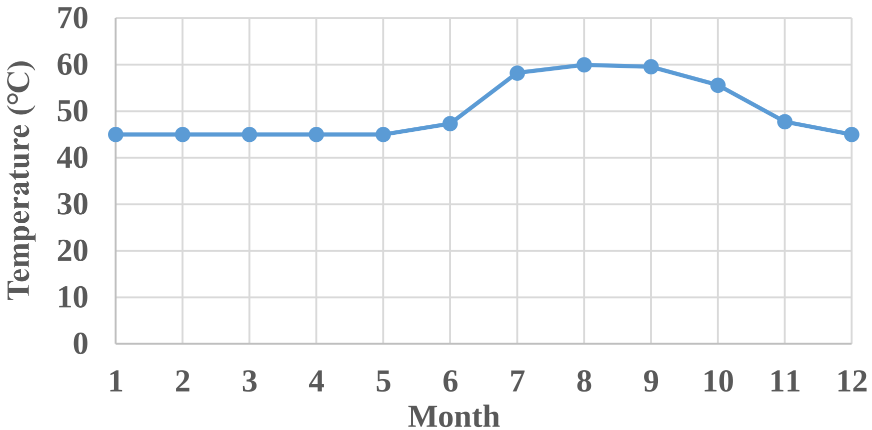

Fig. 21: Space heating storage max. temperature

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

- Highest temperature found around 60 ºC in summer
- Higher solar irradiation and lower heating demand are the reasons
- But, in heating months, value was 45 ºC

Simulation result-2 (con…)

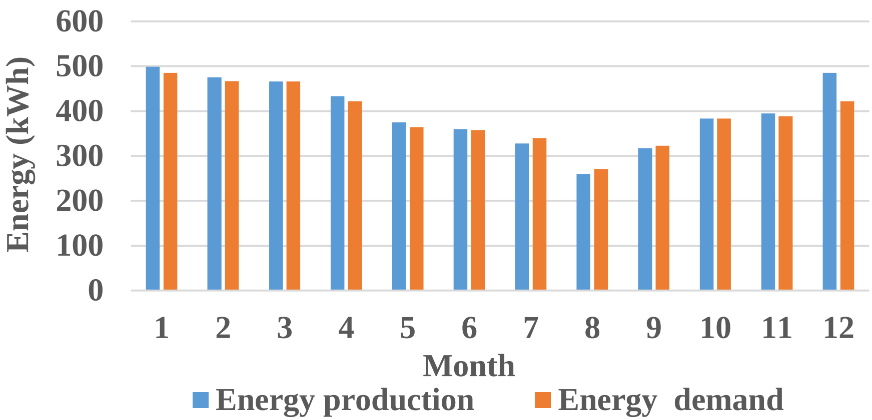

Fig. 22: DHW energy demand and energy production

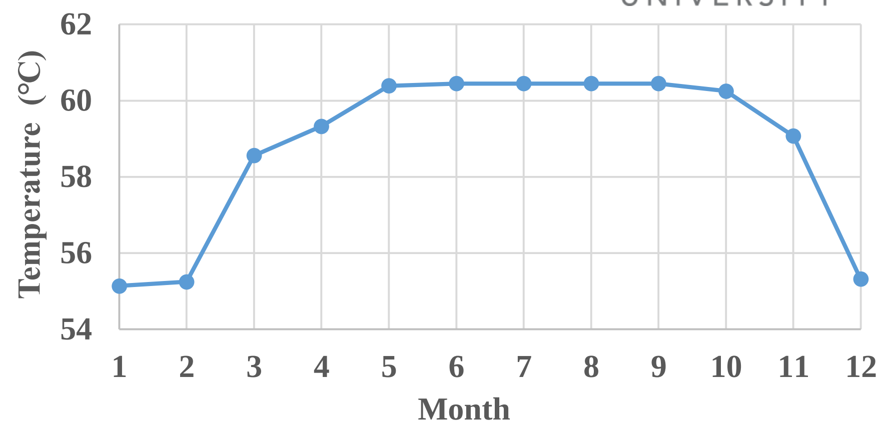

Fig. 23: DHW storage maximum temperature

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

- Highest temperature was over 60 ºC
- In, winter months, upper edge temperature found 55 ºC
- DHW set temperature was 50ºC

Simulation result-2 (con…)

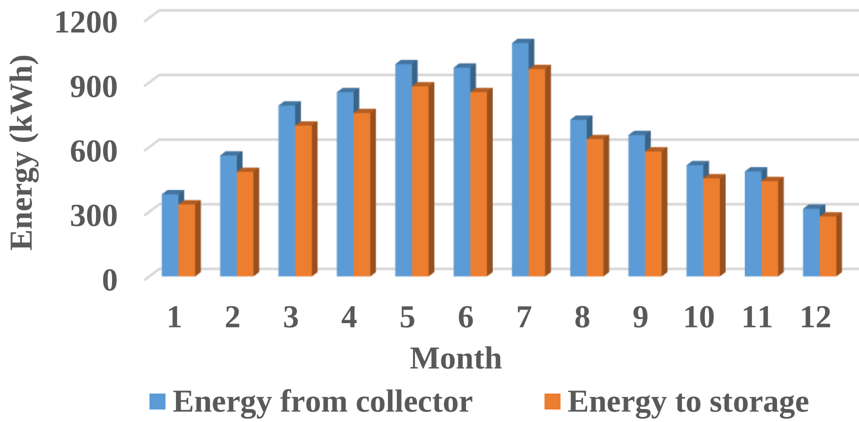

Fig. 24: solar energy from the collector and to the storage tank

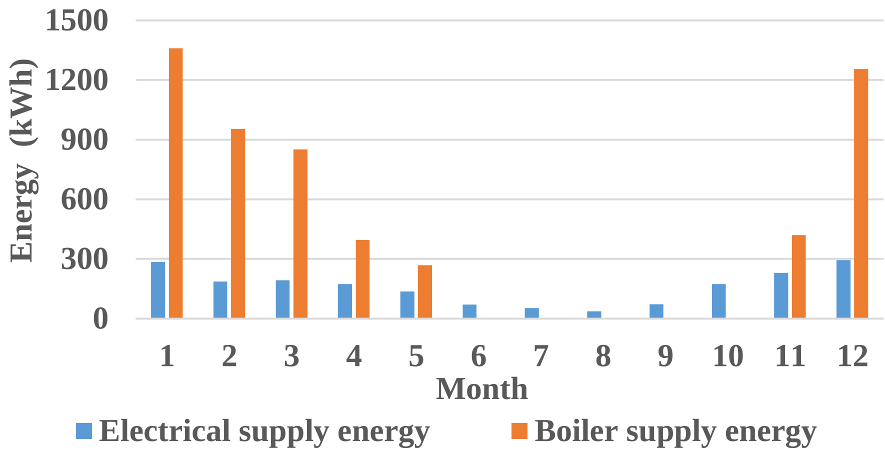

Fig. 25: Supplied electrical and boiler energy

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

- 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

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

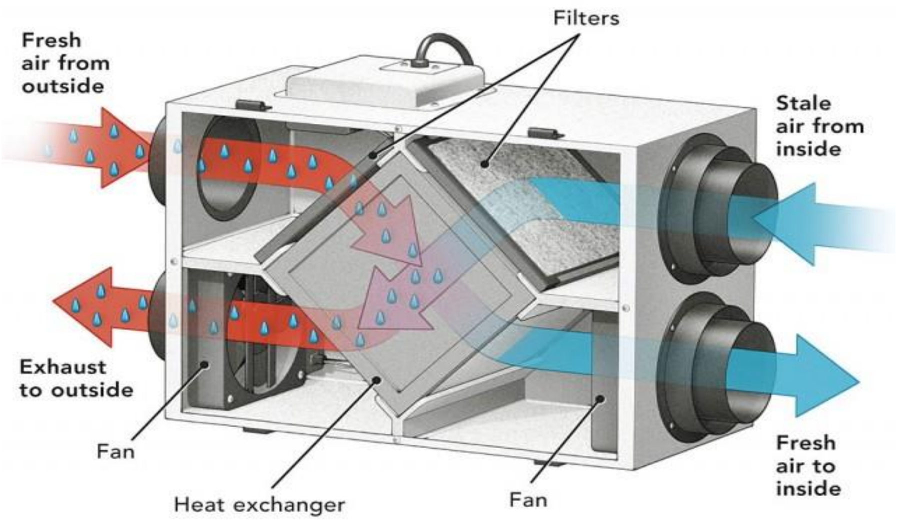

Fig. 26: A typical heat recovery unit [13]

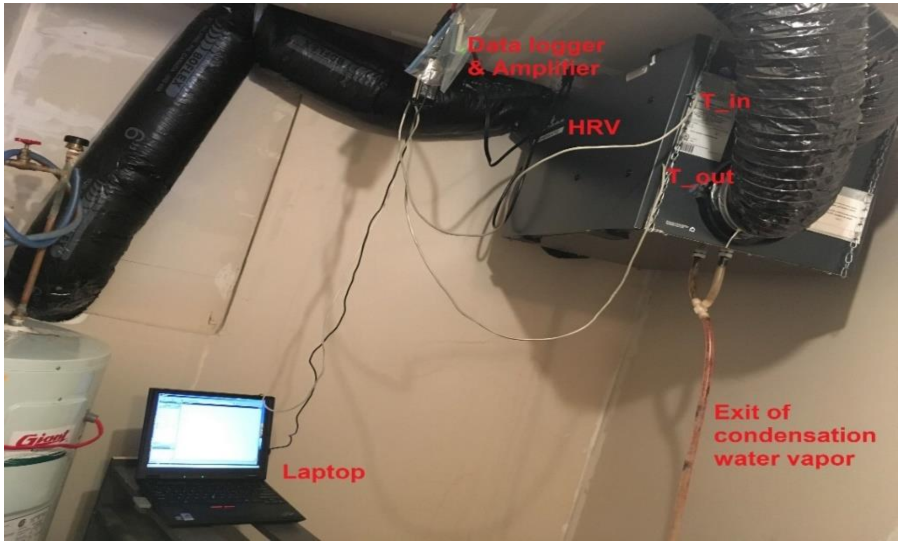

Fig. 27: Experiment set up of HRV

Energy consumption and heat loss of a HRV (con…)

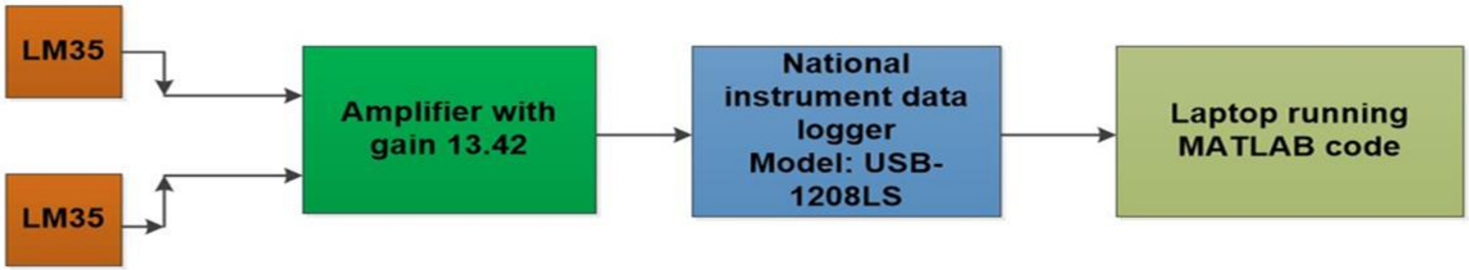

Fig. 28: Block diagram of the experiment procedure

Calculation of heat loss and power consumption:

- Heat loss through, $HRV = Q_v * d * C_p * \Delta T$ … … … … … … … … … … … … … . . . (17)
- Flow rate of air, $Q_v = A * V$ ……………………………………………….(18)
- Electrical energy consumption=Power*24*273 ……………………………(19)
- Total HRV losses= HRV losses + electrical energy consumption ………….(20)

Energy consumption and heat loss of a HRV (con…)

Result analysis:

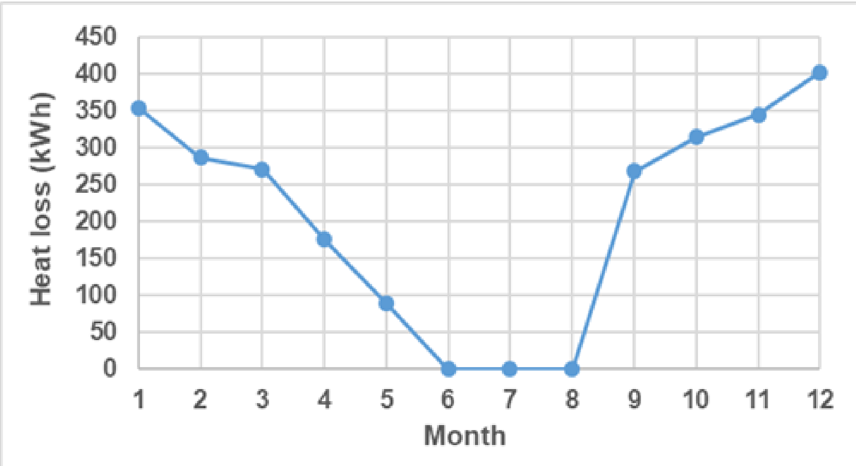

Fig. 29 : Monthly HRV energy loss

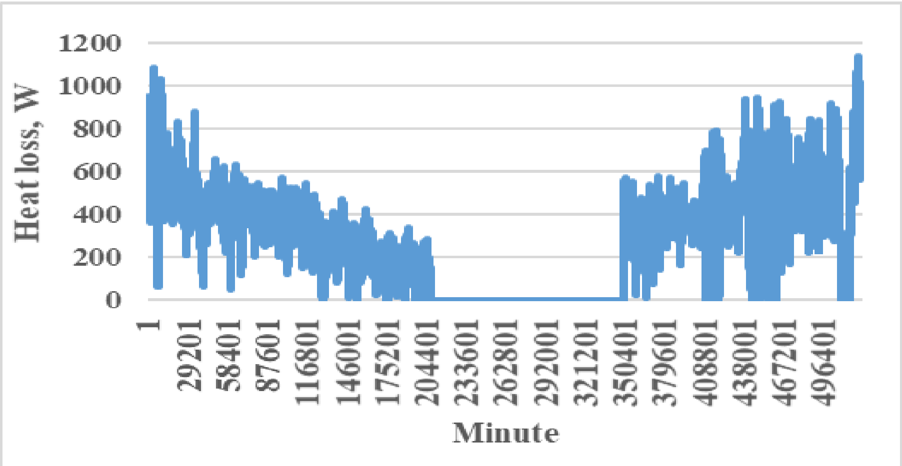

Fig. 30: Heat loss per minute from HRV

- 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

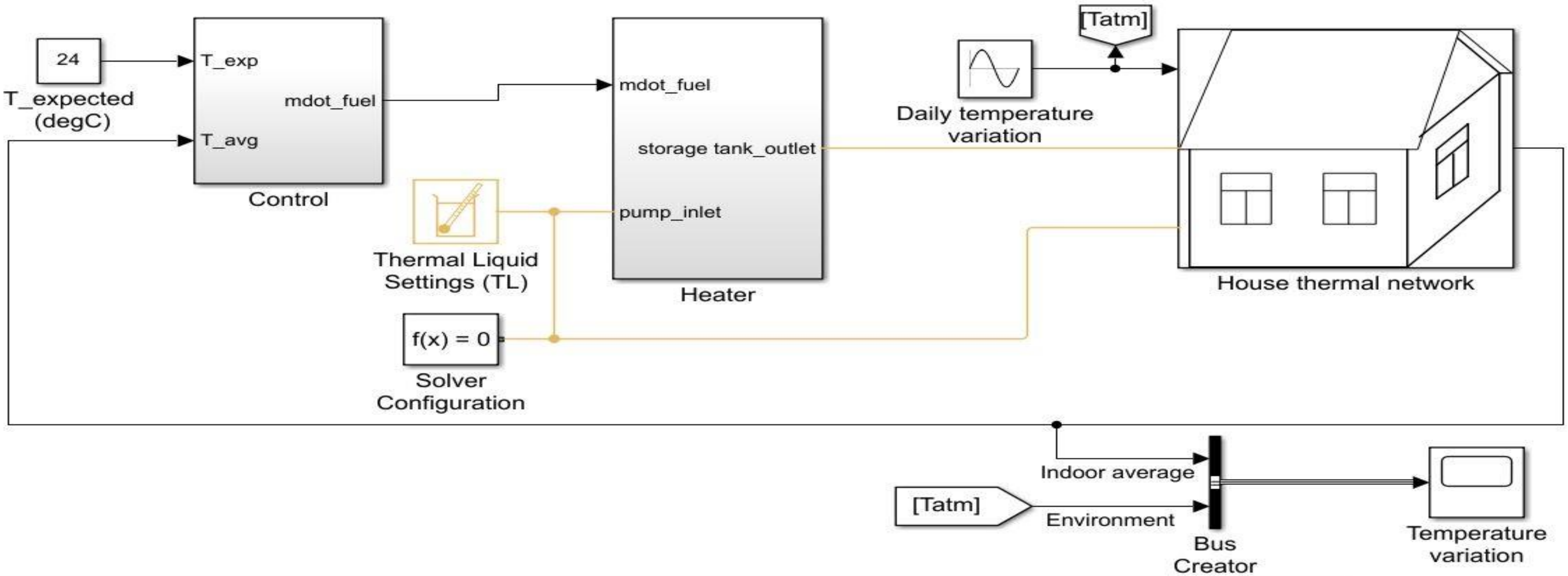

Fig. 31: Simulink design of the full system [14]

Dynamic simulation (con…)

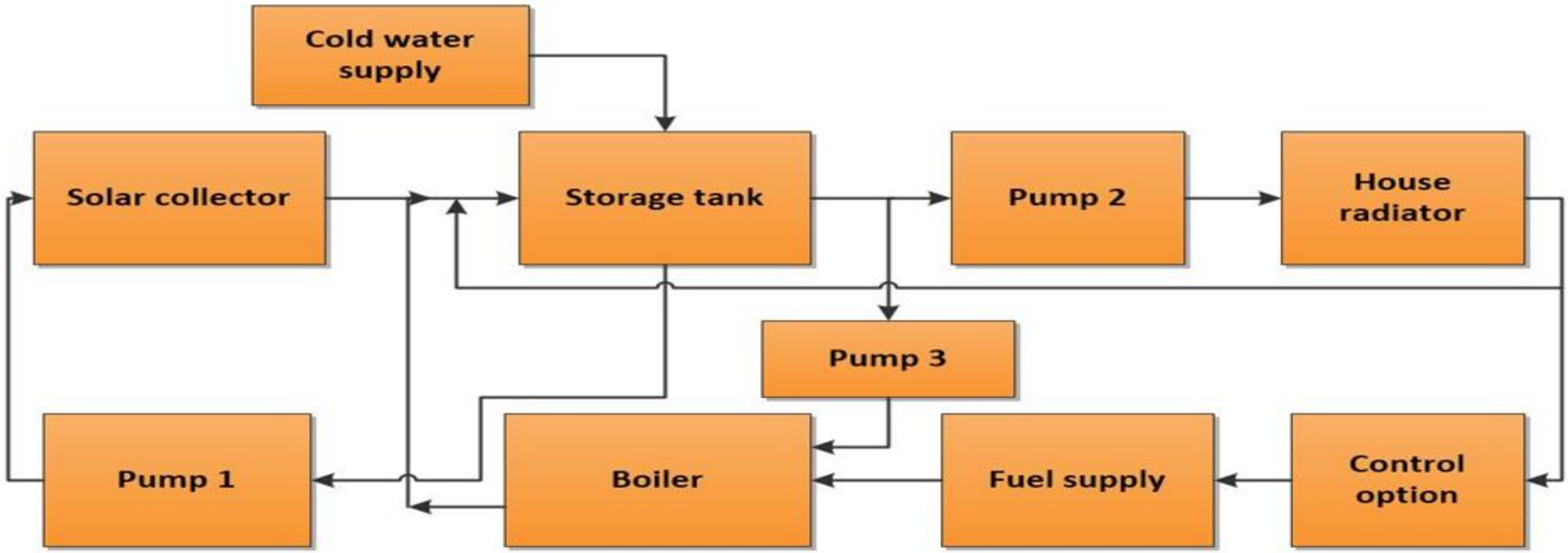

Fig. 32: Simulink block diagram of the system

Dynamic simulation (con…)

Result analysis:

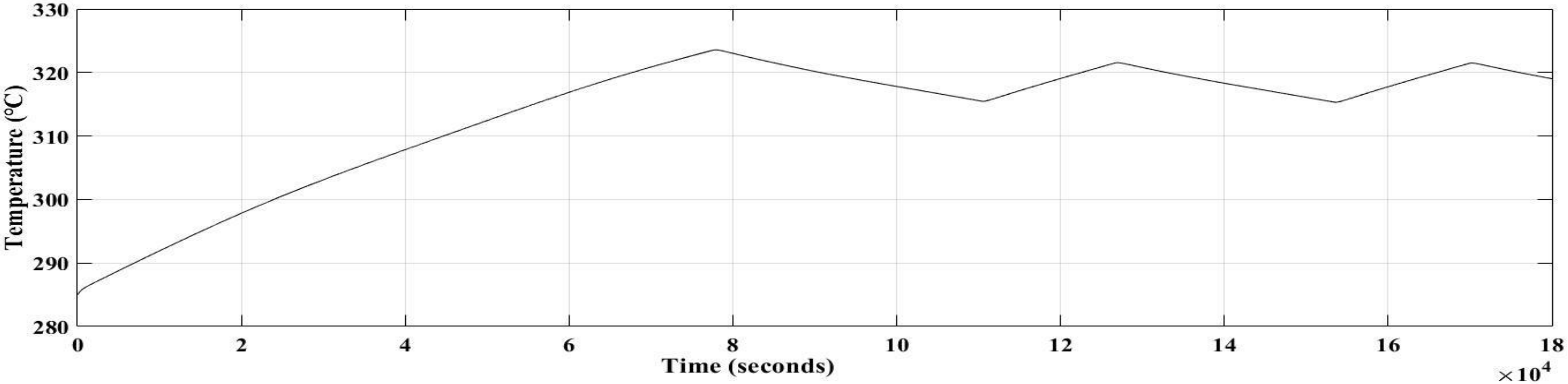

Fig. 33: Storage tank output temperature

- Simulation step size was 50 hr
- Initial liquid temperature was 11 ºC
- Highest temperature found 52 ºC
- Fluctuates between (44 to 49) ºC

Dynamic simulation (con…)

Result analysis:

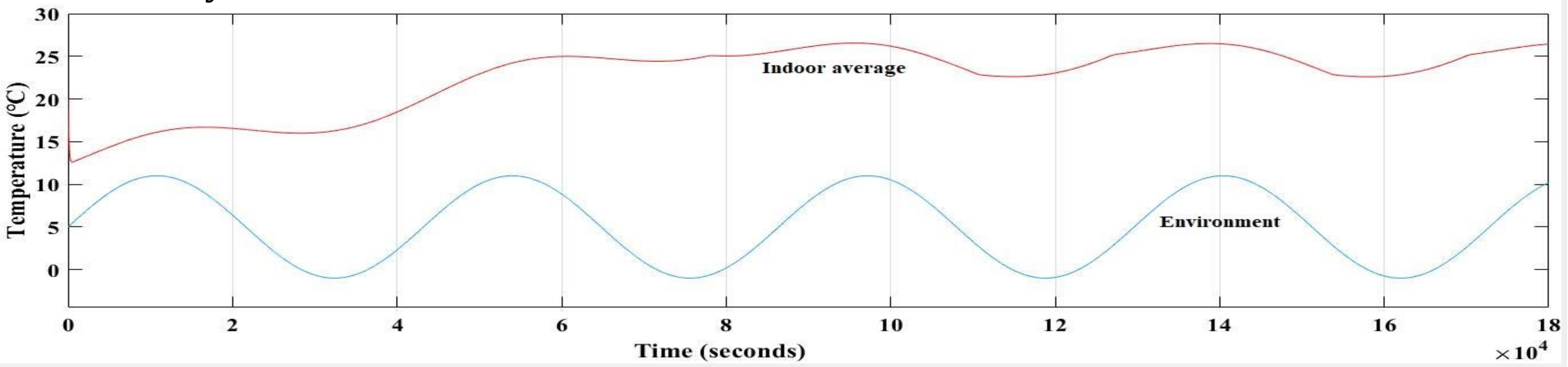

Fig. 34: Comparing the outdoor and indoor average temperature

- ❖ 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

Conclusion

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- ✓ 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

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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)

2. Rabbani Rasha, M. Tariq Iqbal, Yearly Heat Loss Analysis of a Heat Recovery Ventilator Unit for a Single-Family House in St. John's, NL, Canada, European Journal of Electrical Engineering & Computer Science (EJECE) Vol 3 No 5. 2019

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

2. Md. Habibur Rahaman, Rabbani Rasha, M. Tariq Iqbal, Design and Analysis of a Solar Water Heating System for a Detached House in Newfoundland, presented at CCECE 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

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Thank you!