Monitoring, Analysis and Evaluation of an Owners-Occupied Net-Zero Energy House (NZEH) with Hybrid Space Heating System in Cold Climate – Ontario, Canada

King Tung, Gülsün Demirezen, Alan S. Fung*, Rakesh Kumar

https://www.torontomu.ca/mechanical-industrial-mechatronics/people/faculty/alan-fung/

Toronto Metropolitan University

12th International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL'24)

Kitakyushu-city, Japan

October 7 to 9, 2024

Long-Term Monitoring and Evaluation of Market Driven Owners-Occupied NZEH

Location: Strathroy, ON (near London, Ontario)
Type: Residential
Number of Occupants: 2

Main Objectives:

1. *Is this a NZEH as built and lived in?*
2. *Does electric-natural gas hybrid system work?*

Combo Electric-Natural Gas Hybrid HVAC System

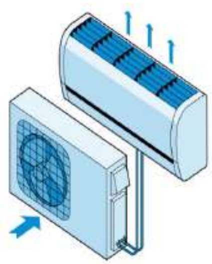
+ Super Airtight & Highly Insulated Envelope
  Combo Hybrid System of ASHP and NG Furnace
  Energy Recovery Ventilator (ERV)
  Drian Water Heat Recovery
  Wall-Hung Natural Gas Instant Hot Water Heater
  Roof Top Solar PV
  Backup Generator

Main Objective:

Feasibility of Hybrid Heating System

Secondary Objective:

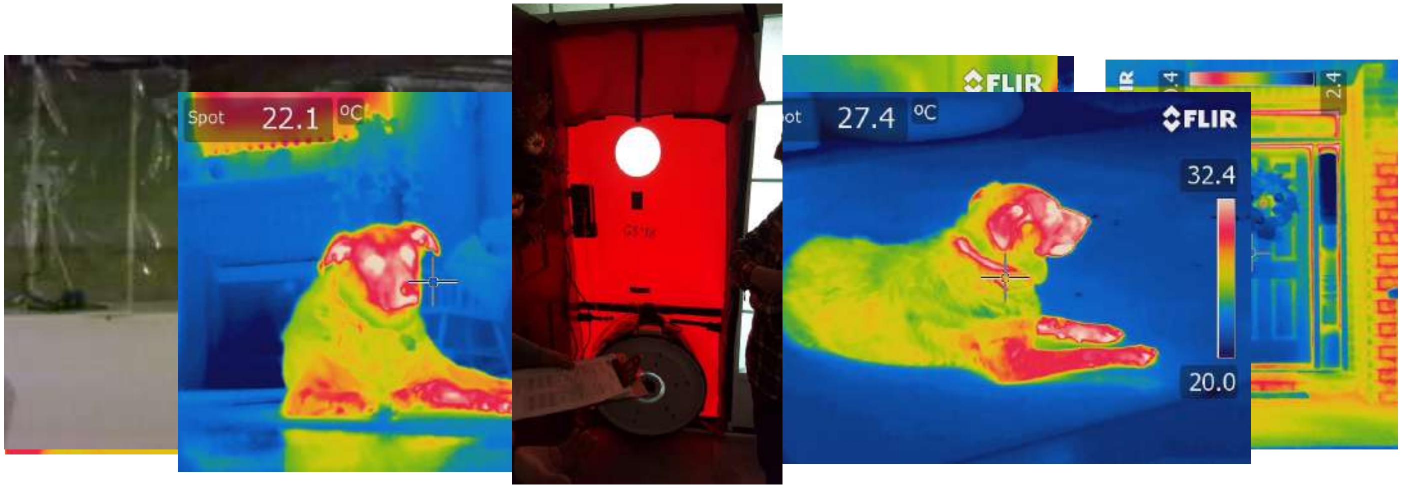
Feasibility of cloud based Smart Dual Fuel Switching System (SDFSS)



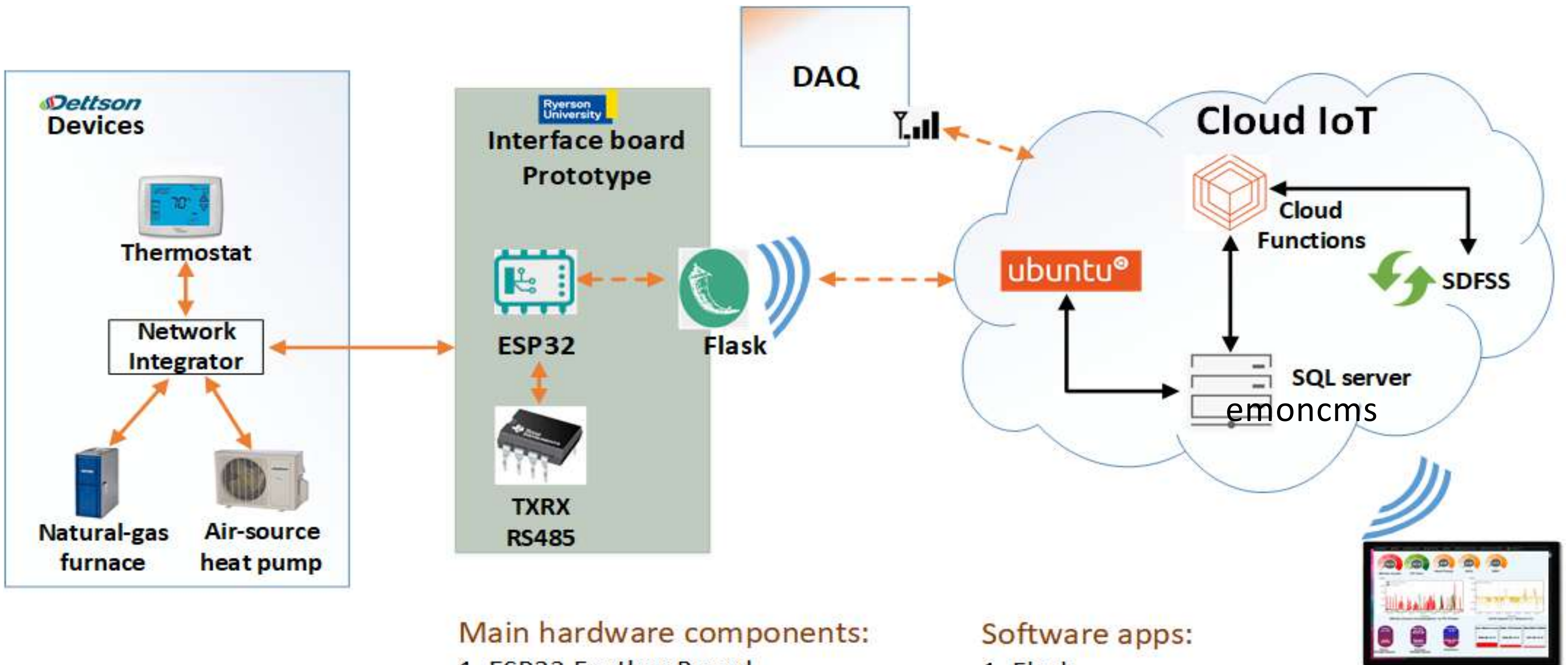
Based on:
1. Weather
2. Energy Cost
3. GHG Emission

Tasks:
- Perform detailed energy audit
- Modeling/simulation of the house
- Design, installation, calibration and commissioning of meters/sensors (with real-time dashboard)
- Develop the SDFSS controller, making a prototype, and testing it
- Monitoring over a period of one year (1 winter + 1 summer)
- Data analysis

Detailed Energy Audit



Cloud-based IoT Architecture for SDFSS



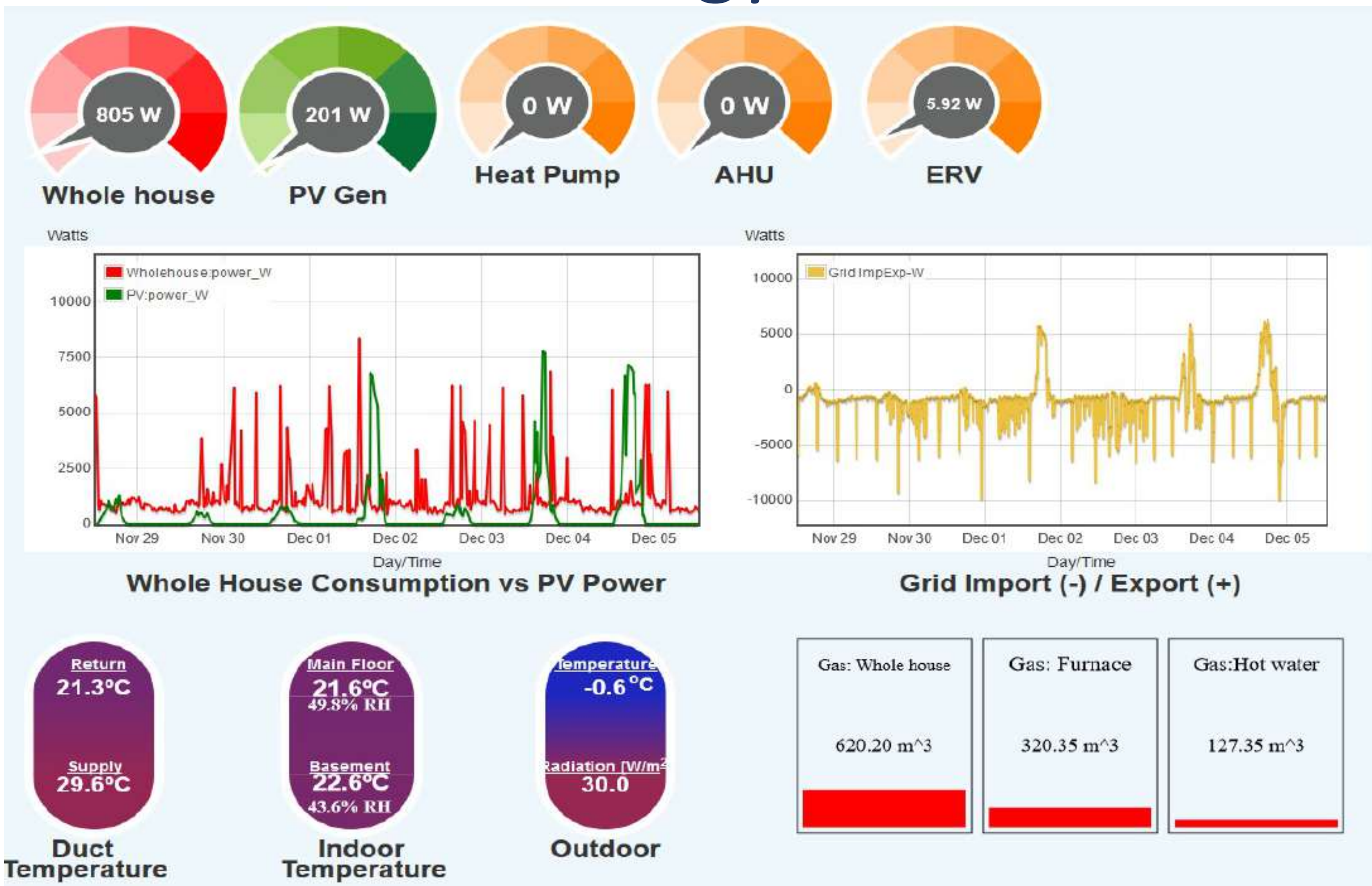
Main hardware components:

1. ESP32 Feather Board
2. TXRX RS485
3. DC-DC Converter
4. Voltage Regulator
5. Arduino Uno

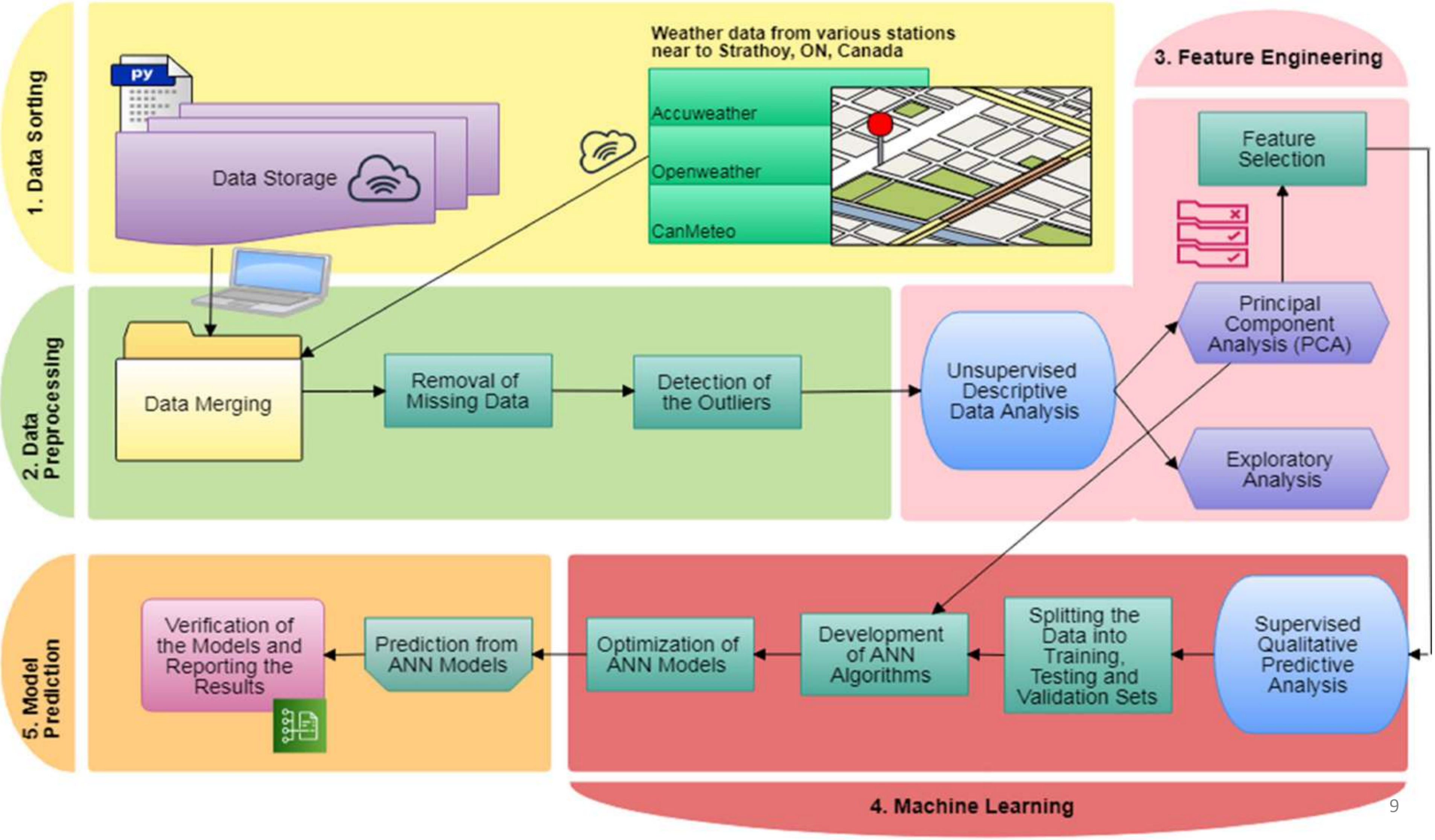
Software apps:

1. Flask
2. Python scripts
3. Arduino
4. MySQL

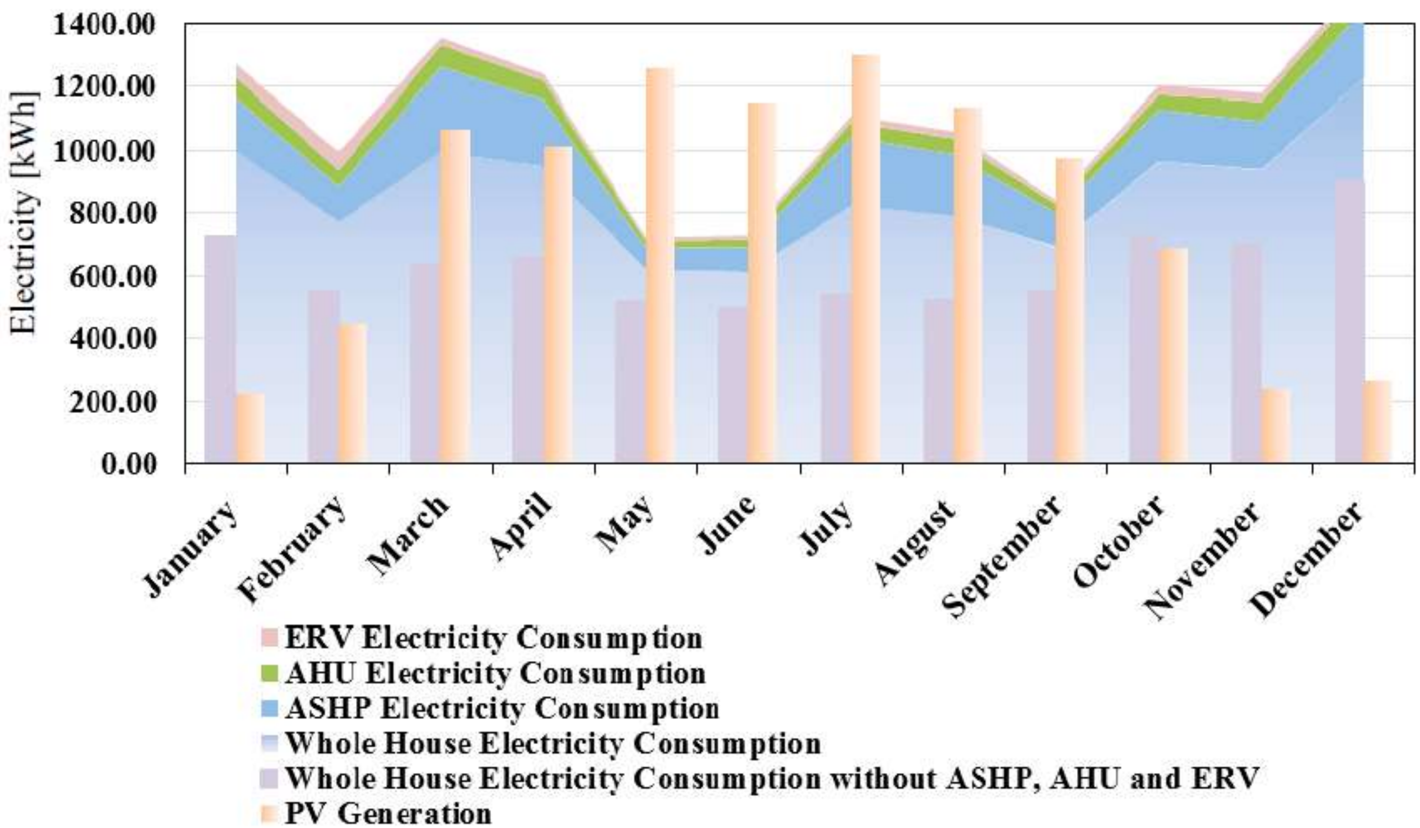
Real-Time Energy Dashboard



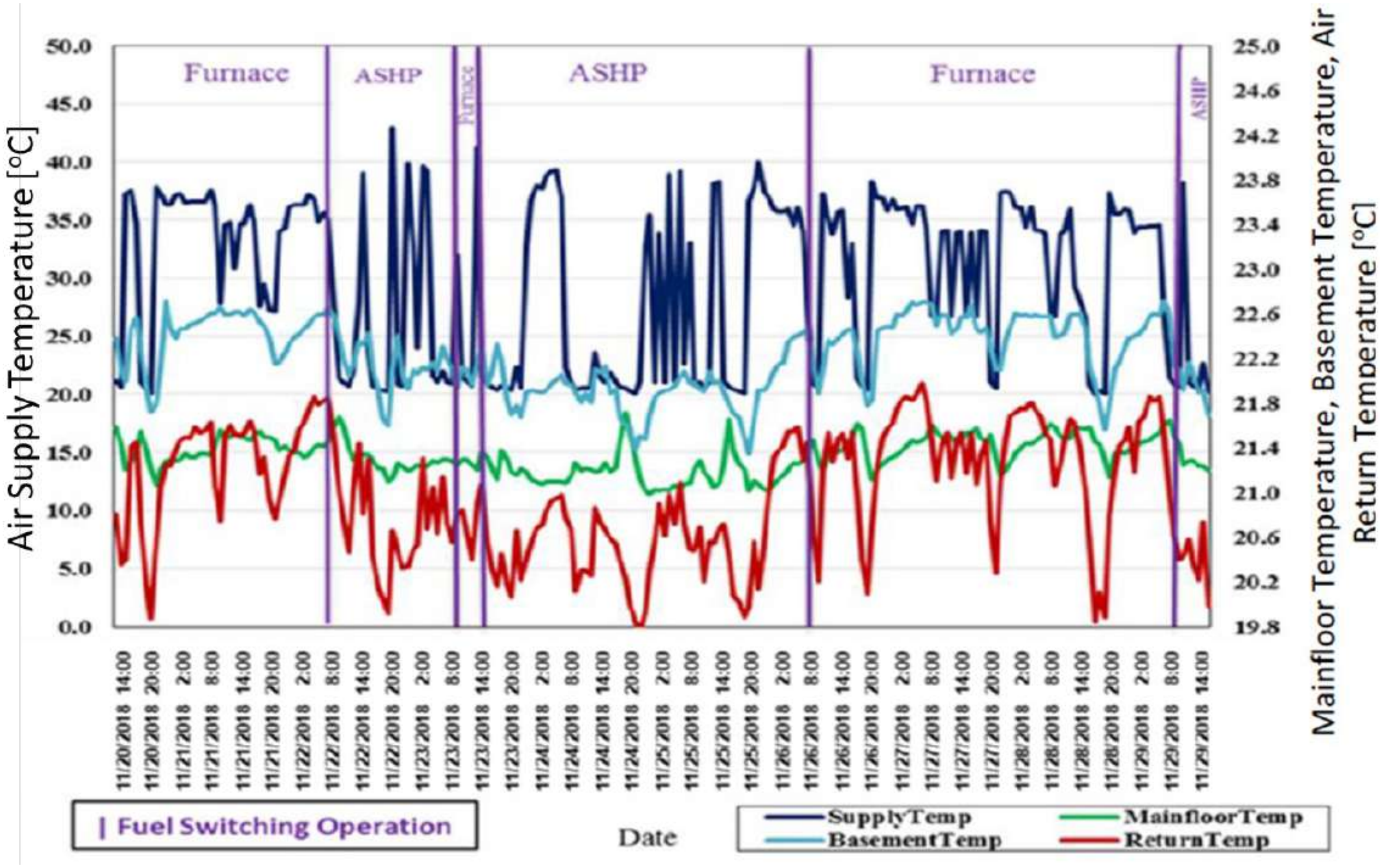
House Modelling & Data Analysis


1. Data Sorting
Weather data from various stations near to Strathoy, ON, Canada
Data Storage
Accuweather
Openweather
CanMeteo
3. Feature Engineering
Feature Selection
2. Data Preprocessing
Data Merging
Removal of Missing Data
Detection of the Outliers
Unsupervised Descriptive Data Analysis
Principal Component Analysis (PCA)
Exploratory Analysis
5. Model Prediction
Verification of the Models and Reporting the Results
Prediction from ANN Models
Optimization of ANN Models
Development of ANN Algorithms
Splitting the Data into Training, Testing and Validation Sets
Supervised Qualitative Predictive Analysis
4. Machine Learning

Data Analysis from the Experiments



Data Analysis from the Experiments



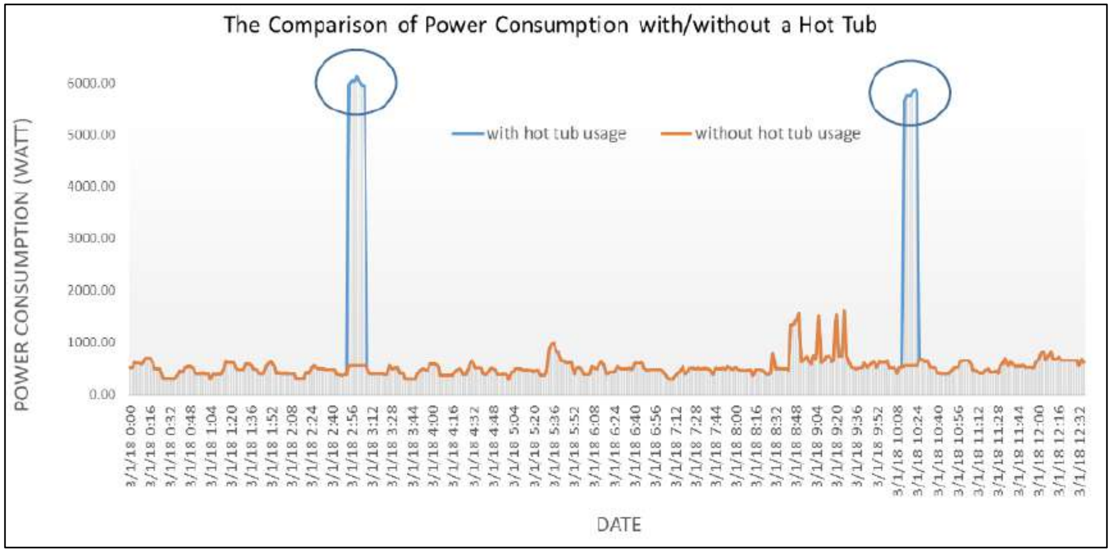
Data Monitoring, Evaluation, and Analysis

Natural Gas Consumption from	Whole house	Domestic Hot Water (DHW) (measured efficiency = 89%)	Furnace (measured efficiency = 89%)	Others (Cooking + Fireplace)
m^3	794.2	158.9	471.7	162.4
GJ	29.6	5.9	17.6	6.0
kWh	8,228	1,647	4,887	1,683

* NG conversion to PV generated electricity
8228 kWh_NG / 3 = 2743 kWh of PV

Data Monitoring, Evaluation, and Analysis

- Homeowners were using an electric outdoor hot tub, which largely contributes to the overall electricity consumption of the house.
- Further analysis was performed to identify, isolate, and estimate the consumption of the hot tub, which was found to be 1,501 kWh (close to 15% of the overall electricity consumption).



Data Monitoring, Evaluation, and Analysis

- Based on electricity generation and consumption alone, there is a deficit of 629 kWh/year
- If hot tub is excluded then there is 871 kWh/year of surplus of electricity generation, not enough to offset the natural gas consumption

Data Monitoring, Evaluation, and Analysis

- The studied house was designed and built as a net zero energy house and it is equipped with solar PV panels with the total capacity of 8.745 kWp
- Data analysis shows that total on-site PV electricity generation is less than the total electricity consumption of the house (including hot tub) by 6% and it is less than total electricity and natural gas consumption of the house by 47%
- This house is a nearly-zero energy house as built and operated
- The house is modelled in TRNSYS
- The TRNSYS model was calibrated accordingly by the experimental data

Data Analysis from the Experiments VS HOT2000 Model

Electricity Consumption & Generation Activities (kWh)	Experimental Results	HOT2000 Simulation (Original NZEH Consultant)	Difference %
Whole House Electricity Consumption (kWh)	10,375	9,188	+13
ASHP Electricity Consumption (kWh)	1,952	2,035	-4
AHU Electricity Consumption (kWh)	603	N/A (included as AHU+ERV)	N/A
ERV Electricity Consumption (kWh)	309	N/A (included as AHU+ERV)	N/A
AHU + ERV Electricity Consumption (kWh)	912	95.5	+950
Whole House Electricity Consumption without ASHP, AHU, and ERV (kWh)	7,509	7,117	+5.5
Whole House Electricity Consumption without hot-tub, ASHP, AHU, and ERV (kWh)	6,008	N/A (not included)	-15.6
Hot Tub Total Electricity Consumption (kWh)	1,501	N/A (not included)	N/A
PV Generation (kWh)	9,746	10,636	-8.4
Natural Gas Furnace (m^3)	472	7.6	+620
Natural Gas DHW (m^3)	159	248	-36

Solar PV

- Actual measurements taken from sensors installed by the PV installer showed an annual production of 10,323 kWh (or 1180 kWh/year per 1 kWp PV capacity) compared to the installer's estimate of 11,471 kWh/year. RETScreen simulations produced 11,320 kWh per year. (Note: Southern Ontario generates ~1200 kWh/year per 1 kWp PV)
- Sensors measured an annual production of 9,747 kWh. Starting at the full months when the project started and ended (March to November), there is a 2% difference between installer's and actual measurements.
  - This difference can be attributed to the current transformers and power meters of the installer and the calibration of the instruments
- There is a big difference between actual measurements and estimated/simulated PV production:

  1) It is not known how much losses were deducted by the installer in their estimates

  2) The inverter capacity used was lower than the maximum output of the PV array, which can result in power being clipped during times with high radiation levels;

  3) Actual measurements show consistently lower PV production in winter compared to the RETScreen simulations and be attributed to snow accumulation on the PV panels, lowering the array's overall efficiency. The installer, HOT2000 and RETScreen estimates of the annual PV production is overly optimistic.

Solar PV

A more realistic rule-of-thumb estimate of a well-designed and integrated PV system under southern Ontario's climate conditions can be as much as 1,200 kWh/year per 1 kWp. The output of the 8.745 kWp system should be around 10,494 kWh/year. The installer's estimate is equivalent to 1,312 kWh/year per 1 kWp of PV capacity.

The original PV output was overestimated.

Modeling and Optimization of the SDFSS

What is SDFSS

- Smart Dual Fuel Switching System (SDFSS) of hybrid space heating of Air Source Heat Pump (ASHP) and Natural Gas Furnace (NGF)
- Optimizing the switching point for the lowest operating cost
  - Current technology only uses outdoor temperature as the switching parameter
  - Use the NGF as backup heat source during cold temperature and/or during peak electricity pricing
- Optimizing the switching point between ASHP and NGF
- This technology acts as a transitional solution to not only saves energy costs but also reduces GHG emissions (Ontario has very low GHG intensity for electricity)
- This also provides a method to offset electricity with NG during peak-hours

Information on Case Study

- House was modeled on TRNSYS

Summary of the calibrated TRNSYS Model	
Annual Space Heating Demand	12090 kWh
Peak Demand	4.83 kW
Mathematical Model of the House	-0.0822x + 2.8125

- Information was used for the SDFSS model to simulate the overall effect of the system
- Shows overall potential cost savings and GHG emission reduction potential

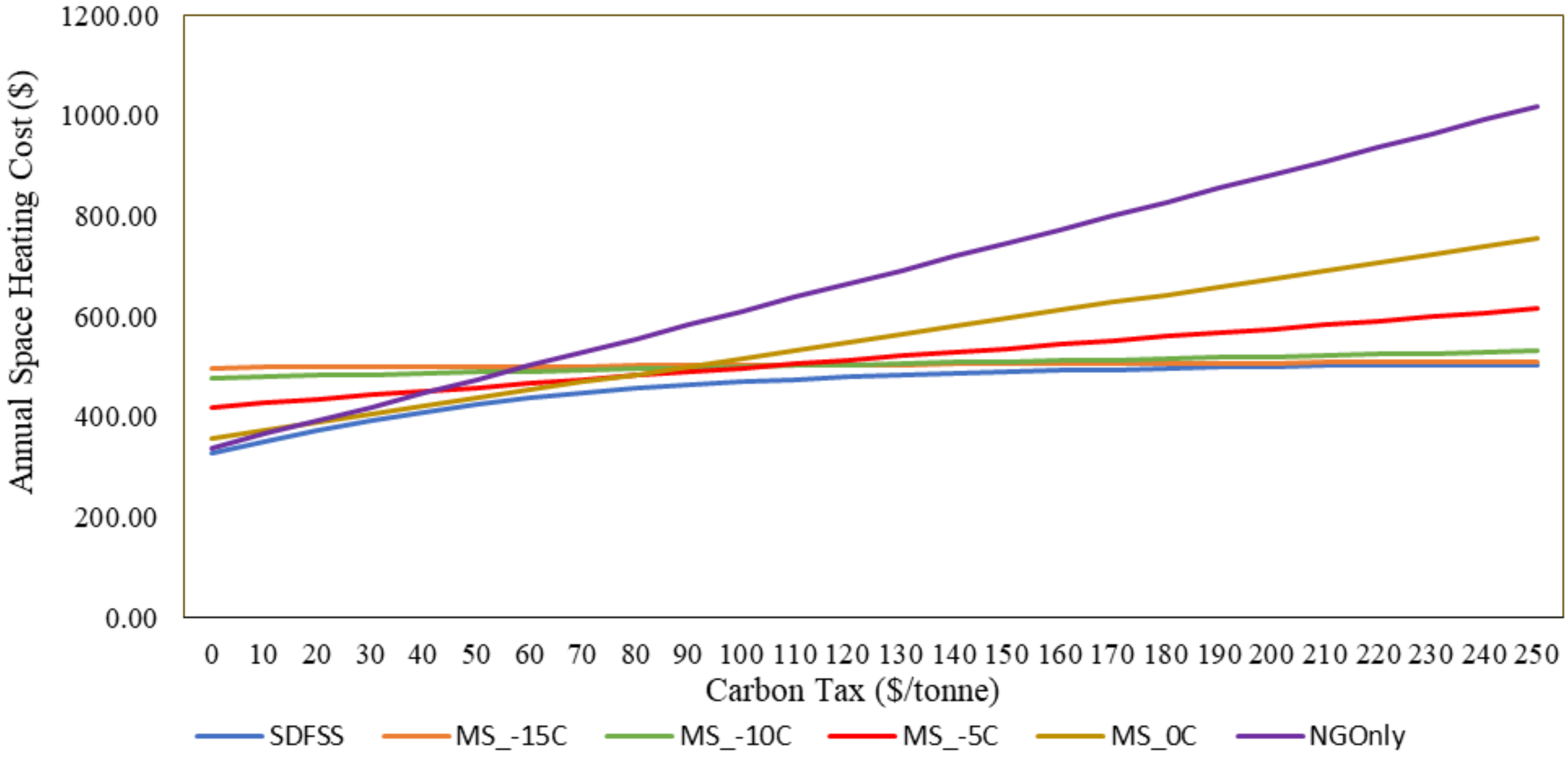
Electricity and NG Pricing in Strathoy

Time of Use (TOU) Electricity Pricing in Strathroy/London, Ontario	
Off-Peak	\$0.092/kWh
Mid-Peak	\$0.124/kWh
On-Peak	\$0.163/kWh

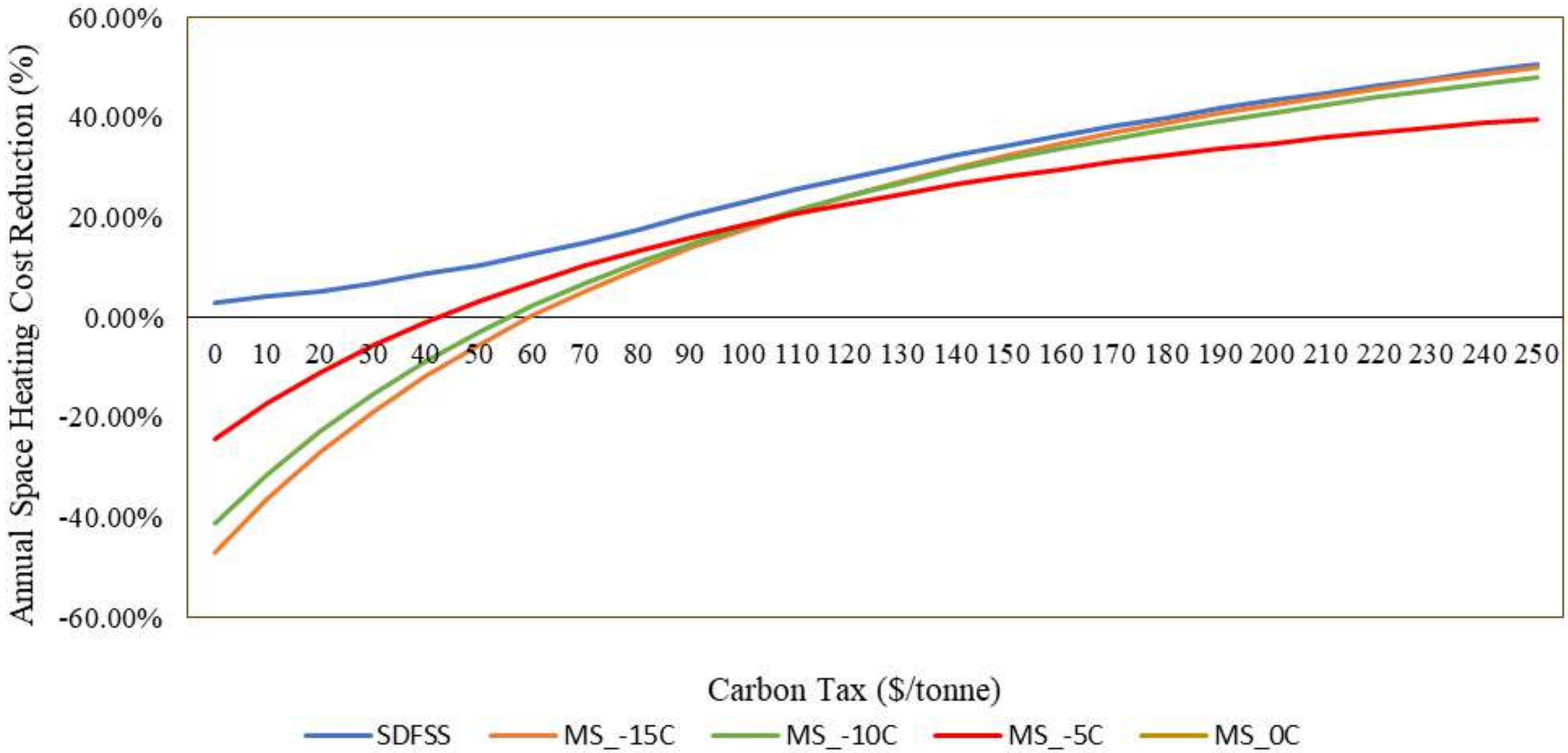
Natural Gas Pricing in Strathroy/London (fixed): \$0.261746/m^3

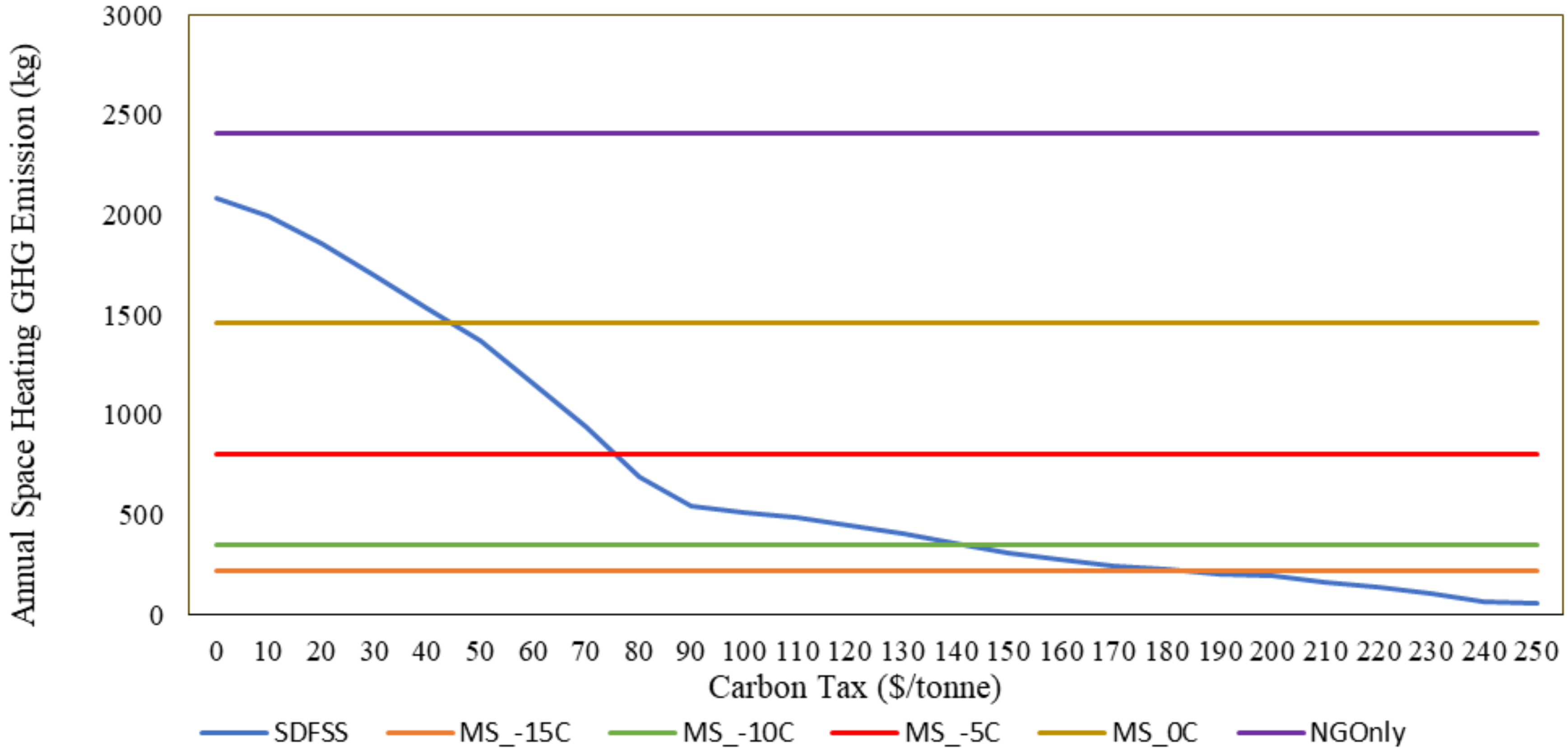
Heat Map of ASHP Operation Hours (2018 energy pricing w/o carbon price)

	1		2		3		4		11		12			
yr 2018	January		February		March		April		November		December			
0	1 dy	3.2%	3 dy	10.7%	6 dy	19.4%	17 dy	56.7%	16 dy	53.3%	1 dy	3.2%	44 hr	1.0%
1	1 dy	3.2%	4 dy	14.3%	5 dy	16.1%	17 dy	56.7%	14 dy	46.7%	1 dy	3.2%	42 hr	1.0%
2	1 dy	3.2%	3 dy	10.7%	4 dy	12.9%	15 dy	50.0%	12 dy	40.0%	2 dy	6.5%	37 hr	0.9%
3	1 dy	3.2%	3 dy	10.7%	4 dy	12.9%	16 dy	53.3%	11 dy	36.7%	1 dy	3.2%	36 hr	0.8%
4	1 dy	3.2%	2 dy	7.1%	4 dy	12.9%	14 dy	46.7%	11 dy	36.7%	1 dy	3.2%	33 hr	0.8%
5	1 dy	3.2%	2 dy	7.1%	4 dy	12.9%	14 dy	46.7%	11 dy	36.7%	1 dy	3.2%	33 hr	0.8%
6	1 dy	3.2%	2 dy	7.1%	5 dy	16.1%	14 dy	46.7%	12 dy	40.0%	1 dy	3.2%	35 hr	0.8%
7	0 dy	0.0%	1 dy	3.6%	2 dy	6.5%	6 dy	20.0%	2 dy	6.7%	0 dy	0.0%	11 hr	0.3%
8	0 dy	0.0%	1 dy	3.6%	3 dy	9.7%	10 dy	33.3%	2 dy	6.7%	0 dy	0.0%	16 hr	0.4%
9	0 dy	0.0%	1 dy	3.6%	3 dy	9.7%	11 dy	36.7%	2 dy	6.7%	0 dy	0.0%	17 hr	0.4%
10	0 dy	0.0%	2 dy	7.1%	2 dy	6.5%	12 dy	40.0%	5 dy	16.7%	2 dy	6.5%	23 hr	0.5%
11	0 dy	0.0%	2 dy	7.1%	6 dy	19.4%	22 dy	73.3%	13 dy	43.3%	2 dy	6.5%	45 hr	1.0%
12	0 dy	0.0%	2 dy	7.1%	6 dy	19.4%	22 dy	73.3%	13 dy	43.3%	3 dy	9.7%	46 hr	1.1%
13	0 dy	0.0%	2 dy	7.1%	7 dy	22.6%	21 dy	70.0%	15 dy	50.0%	3 dy	9.7%	48 hr	1.1%
14	0 dy	0.0%	2 dy	7.1%	9 dy	29.0%	22 dy	73.3%	16 dy	53.3%	3 dy	9.7%	52 hr	1.2%
15	0 dy	0.0%	2 dy	7.1%	10 dy	32.3%	22 dy	73.3%	15 dy	50.0%	2 dy	6.5%	51 hr	1.2%
16	0 dy	0.0%	2 dy	7.1%	9 dy	29.0%	22 dy	73.3%	14 dy	46.7%	2 dy	6.5%	49 hr	1.1%
17	0 dy	0.0%	2 dy	7.1%	5 dy	16.1%	11 dy	36.7%	4 dy	13.3%	2 dy	6.5%	24 hr	0.6%
18	0 dy	0.0%	2 dy	7.1%	4 dy	12.9%	10 dy	33.3%	4 dy	13.3%	2 dy	6.5%	22 hr	0.5%
19	1 dy	3.2%	3 dy	10.7%	9 dy	29.0%	26 dy	86.7%	17 dy	56.7%	2 dy	6.5%	58 hr	1.3%
20	1 dy	3.2%	3 dy	10.7%	8 dy	25.8%	25 dy	83.3%	14 dy	46.7%	2 dy	6.5%	53 hr	1.2%
21	1 dy	3.2%	3 dy	10.7%	8 dy	25.8%	23 dy	76.7%	14 dy	46.7%	2 dy	6.5%	51 hr	1.2%
22	1 dy	3.2%	3 dy	10.7%	6 dy	19.4%	21 dy	70.0%	15 dy	50.0%	1 dy	3.2%	47 hr	1.1%
23	1 dy	3.2%	3 dy	10.7%	6 dy	19.4%	21 dy	70.0%	14 dy	46.7%	1 dy	3.2%	46 hr	1.1%
Monthly Total	12 hr	1.6%	55 hr	8.2%	135 hr	18.1%	414 hr	57.5%	266 hr	36.9%	37 hr	5.0%	919 hr	21.3%
													4321 hr	

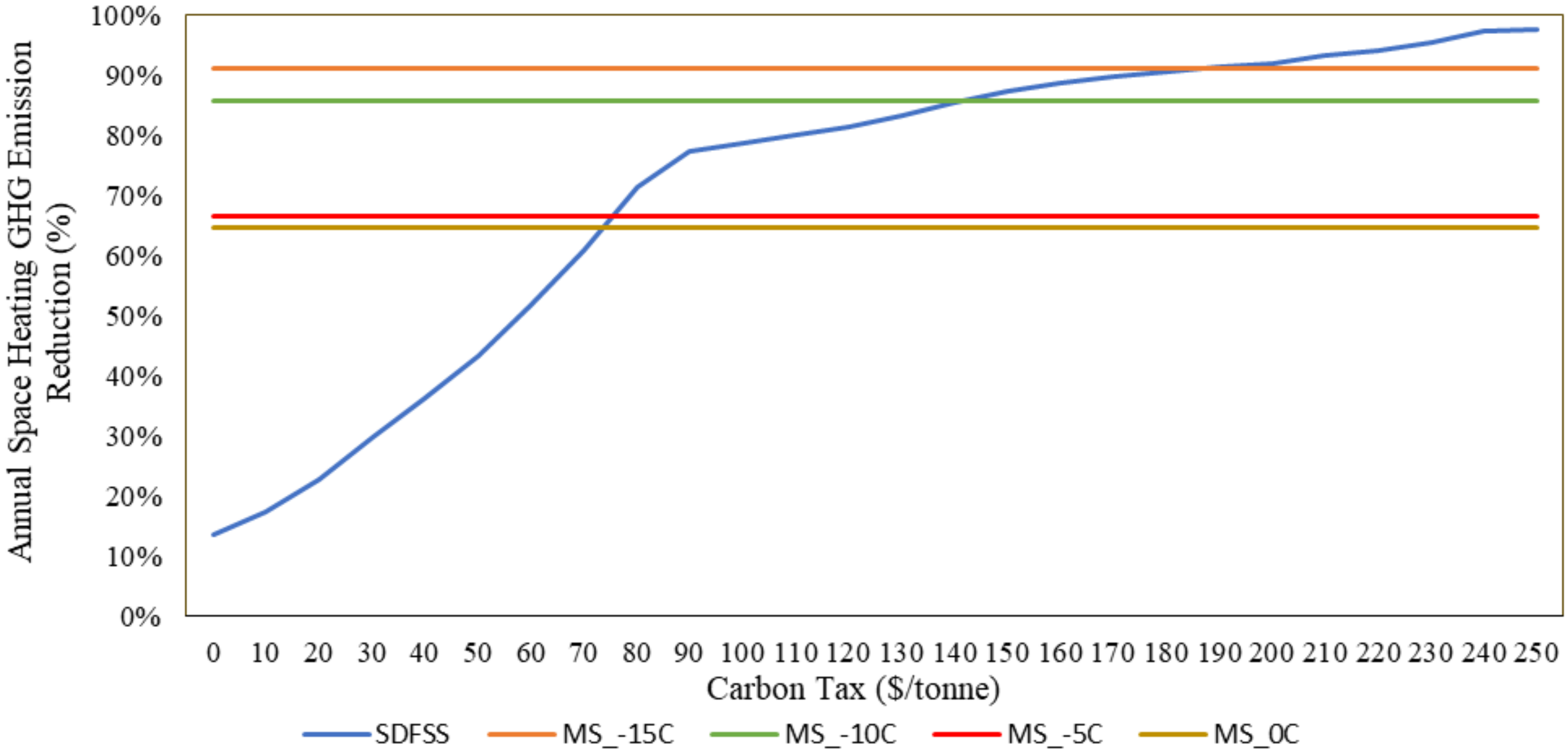


Annual Space Heating Cost ($)
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250
Carbon Tax ($/tonne)
SDFSS
MS_-15C
MS_-10C
MS_-5C
MS_0C
NGOnly

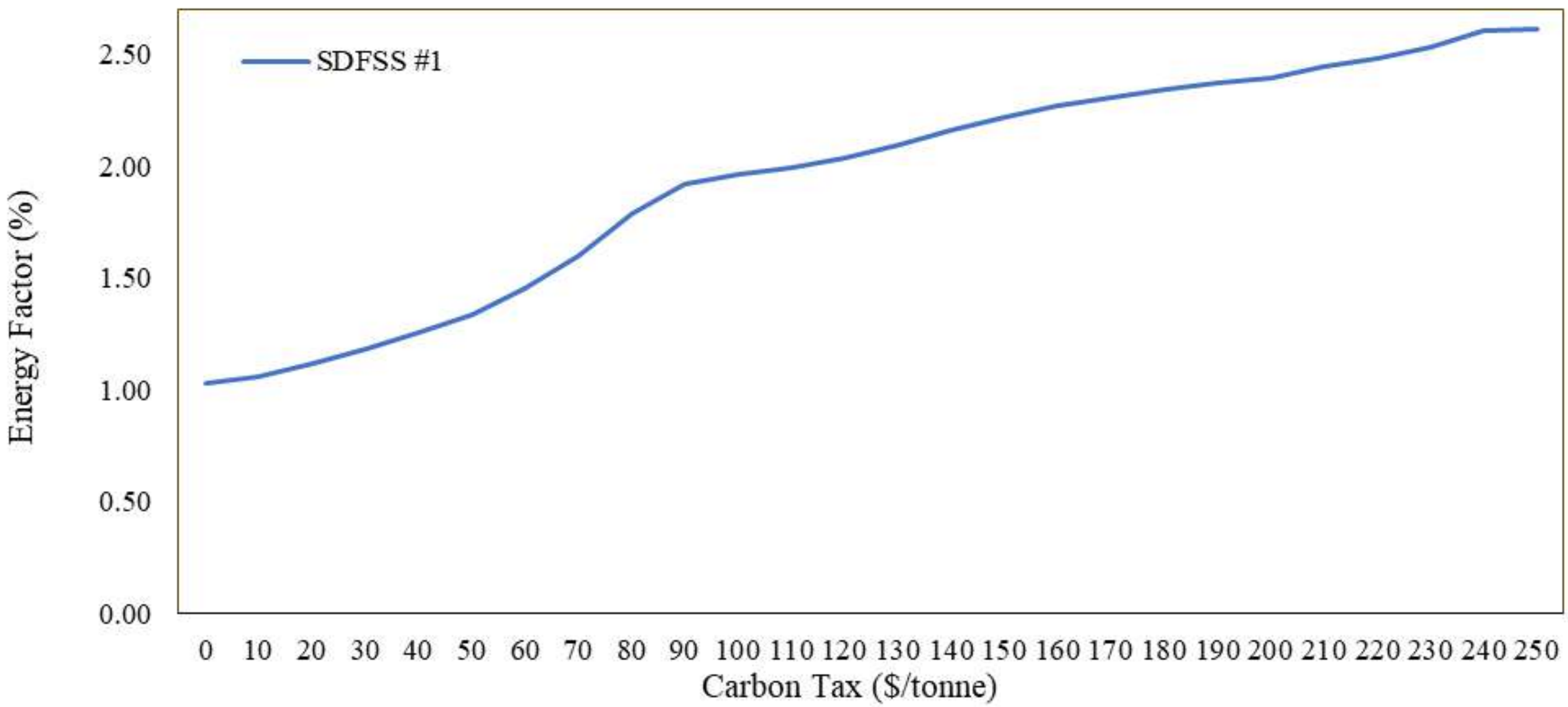

60.00%
40.00%
20.00%
0.00%
-20.00%
-40.00%
-60.00%
Annual Space Heating Cost Reduction (%)
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250
Carbon Tax ($/tonne)
SDFSS
MS_-15C
MS_-10C
MS_-5C
MS_0C



Annual Space Heating GHG Emission (kg)
3000
2500
2000
1500
1000
500
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250
Carbon Tax ($/tonne)
SDFSS
MS_-15C
MS_-10C
MS_-5C
MS_0C
NGOnly



Annual Space Heating GHG Emission Reduction (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250
Carbon Tax ($/tonne)
SDFSS
MS_-15C
MS_-10C
MS_-5C
MS_0C



SDFSS #1
Energy Factor (%)
2.50
2.00
1.50
1.00
0.50
0.00
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
Carbon Tax ($/tonne)

Discussion/Conclusion

- The results shows that regardless of different scenarios, there are still substantial savings
- It can be seen in general that the operating cost increases as the climate gets colder
- Relatively consistent cost savings in terms of percentage

Observations/Suggestions:

- House's envelope is very good and close to the PassiveHouse standard
- HOT2000 models underestimate space heating demand and RETScreen overestimate PV electricity generation
- Non-HVAC appliance + lighting electricity consumption is still on the high side even if hot tub consumption is excluded. (Presence of home workshops)
- Net-zero energy could be reached if 1) larger PV (10 kWp), 2) lower ASHP switching temperature, and 3) conservation for the discretionary end-use are employed.
- Suggested rough energy budget:
  - PV: 12000 kWh with 10kWp capacity with larger inverter;
  - ASHP: 4000 kWh; AHU+ERV: 1000 kWh; DHW: 1500 kWh; Non HVAC appliance + light: 5500 kWh

Acknowledgement

- Union Gas Limited
- Natural Sciences and Engineering Research Council (NSERC) of Canada
- MITCAS Accelerate Student Internships
- Doug Tarry Homes
- Homeowners and their 2 dogs

Thank You!

ありがとう ございます！

Questions?

Toronto Metropolitan University