Smart Control of Hybrid Space Heating System for Cold Climate Residential Sector Decarbonization – Case Study of Ontario, Canada

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What is SDFSS (Smart Dual Fuel Switching System)?

- **Conventional Forced-Air AHU and RTUs:** Consisted of Air Conditioner (A/C) and Natural Gas/Fossil Fuel Furnace (NGF/FFF)
  - FFF for heating in winter
  - A/C for cooling in summer
- **Hybrid Space Heating System:** Consisted of Air Source Heat Pump (ASHP) and Natural Gas/Fossil-Fuel Furnace (NGF/FFF)
  - ASHP replaces A/C and provides cooling in summer and partial/base heating in winter
  - NGF as backup heat source
- **Smart Dual Fuel Switching System** (SDFSS) optimizes the operation between ASHP and NGF/FFF of the hybrid system to reduce both energy cost and GHG emission.

How Does SDFSS Work?

- **Electricity (Ontario, Canada for example):**
  - Relatively higher price, but with Time of Use (TOU) pricing – different prices depending on the time of day with lower off-peak pricing that can be cost-effective w/ASHP
  - Low GHG intensity - ~30 to 40g of CO_2 per kWh
- **Natural Gas:**
  - Relatively lower price now, but increases with carbon price of up to $170/tonne in 2030 (or extra ~32¢/m^3 on top of NG price)
  - High GHG intensity - ~180g of CO_2 per kWh (or 1.888 kg CO_2 per m^3)
- **SDFSS**: optimizes the operation between the ASHP and NGF/FFF hourly
  - Based on which equipment/energy source has lower cost b/c ASHP performance (COP) and capacity are dependent on outdoor temperature.

How Does SDFSS Work? (cont.)

- **SDFSS**: optimizes the operation between the ASHP and NGF/FFF hourly
  - GHG intensity with ASHP could be 15X (or 200 / 13) lower than NGF/FFF
  - ASHP with sCOP of 3 (40/3 = 13 g CO_2/kWh of heat delivered) vs NGF/FFF with 90% efficiency (180/0.9 = 200 g CO_2/kWh of heat delivered)
  - The more ASHP is used the higher the GHG reduction, but it could cost more to heat with peak demand for electricity
  - NGF/FFF will be used whenever outdoor temp. is too cold and/or TOU price is too high for ASHP to run efficiently/cost effectively.
  - Conventional hybrid systems switch from ASHP to NGF/FFF based on technical balance point b/w ASHP and building or at fixed outdoor temp. which works fine but not optimal and not flexible.
  - SDFSS uses many temporal variables to optimize the overall operation of the hybrid heating system.
  - SDFSS now optimizes/minimizes operating cost for now.
  - Future SDFSS will include locally/regionally generated RE (wind and PV) and Demand Response (DR)/Load Dispatching.

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Benefits of SDFSS

Main Idea:

- Deploy adaptable, flexible technologies to electrify residential houses and small commercial/industrial buildings with RTUs, while utilizing the existing natural gas (NG) network for Renewable Natural Gas (RNG)/biogas/green hydrogen backup.
- SDFSS ensures resilience and aligns with Canada's cold climate, enabling a cost-effective smooth transition to a low-carbon infrastructure integrated with smart grid, IoT, AI/ML, and Blockchain technologies.

Benefits of SDFSS

- **Society:** Cleaner energy, lower emissions, improved energy resilience.
- **Building Owners/Operators:** Reduced energy costs, AI/ML-driven optimization for operational flexibility.
- **NG Utility:** Continued role through renewable gases/green hydrogen for backup and resilience.
- **Electric Utility:** Access to millions of dispatchable loads to stabilize the grid and integrate high penetration of renewable energy (RE).

Studied Houses

Exterior Photographs of the NZEB

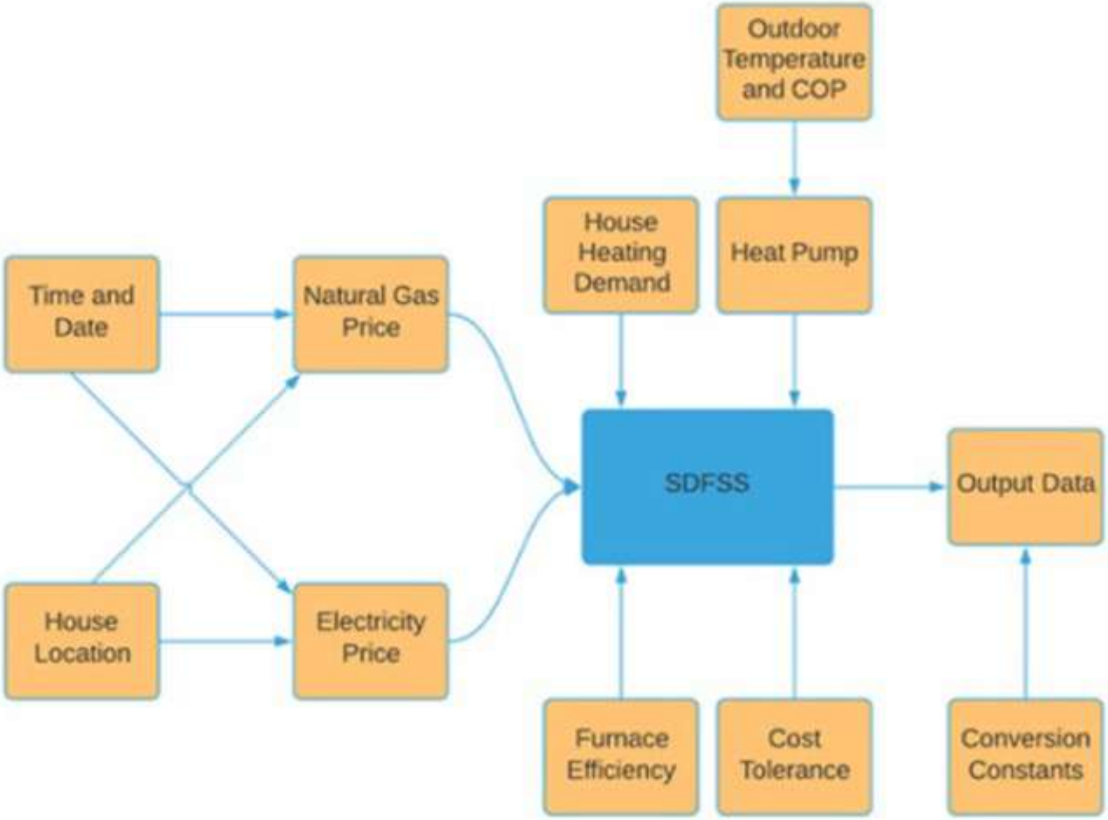
Archetype Sustainable House (ASH) Twin Houses of the Toronto and Region Conservation Authority (TRCA)

CCHT Twin-Test House Facility, in Ottawa, Canada

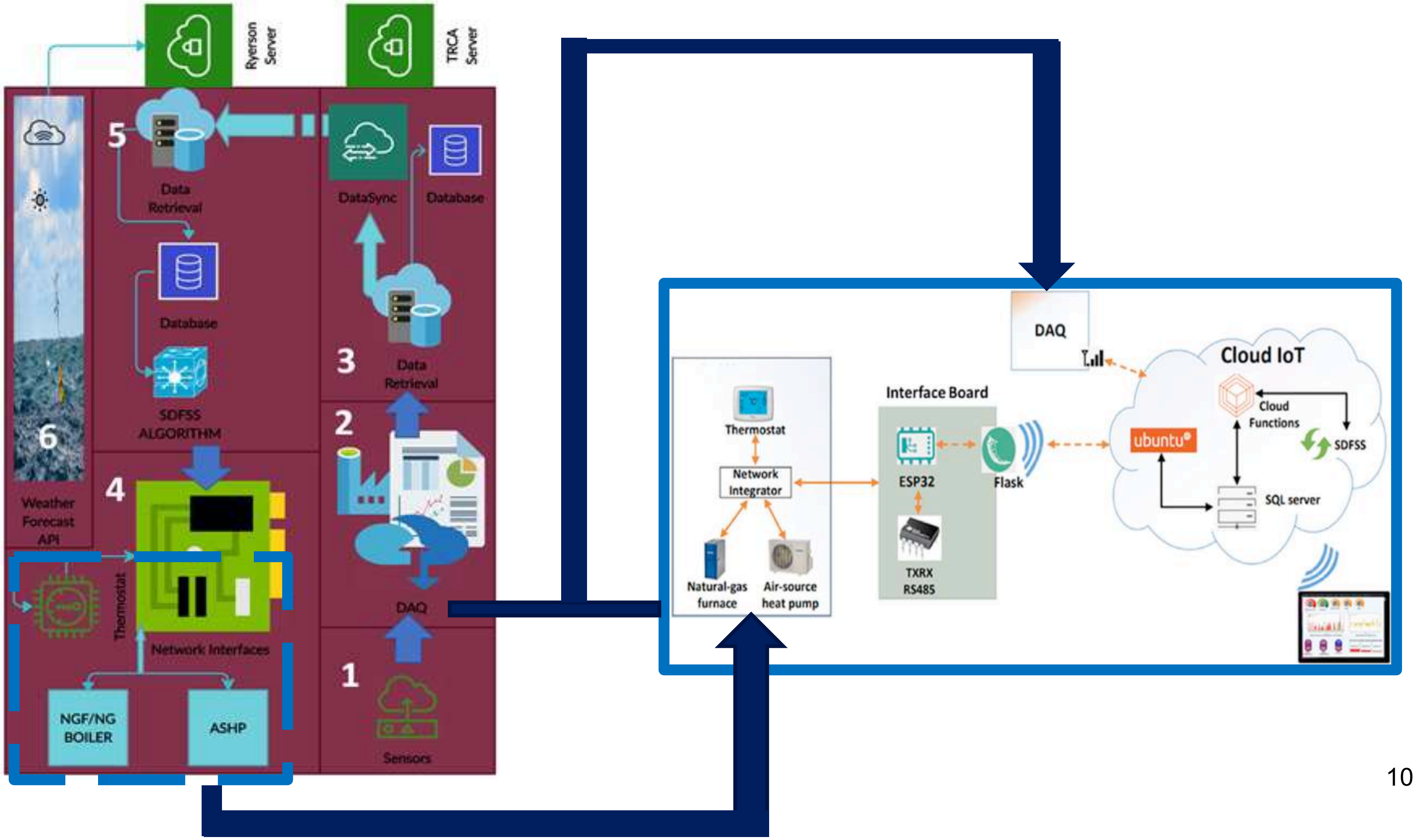
Studied Houses (w/ SDFSS Proof of Concepts)

- **TRCA Archetype Sustainable House A:**
  - Equipped with Mitsubishi Zuba ccASHP and NG Viessmann wall-hung boiler
  - Control was done via NI Labview system (pure experimental research)
- **London NZEH:** (real NZEH occupied by a retired couple with 2 dogs)
  - Equipped with Dettson hybrid space heating system of modulating ASHP+NGF
  - Control was done via a ClimateTalk based (non WiFi based) thermostat over cloud server
- **TRCA Archetype Sustainable House B**:
  - Two sets of hybrid systems comprised of conventional ASHPs and NG equipments
  - #1 Goodman ASHP and Goodman NG furnace
  - #2 Bosch ASHP and Goodman NG furnace or Bosch wall-hung boiler
  - Control was done via Ecobee 3 WiFi smart thermostat over cloud server

SDFSS Control Strategies



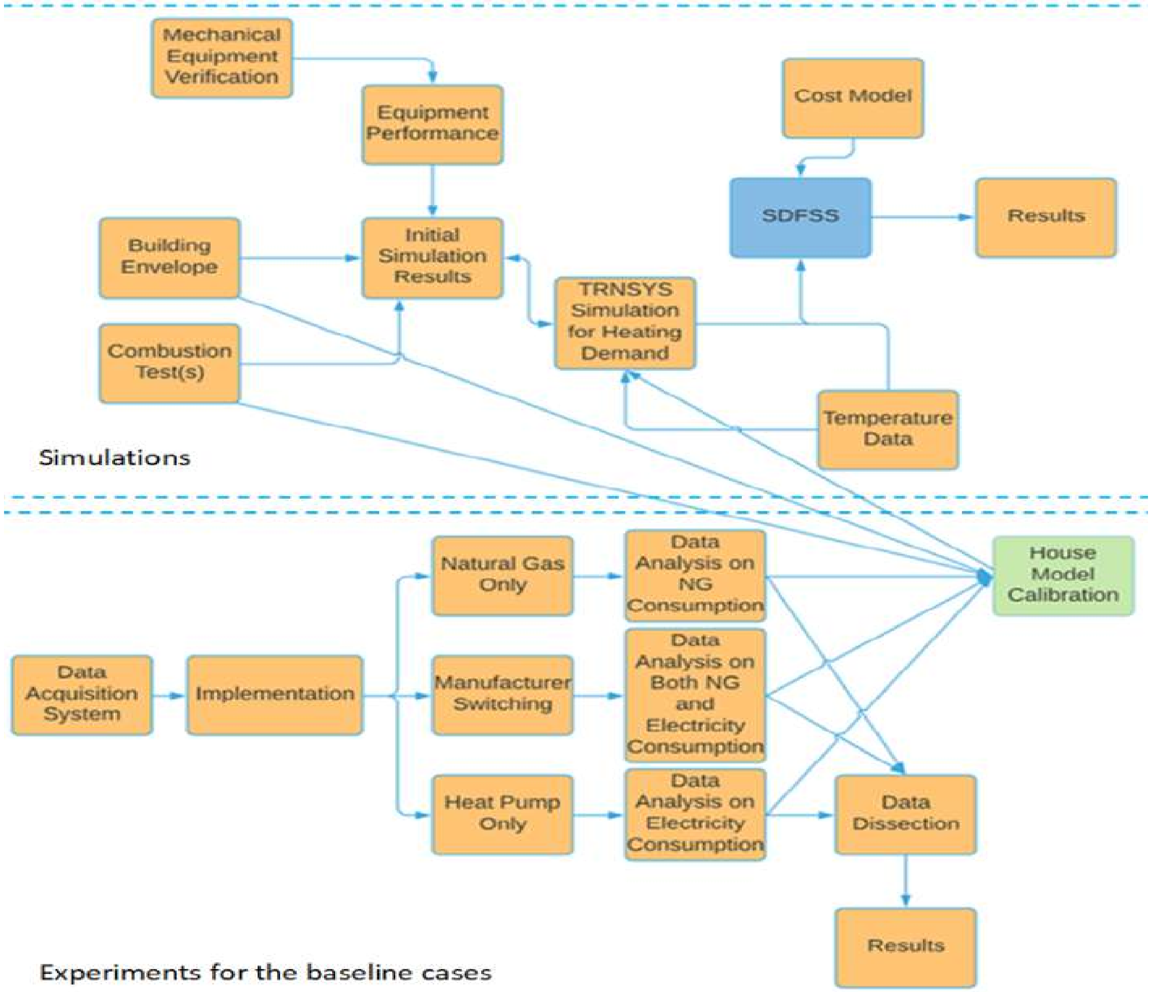
Schematics of SDFSS



SDFSS Analysis of the 4 Sets of Hybrid System in Different Houses in Different Ontario Cities under Different Carbon Prices

- **Houses**
  - TRCA Archetype Sustainable House (ASH) (large, super-efficient, semi-detached)
  - London NZEH (owners occupied single detached bungalow + basement)
  - CCHT House (typical suburban 2-storey detached R-2000 built in early 2000)
- **Cities (Ontario, Canada)**
  - Windsor (warmest w/ T_{min} = -17°C and HHD = 3400 °C-day)
  - Toronto (w/ T_{min} = -23°C and HHD = 3600 °C-day)
  - Strathroy/London (w/ T_{min} = -24°C and HHD = 3900 °C-day)
  - Ottawa (w/ T_{min} = -29°C and HHD = 4500 °C-day)
  - Thunder Bay (coldest w/ T_{min} = -34°C and HHD = 5600 °C-day)
- **Carbon Price**:
  - $0 up to $170/tonne (in 2030)

Methodology of the SDFSS Analysis



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Energy Pricing

Electricity

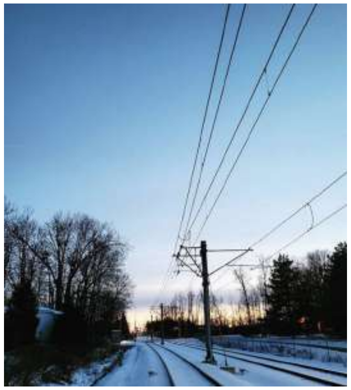


Table 1.

Summer (May 1- Oct 31)	Winter (Nov 1 – Apr 30)
Off-Peak	Off-Peak
Mid-Peak	On-Peak
On-Peak	Mid-Peak
Mid-Peak	On-Peak
Off-Peak	Off-Peak

Table 2.

City Period	Toronto	Ottawa	Strathroy	Windsor	Thunder Bay
Off-Peak	$0.092	$0.110	$0.097	$0.097	$0.093
Mid-Peak	$0.124	$0.141	$0.129	$0.129	$0.125
On-Peak	$0.163	$0.180	$0.168	$0.168	$0.163

Natural Gas

- City
  - Toronto
  - Ottawa
  - Strathroy
  - Windsor
  - Thunder Bay
- House
  - NZEB
  - HouseB
  - CCHT
- SDFSS
  - SDFSS #1
  - SDFSS #2
  - SDFSS #3
  - SDFSS #4

Table 3.

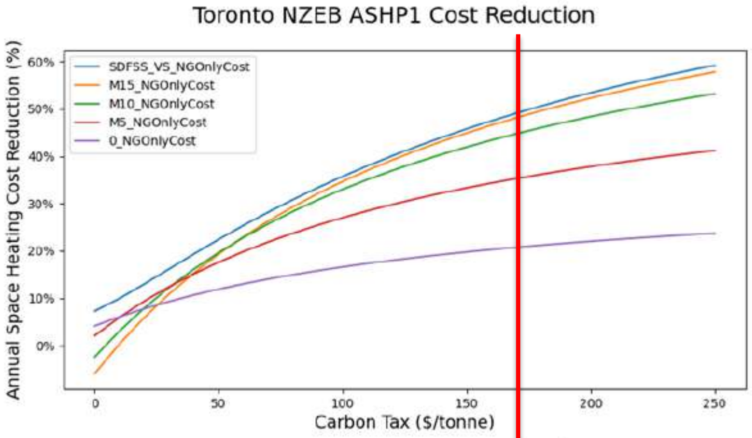
City Period	Toronto	Ottawa	Strathroy/ London	Windsor	Thunder Bay
Fixed-Price	$0.261746	$0.322512	$0.322512	$0.261746	$0.342767

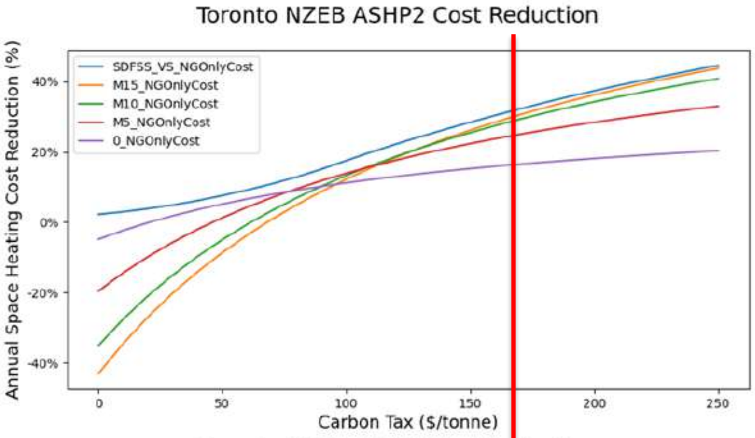
Summary of SDFSS results for different CPs in terms of heating energy cost reduction to NGF only

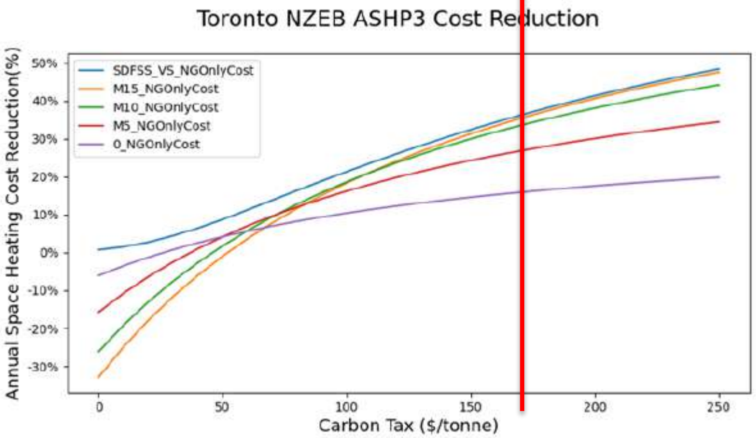
CASE	TORONTO NZEB					TORONTO ASH House B					TORONTO CCHT			
CT ($/tonne)	SDFSS #1	SDFSS #2	SDFSS #3	SDFSS #4	CT ($/tonne)	SDFSS #1	SDFSS #2	SDFSS #3	SDFSS #4	CT ($/tonne)	SDFSS #1	SDFSS #2	SDFSS #3	SDFSS #4
	%	%	%	%		%	%	%	%		%	%	%	%
0	7.3	2.2	1.2	0.8	**0**	5.9	1.7	1.0	0.6	**0**	7.1	2.0	1.1	0.6
50	22.4	7.5	9.6	8.7	**50**	19.6	6.4	8.5	8.2	**50**	22.3	7.0	9.2	8.4
60	25.4	9.1	11.5	11.2	**60**	22.5	8.0	10.1	10.7	**60**	25.3	8.6	11.3	10.8
70	28.2	10.9	13.4	13.8	**70**	25.3	9.7	11.7	13.2	**70**	28.1	10.3	13.3	13.4
80	30.8	12.8	15.2	16.4	**80**	28.0	11.8	13.2	15.8	**80**	30.8	12.2	15.2	15.9
100	35.7	17.5	18.6	21 .3	**100**	32.9	16.6	16.1	20.6	**100**	35.6	16.8	18.7	20.9
170	49.1	32.2	28.5	36.2	**170**	46.6	30.6	24.4	34.8	**170**	49.0	32.2	29.0	35.8
200	53.4	37.3	31.7	41.3	**200**	51.0	35.5	27.1	39.7	**200**	53.4	36.7	32.5	40.9
250	59.2	44.6	36.1	48.4	**250**	57.1	42.5	31.0	46.4	**250**	59.1	44.0	37.1	48.1

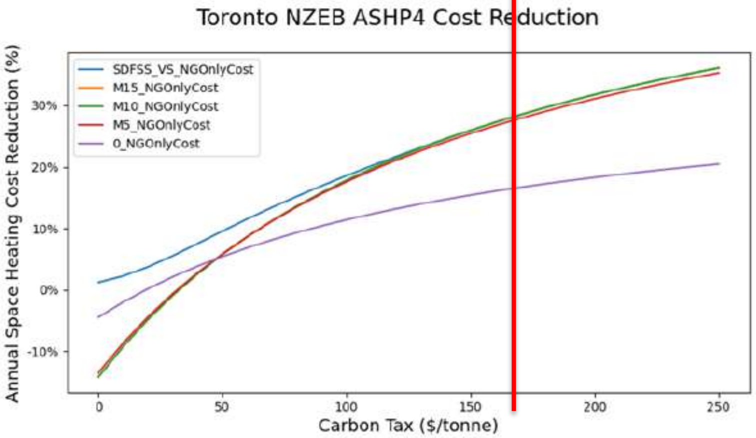
2030 Carbon Price → 170

Summary of SDFSS results for different CPs in terms of NZEH heating energy cost reduction to NGF only


Toronto NZEB ASHP1 Cost Reduction


Toronto NZEB ASHP2 Cost Reduction


Toronto NZEB ASHP3 Cost Reduction


Toronto NZEB ASHP4 Cost Reduction

2030 Carbon Price @ $170/tonne

2030 Carbon Price @ $170/tonne

Summary of SDFSS results for different CPs in terms of GHG emission reduction to NGF only

CASE	TORONTO NZEB					TORONTO ASH House B					TORONTO CCHT			
CT ($/tonne)	SDFSS #1	SDFSS #2	SDFSS #3	SDFSS #4	CT ($/tonne)	SDFSS #1	SDFSS #2	SDFSS #3	SDFSS #4	CT ($/tonne)	SDFSS #1	SDFSS #2	SDFSS #3	SDFSS #4
	%	%	%	%		%	%	%	%		%	%	%	%
0	43.5	10.2	12.1	7.2	**0**	36.9	7.8	10.7	6.0	**0**	43.2	9.2	11.1	6.3
50	82.2	36.3	48.0	55.7	**50**	76.7	34.2	40.1	54.5	**50**	82.4	34.8	49.9	54.9
60	85.1	42.0	50.8	63.5	**60**	80.7	40.6	42.9	62.4	**60**	85.1	40.4	52.7	62.7
70	87.6	49.9	52.0	69.3	**70**	85.0	50.1	44.0	68.4	**70**	87.6	47.7	53.9	68.7
80	89.6	59.8	53.8	73.6	**80**	87.3	62.6	45.8	72.9	**80**	89.5	58.0	55.6	73.1
100	92.3	77.6	57.5	80.6	**100**	90.6	73.5	48.1	77.1	**100**	92.4	77.3	59.8	80.2
170	98.0	89.1	64.8	93.0	**170**	97.0	84.8	54.2	88.9	**170**	98.2	88.8	67.7	92.9
200	98.3	91.2	64.8	95.2	**200**	97.8	87.2	54.2	91.2	**200**	98.4	90.8	67.7	95.1
250	98.3	97.1	64.8	97.0	**250**	98.4	92.8	54.2	92.8	**250**	98.4	97.1	67.7	97.1

2030 Carbon Price →

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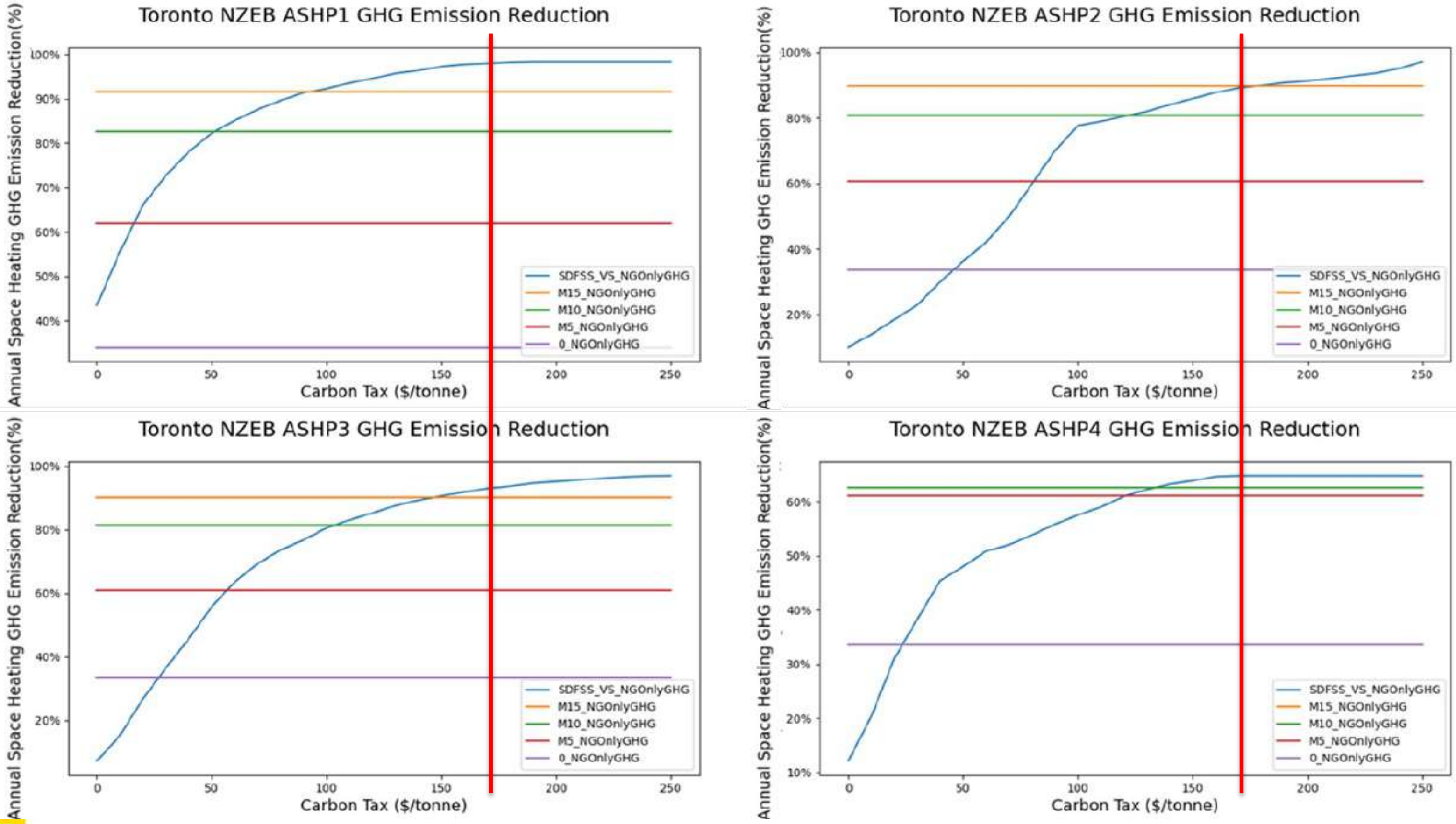
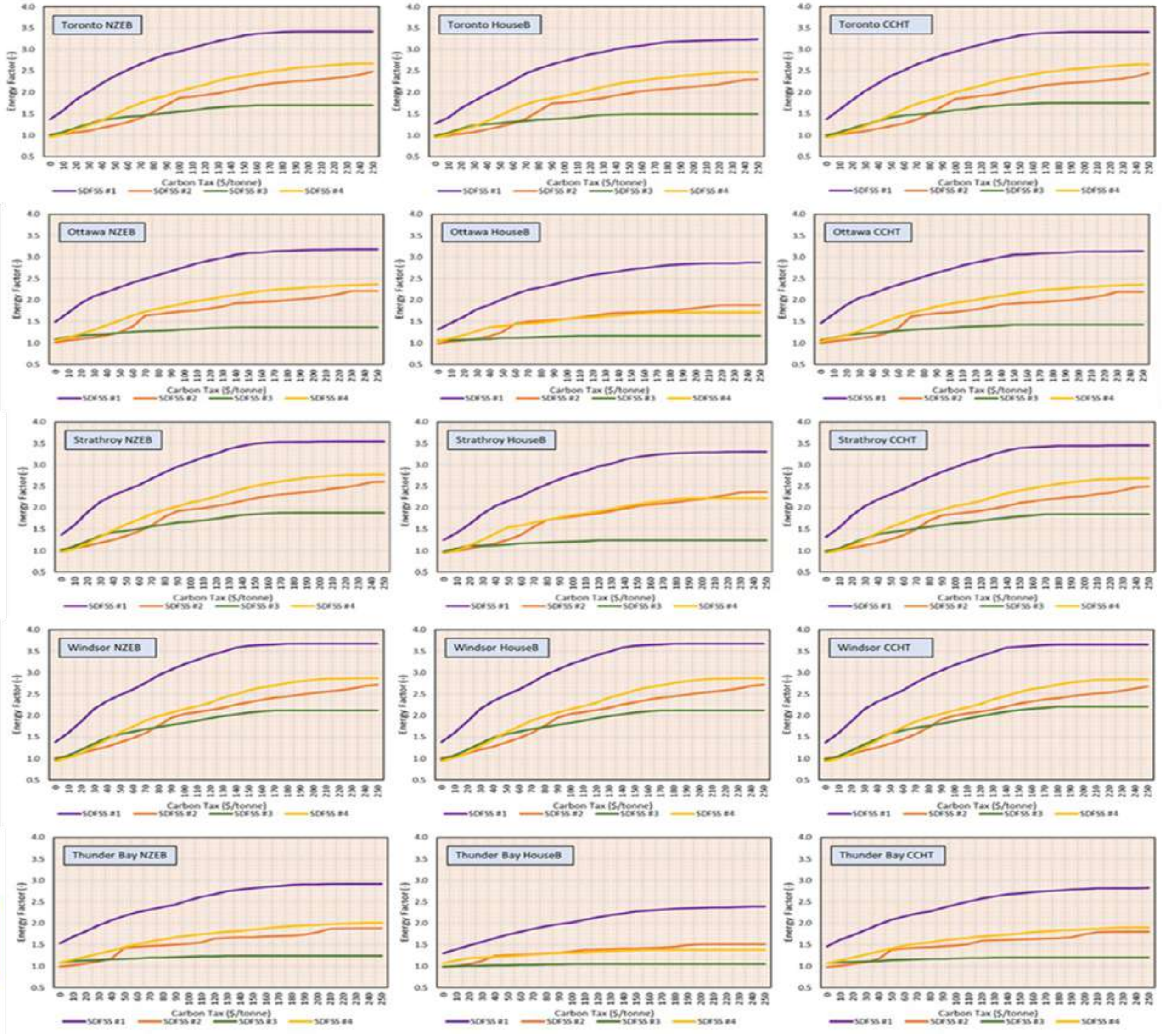
Summary of SDFSS results for different CPs in terms of NZEH GHG emission reduction to NGF only



2030 Carbon Price @ $170/tonne

2030 Carbon Price @ $170/tonne

Energy Factors



Energy Factor (EF) =

Total Energy Delivered / Total NG + Electricity

EF = sCOP if only ASHP is used

EF = NGF efficiency if only NGF is used

EF for high performance ccASHP could reach sCOP under high carbon price environment which means ccASHP could be used almost 100% of the time.

Key Findings

- **Smart Dual Fuel Switching System (SDFSS)** improves residential heating by dynamically switching between **air-source heat pumps (ASHP)** and **natural gas furnaces (NGF).**
- By using real-time data on weather, fuel prices, and equipment performance & capacity, the system optimizes for both **energy cost savings** and **greenhouse gas (GHG)** reductions.
- Performance Highlights: Up to **30% annual energy cost savings** compared to traditional natural gas furnace systems.
- **Up to 90% (depending on ASHP) GHG emission reduction** by 2030, supporting Canada's 2030 and 2050 climate targets.

Environmental & Economic Impact:

- Outperforms **fixed set-point switching** and **natural gas-only** systems.
- Aligns with Canada's goals for a **low-carbon economy**.

Policy & Future Research Recommendations for SDFSS Implementation

- **Support for SDFSS:** Policymakers should introduce incentives and regulations to promote energy-efficient and GHG-reducing technologies like the SDFSS.
- Encouraging adoption of **adaptive, intelligent systems** is key for transitioning to **low-carbon residential heating.**
- Further R&D is needed to **streamline** and **refine** the **SDFSS algorithms** and ensure its scalability across different **building types** and **climatic conditions**.
- Continued innovation will help enhance both **economic viability** and **environmental sustainability** in residential heating systems.

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Thank You!

ありがとう ございます！

Questions?