Space-conditioning and water heating with a Ground-Source Integrated Heat Pump (GS-IHP) for residential NZEBs

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Project Update for IEA HP Annex 61

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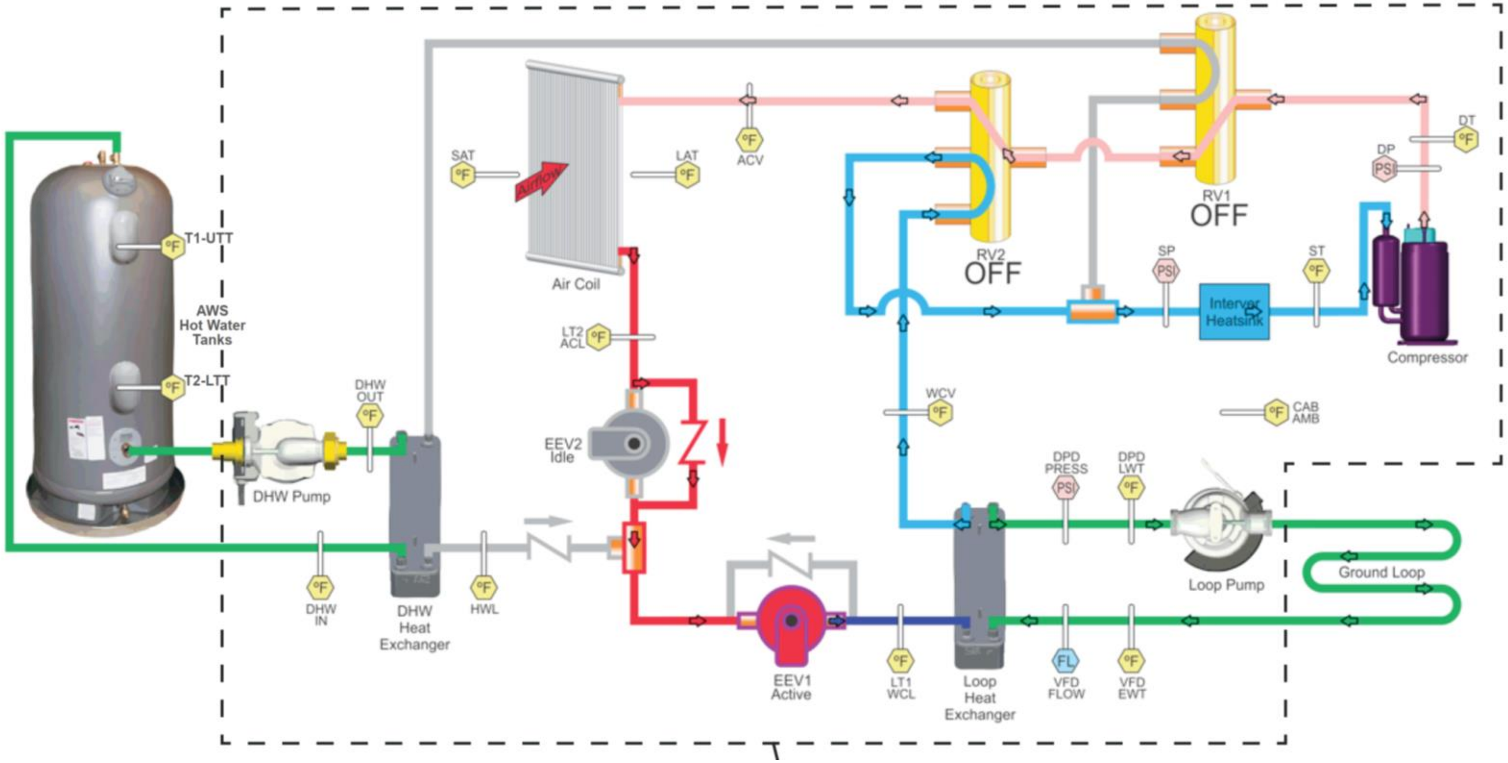
Outline

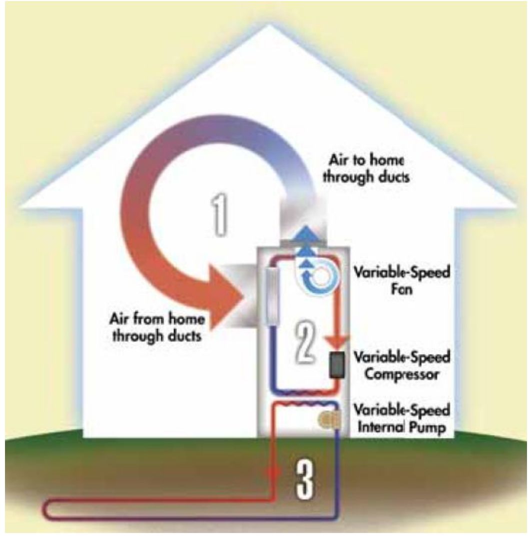
- Introduction – GS-IHP function and purpose
- Research plan
- Preliminary simulation results

Introduction

What is the Ground-source Integrated Heat Pump (GS-IHP)?

- Commercially-available, variable-speed GSHP that heats, cools, and makes 100 % DHW [1-6]
  - Can recover cooling energy into DHW
- High efficiency makes system attractive for NIST's Net-Zero, High-Performance Building Program[1]





space conditioning


water heating

[1]https://www.nist.gov/programs-projects/net-zero-energy-high-performance-buildings-program

Research Plan

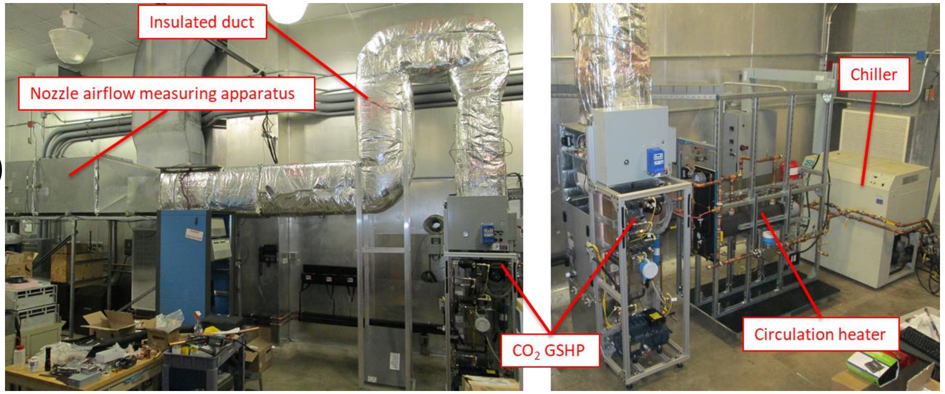
1. Evaluate performance of GS-IHP for residential NZEBs in varied climates
2. Assess existing GHX sizing guidelines for GS-IHP
3. Compare field vs. standard performance (ASHRAE 206-2013)
4. Assess impact of new DOE DHW test procedures on GS-IHP rated efficiency
5. Look for opportunities to improve GS-IHP system performance and/or controls

Research Plan

1. Laboratory evaluation

Construction in progress

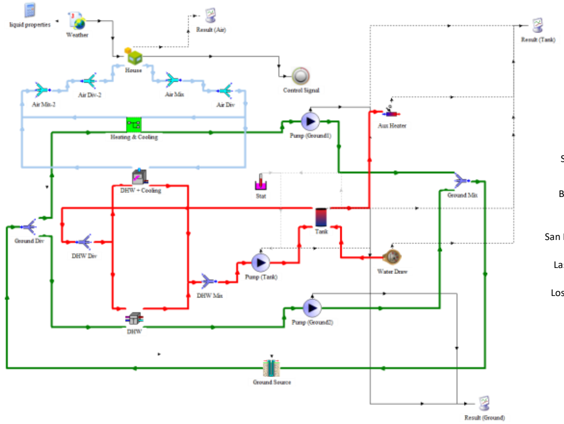
- Multipurpose Heat Pumps (ASHRAE 206-2013)
- DHW (ASHRAE 118.2, DOE 10 CFR Part 430, NZEB house draw profiles)

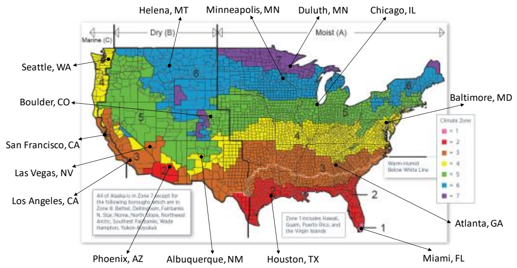


GSHP in environmental chamber

2. TRNSYS annual simulations

Preliminary results





TRNSYS annual building simulation

TRNSYS 18

3. 12-months field test in NIST residential NZEB

Future plans

NIST residential NZEB

Building Simulations: Configuration

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Building Simulations: Equipment Options

Used TRNSYS model of NIST residential NZEB to evaluate:

- **GS-IHP**
  - ✓ Heating, Cooling, Cooling+DHW, and DHW
- **GSHP-VS**: Same variable-speed (VS) components as GS-IHP, but no water heating
  - ✓ DHW provided by HPWH[5,6]
- **GSHP**: Conventional two-speed ground source heat pump
  - ✓ Heating and Cooling
  - ✓ DHW provided by HPWH
- **SHW**: Solar hot-water system

COP[1]			
	GSIHP[2]	GSHPVS[3]	GSHP[4]
Cool			
Full	7.1	7.1	4.6
Part	12.7	12.7	6.0
Heat			
Full	3.6	3.6	3.8
Part	5.1	5.1	4.1

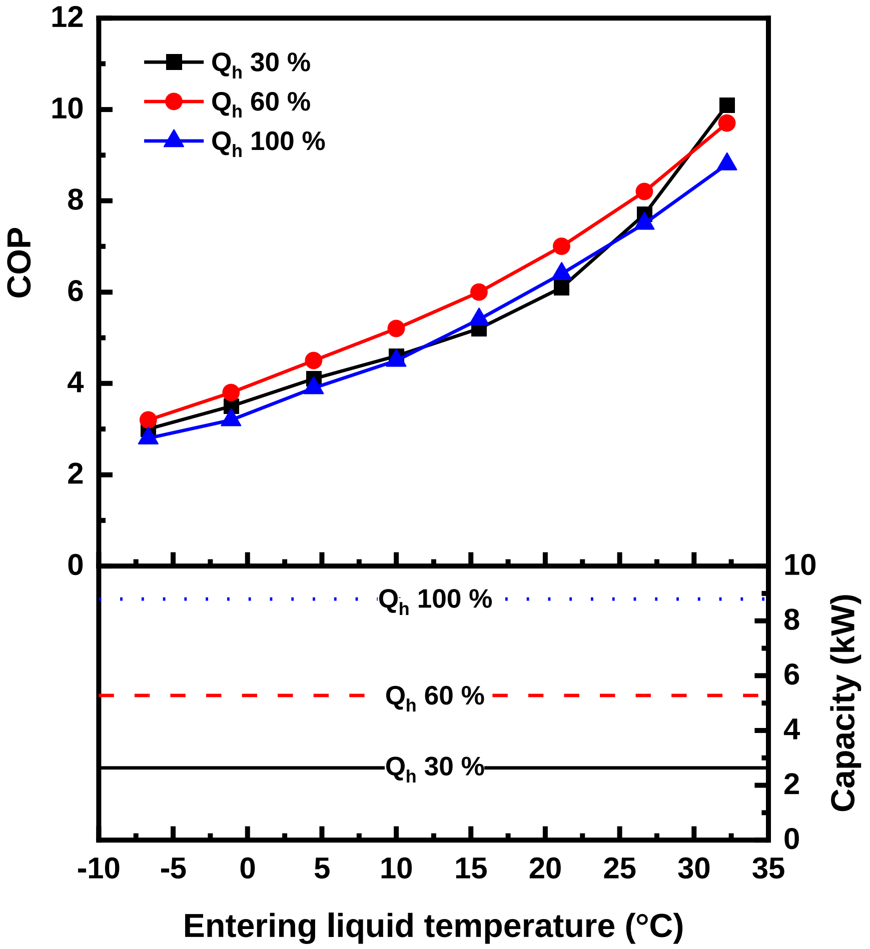
DHW = domestic hot water
HPWH = heat-pump water heater (air-source)

1. ISO 13256-1 standard ratings, https://www.iso.org/standard/3330.html.
2. Trilogy QE45 https://www.climatemaster.com/Homeowner/side-links/products/product-details/trilogy
3. Same as 2, but without the water-heating capability
4. WF 300A11-024, https://www.waterfurnace.com/residential/products/geothermal-heat-pumps/300a11
5. Hubbell PBX50SL - IOM Manual for Hybrid Electric HPWH: Base Model 'PBX'
6. Balke, E., (M.S. 2015), "Modeling, Validation, and Evaluation of the NIST Net Zero Energy Residential Test Facility", https://sel.me.wisc.edu/publications/theses/balke15.zip

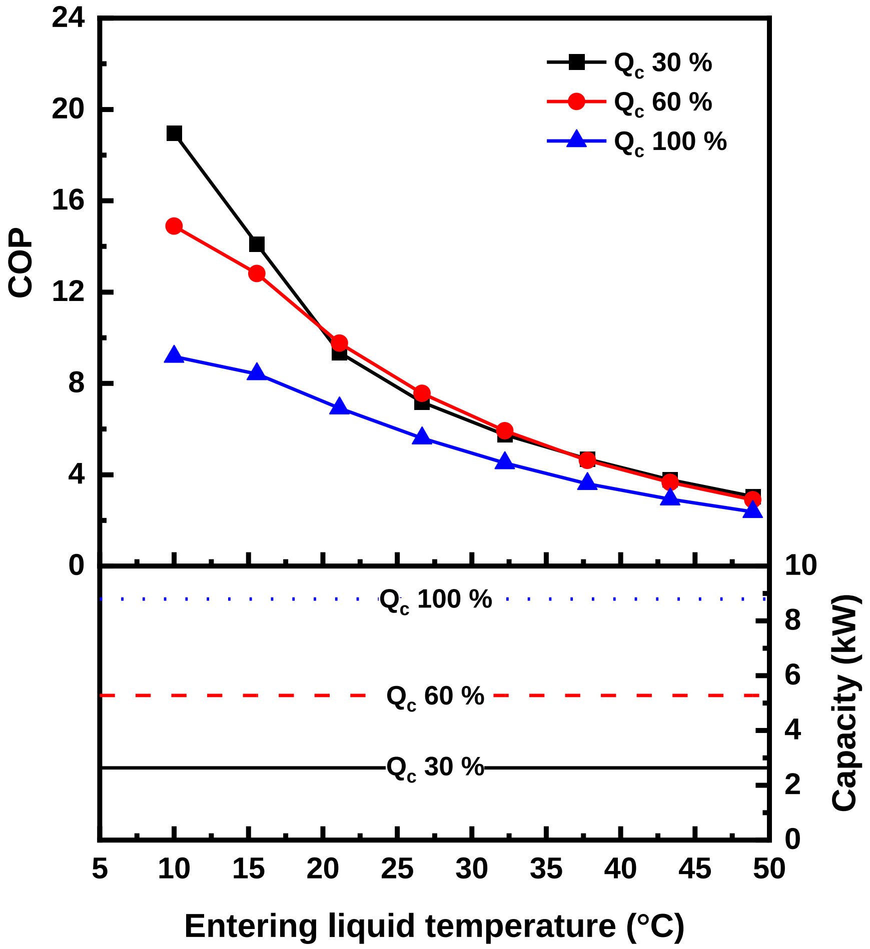
Building Simulations: GS-IHP Performance

- Manufacturer’s performance data mapped to TRNSYS model

Heating

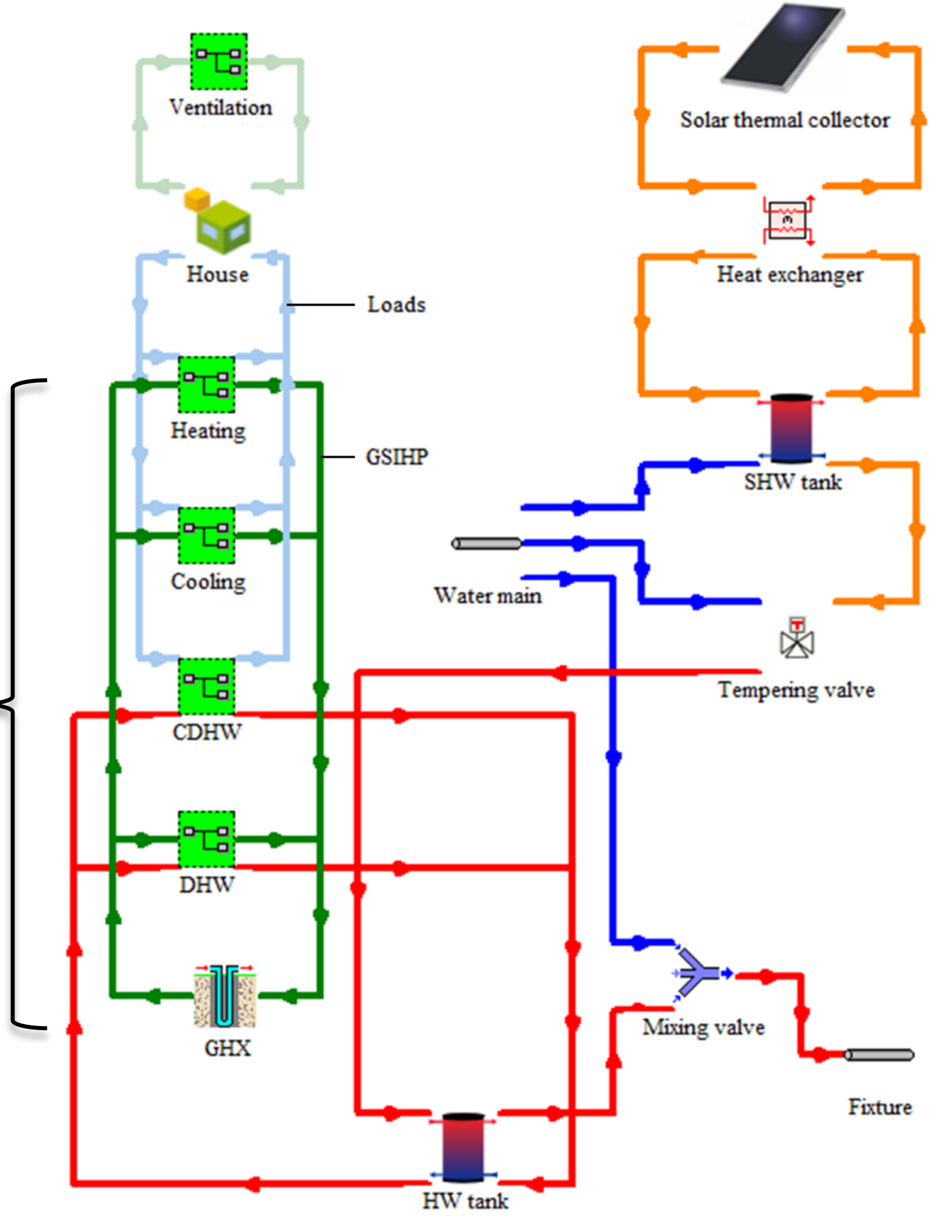


Cooling



Building Simulations: TRNSYS Model

- Detailed control of GS-IHP
  - Heat
  - Cool
  - Cool + DHW
  - DHW



TRNSYS = Transient Systems Simulation Tool

Building Simulations: Preliminary Results

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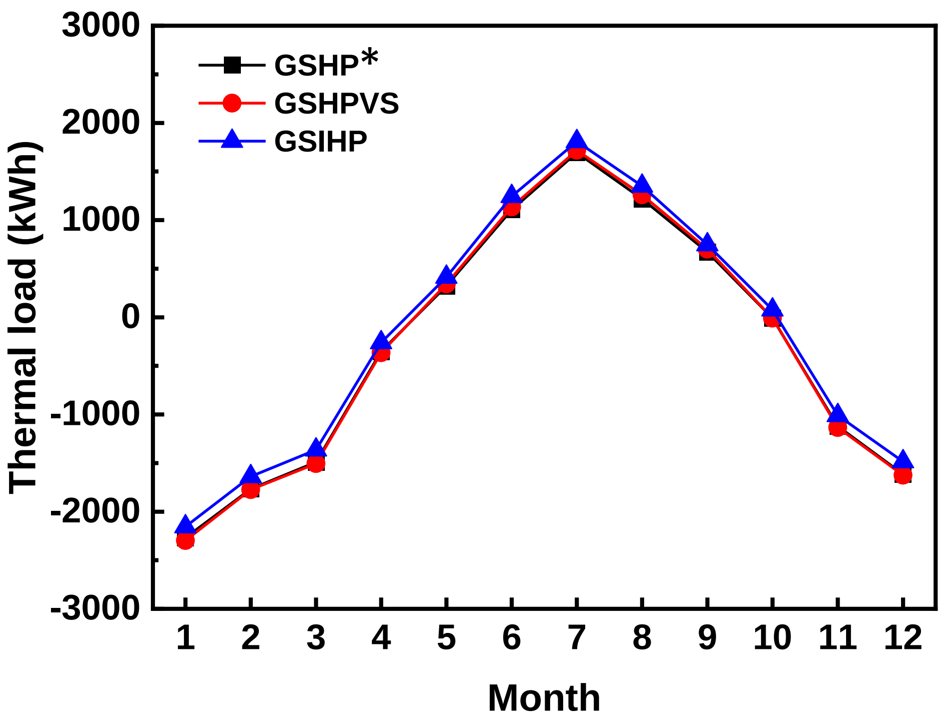
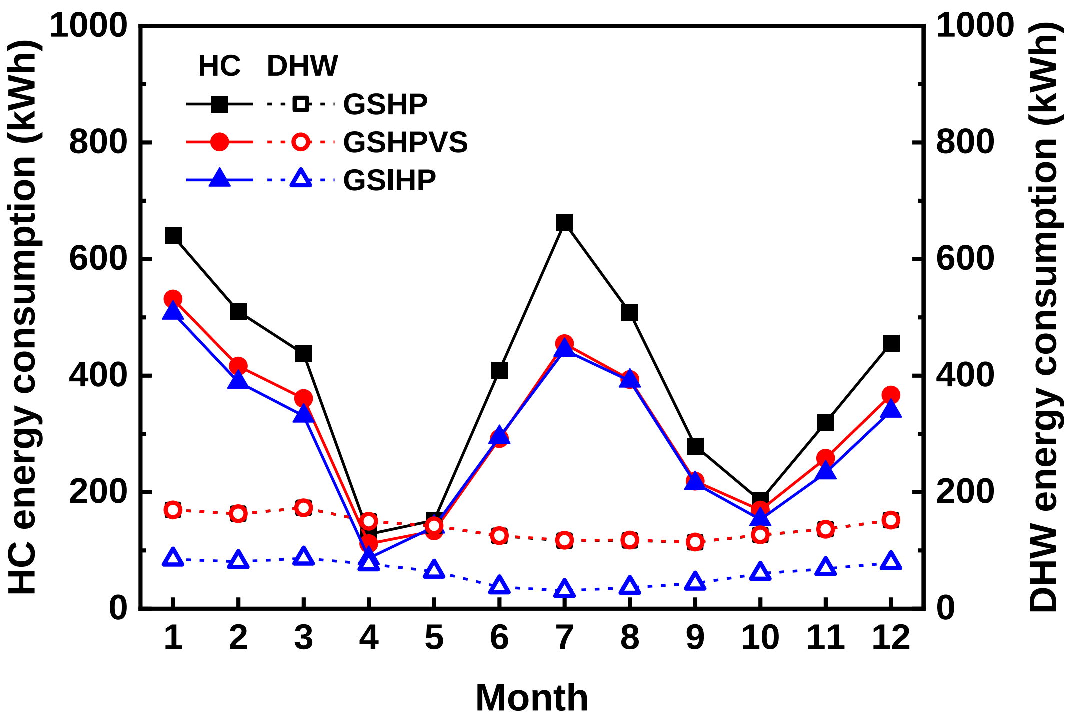
Results: Annual Loads & Electricity Use

- Compare thermal & electrical loads from different GSHPs
  - GSHP and GSHPVS loads are slightly more negative because of cooling from HPWH
- GS-IHP saves energy with higher COP and enhanced DHW efficiency

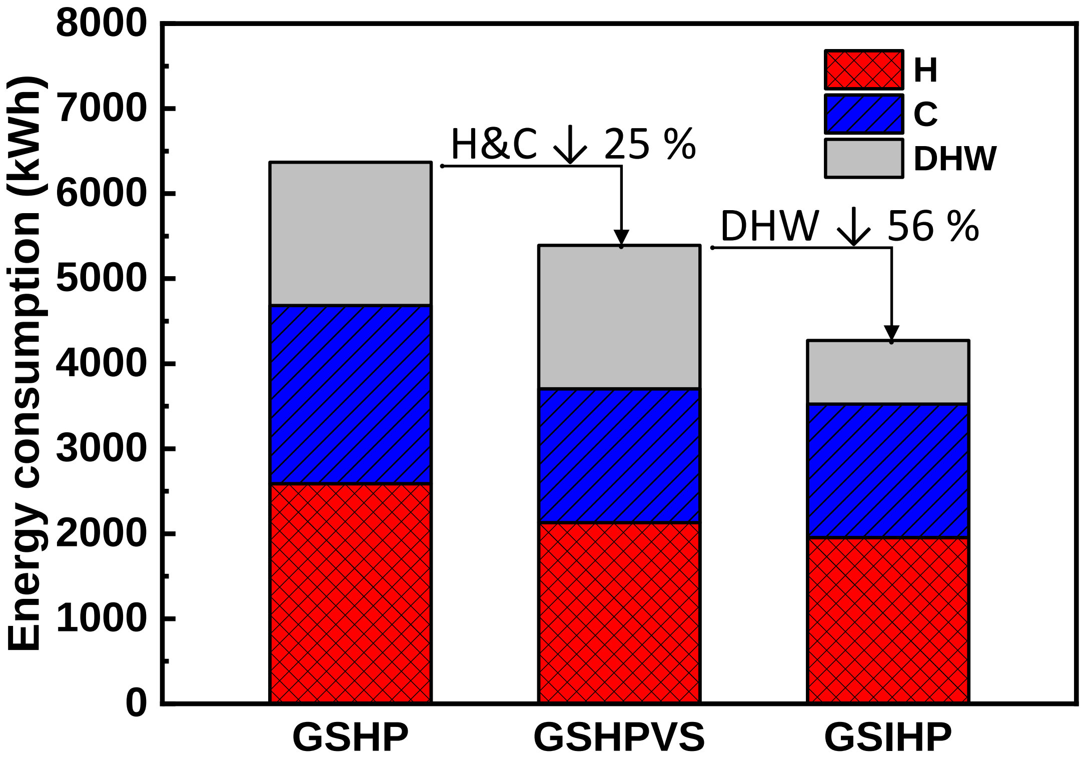




*GSHP and GSHPVS thermal loads are the same

Results: Performance Comparison

- **GS-IHP vs GSHP**
  - Reduced Heating & Cooling (H&C) energy ≈25 %
  - Reduced DHW ≈56 %



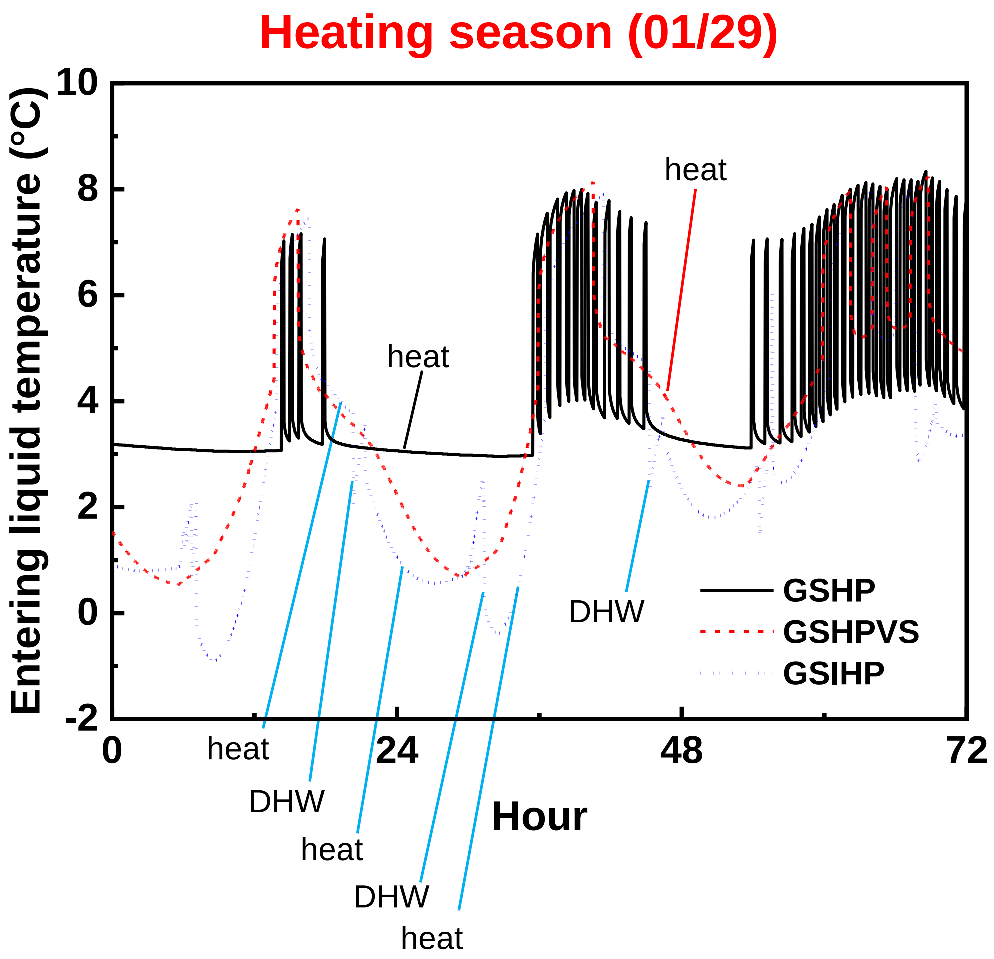
Space-conditioning Annual COP

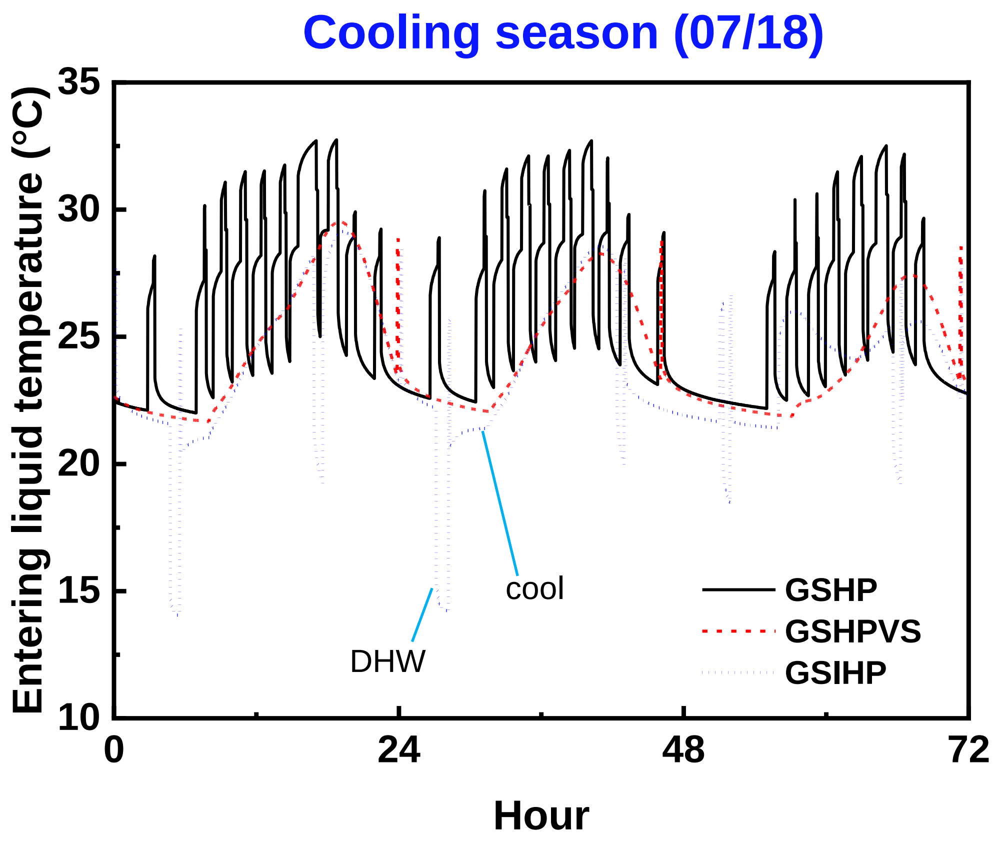
GSHP	GSHP-VS	GS-IHP*
3.16	4.08	4.15

*Includes heating, cooling, and cooling + DHW modes, but not DHW

Results: Entering Liquid Temperature & Controls

- ELT profile shows GS-IHP operating mode: heat, cool, DHW
- Variable-speed (VS) systems have favorable ELT variations during low-load
- Variable-speed systems have less-favorable ELT during high-load (higher capacity)

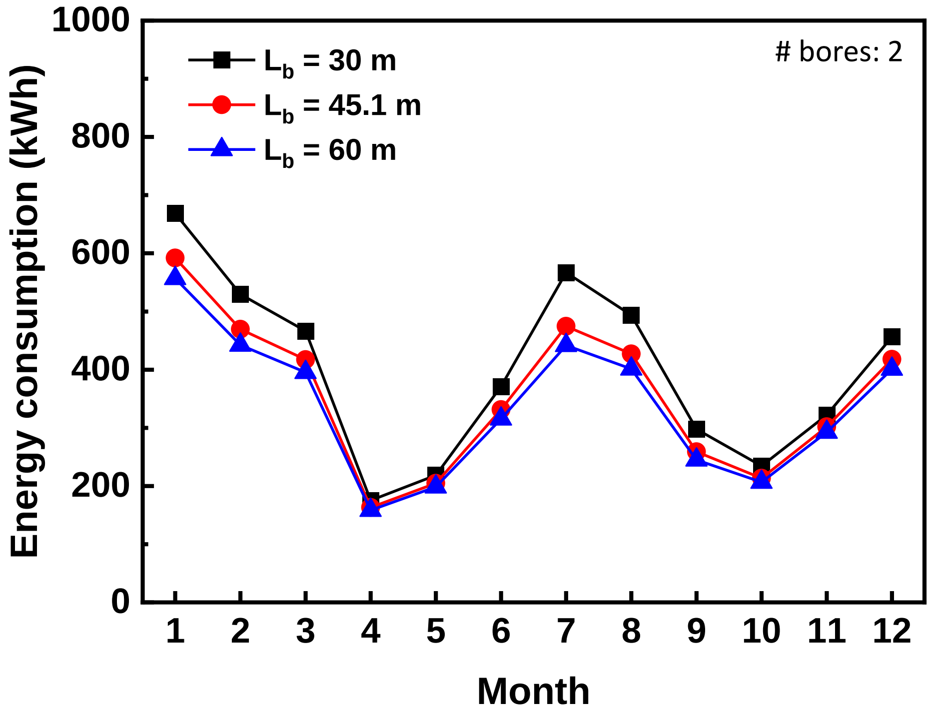


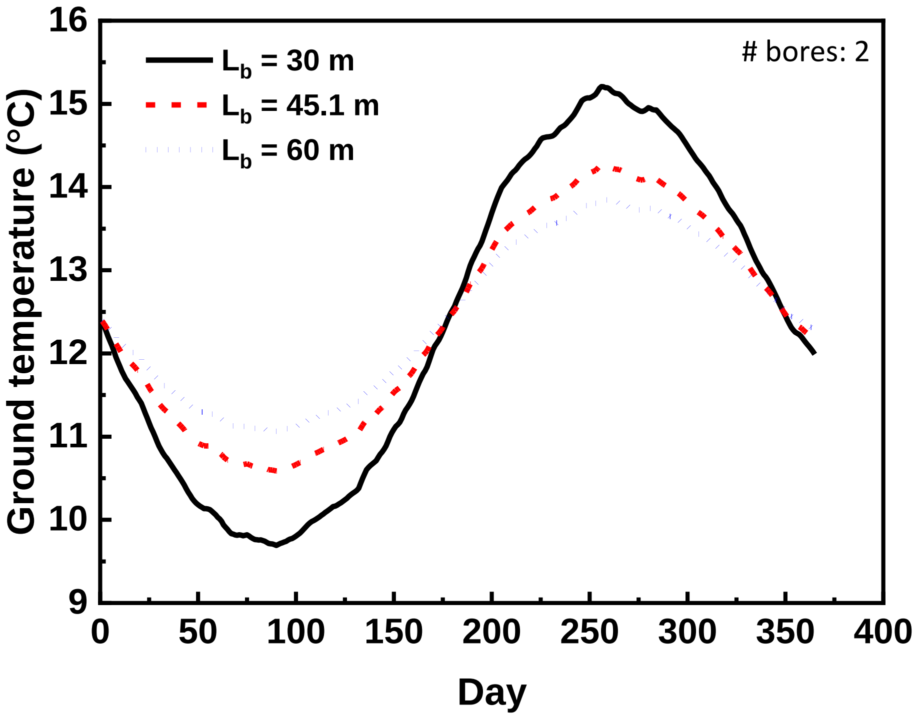


ELT = Entering Liquid Temperature

Results: GHX length

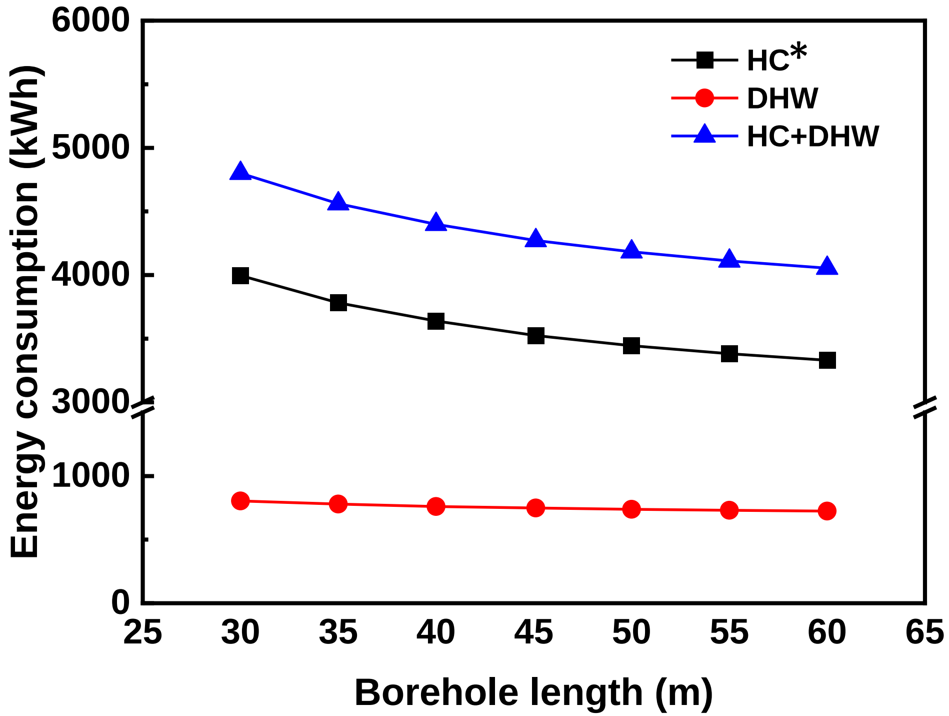
- As borehole length increases, energy consumption decreases
- Beyond 45 m per bore, energy benefit is marginal
  - $Length_{GHX}/Capacity_{GSHP}$ = 45 m/bore×2 bores/8.8 kW ≈ 10 m/kW (120 ft/ton)

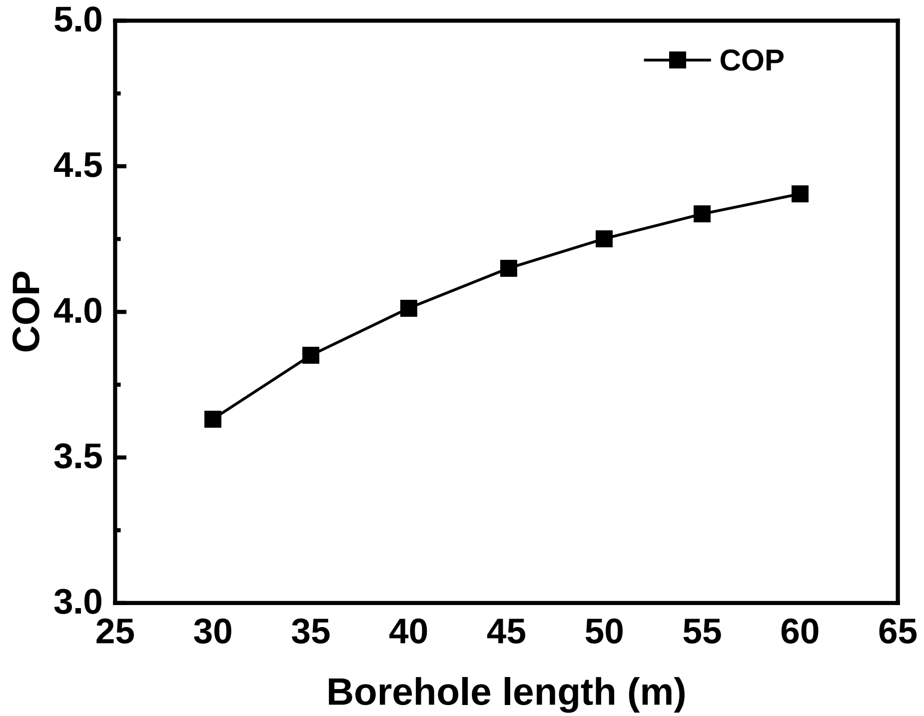




Results: GHX Length

- Annual heating and cooling energy decreased by 17% and DHW energy decreased by 10% with increasing borehole length from 30 m to 60 m.
- Annual COP increases from 3.6 to 4.4 (21% increase).
- Results can be used to size cost-effective systems

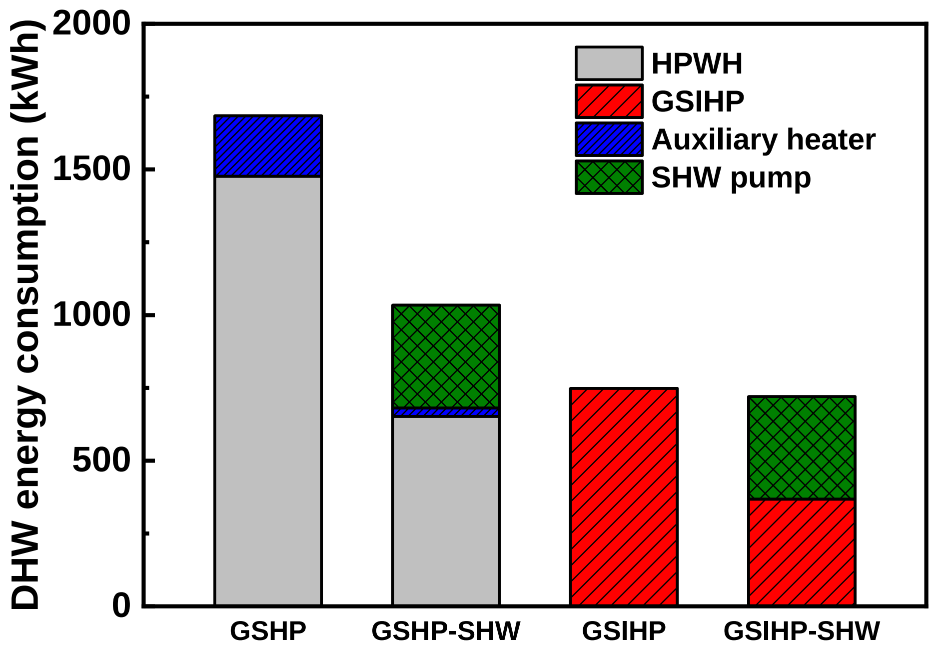


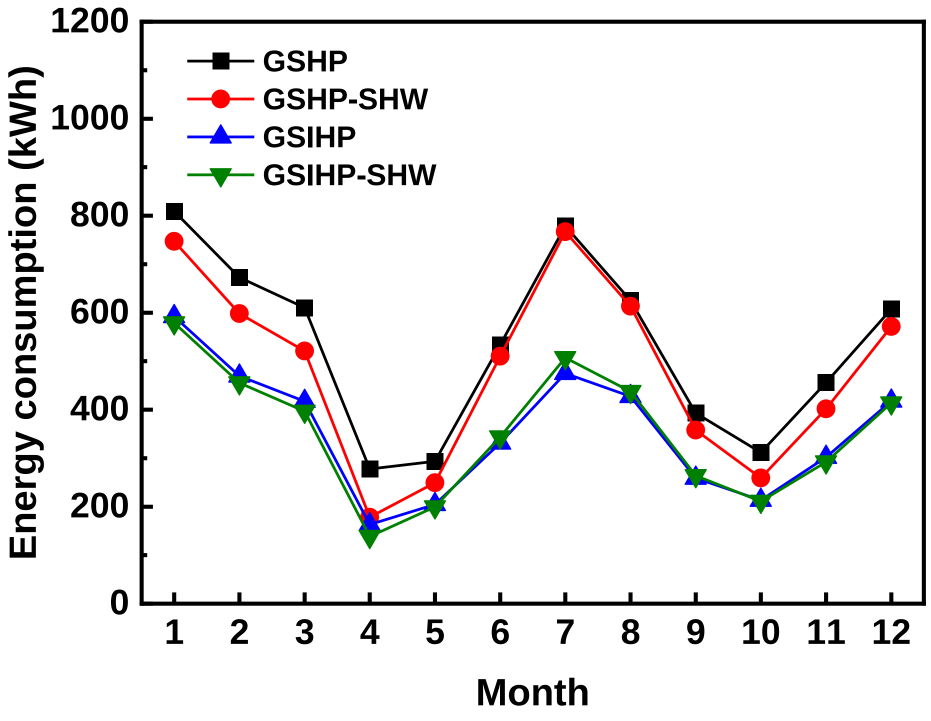


*HC = Heating & Cooling

Results: Solar Hot Water

- For GSHP + HPWH, SHW reduces DHW energy by 40 %
  - Reduces monthly winter thermal loads by ≈ (50 to 100) kWh
- For GS-IHP, SHW saves minimal energy





Future work

1. Use TRNSYS model to GHX sizing methods for GS-IHPs
2. Troubleshoot high humidity levels in TRNSYS building model (RH up to ≈80%)
3. Laboratory measurements of GS-IHP performance
4. TRNSYS simulations of GS-IHP in alternate climates
5. Test GS-IHP in NIST residential NZEB

End

References

1. Baxter, V.D., 2007. Integrated Heat Pump HVAC Systems for Near-Zero-Energy Homes - Business Case Assessment (ORNL/TM-2007/064).
2. Baxter, V.D., Rice, K., Murphy, R., Munk, J., Ally, M., Shen, B., Craddick, W., 2013. Ground Source Integrated Heat Pump (GS-IHP) Development. Oak Ridge, TN.
3. Murphy, R.W., Rice, C.K., Baxter, V.D., 2007a. Integrated Heat Pump (IHP) System Development: Air-Source IHP Control Strategy and Specification and Ground-Source IHP Conceptual Design.
4. Murphy, R.W., Rice, C.K., Baxter, V.D., Craddick, W.G., 2007b. Ground-Source Integrated Heat Pump for Net-Zero-Energy Houses: Technology Status Report.
5. Murphy, R.W., Rice, C.K., Baxter, V.D., Craddick, W.G., 2007c. Air-source Integrated Heat Pump for Near-Zero Energy Houses: Technology Status Report.
6. Rice, K., Baxter, V.D., Hern, S., McDowell, T., Munk, J., Shen, B., 2013. Development of a Residential Ground-Source Integrated Heat Pump, in: Proceedings of the ASHRAE 2013 Winter Conference. ASHRAE, Dallas, TX.

Abbreviations

ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
CFR	Code of Federal Regulations
COP	Coefficient of Performance
DHW	Domestic Hot Water
DOE	Department of Energy
ELT	Entering Liquid Temperature
GHX	Ground Heat Exchanger
GSHP	Ground-Source Heat Pump
GSHP-VS	Variable-speed GSHP
GS-IHP	Ground-Source Integrated Heat Pump
HC	Heating and cooling
HPWH	Heat Pump Water Heater
HVAC&R	Heating, Ventilating, Air-Conditioning, and Refrigerating
NIST	National Institute of Standards and Technology
NZEB	Net-Zero Energy Building
Q	Capacity
RH	Relative Humidity
SHW	Solar Hot Water
TRNSYS	Transient Systems Simulation tool

Questions?

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Backup slides

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Introduction

NIST

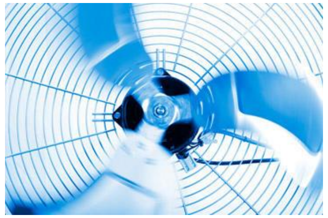
- 2 locations: **Gaithersburg, MD** and Boulder, CO
- 3400 staff, 3800 associates
- Mission: Promote U.S. innovation and competitiveness by advancing measurement science, standards, and technology

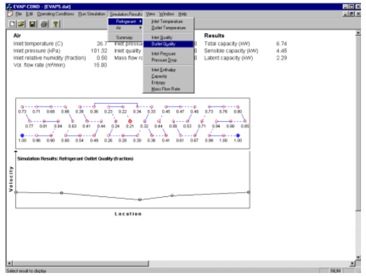
Gaithersburg, MD

Boulder, CO

HVAC&R Equipment Performance Group

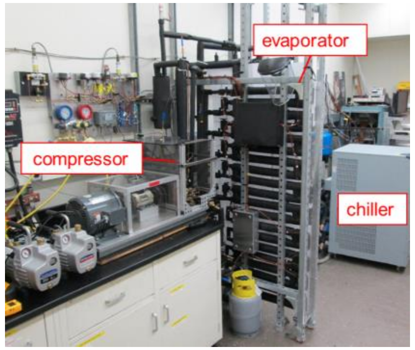
- 13 staff & associates
- Expands scientific knowledge and increase efficiency of HVAC&R technology



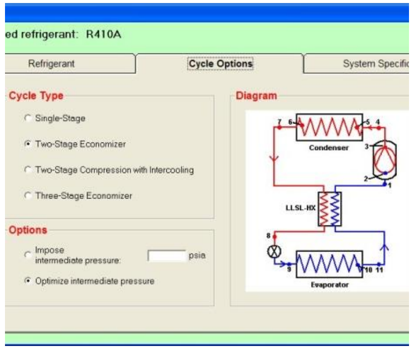


Fault detection and diagnostics

Recent Research

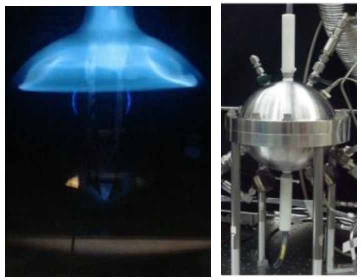


Low GWP refrigerant cycle performance

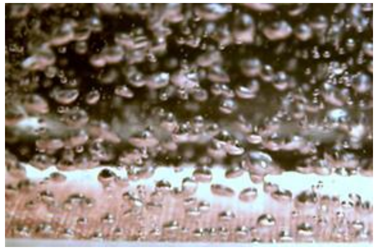


Cycle model software

CO_2 GSHP



Low GWP refrigerant flammability



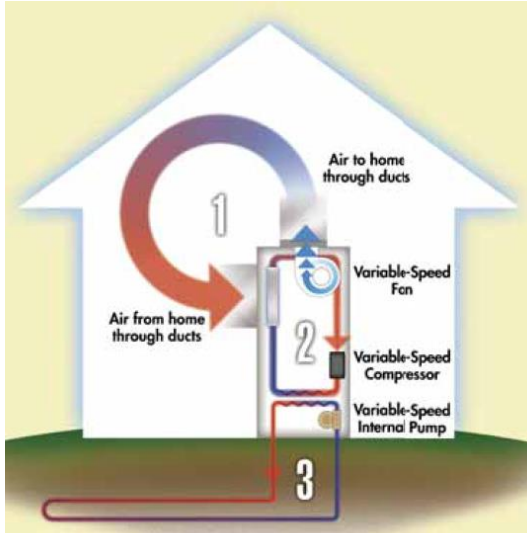
Low GWP refrigerant two-phase heat transfer

Heat exchanger optimization software

Introduction to the GS-IHP

Ground-source Integrated Heat Pump Function

- Provide all space-conditioning & water heating
- High efficiency - COP cooling/heating = 13.2/5.1
- Exchanges heat with favorable temperatures in ground
- Variable speed compressor, fan, pump: 30 % to 100 % capacity
- Recover heat rejected in cooling mode into water tank
- System developed through collaboration with ORNL and OEM



space conditioning

water heating

ORNL reports

Baxter, V.D., 2007. Integrated Heat Pump HVAC Systems for Near-Zero-Energy Homes - Business Case Assessment (ORNL/TM-2007/064).

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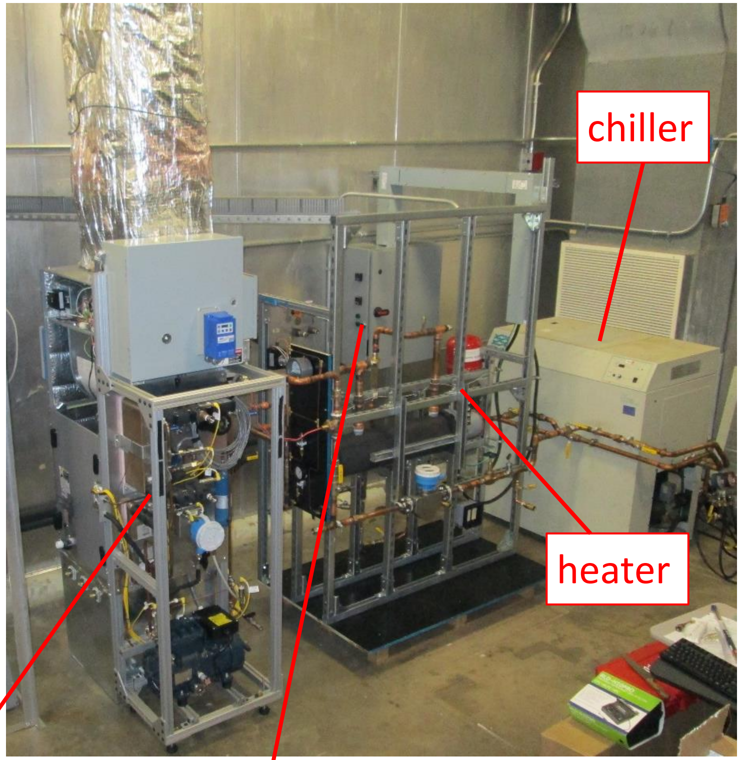
Laboratory Tests

- Environmental chamber with air-enthalpy capacity measurement



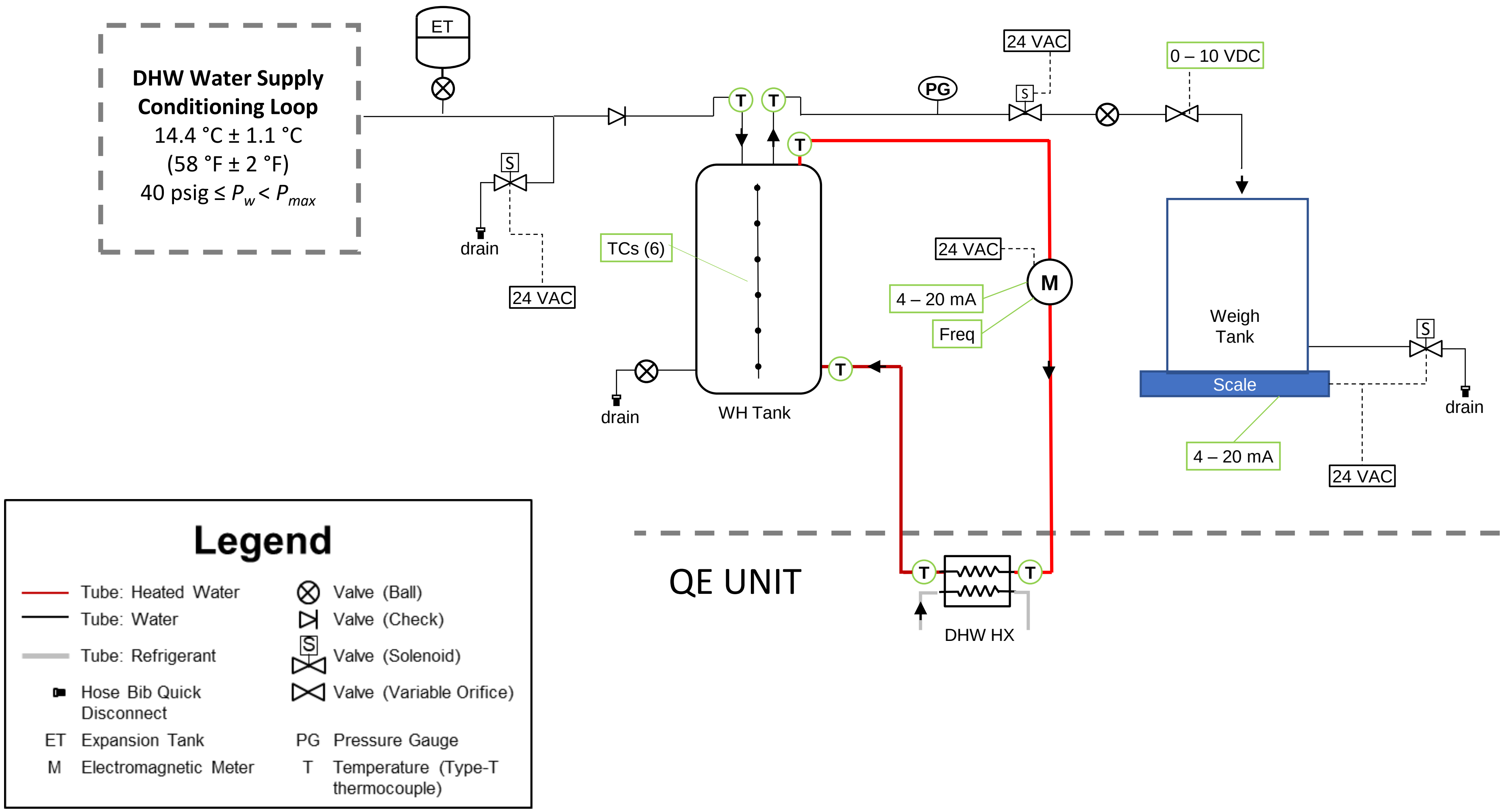
airflow nozzle chamber

GSHP under test

heater control cabinet

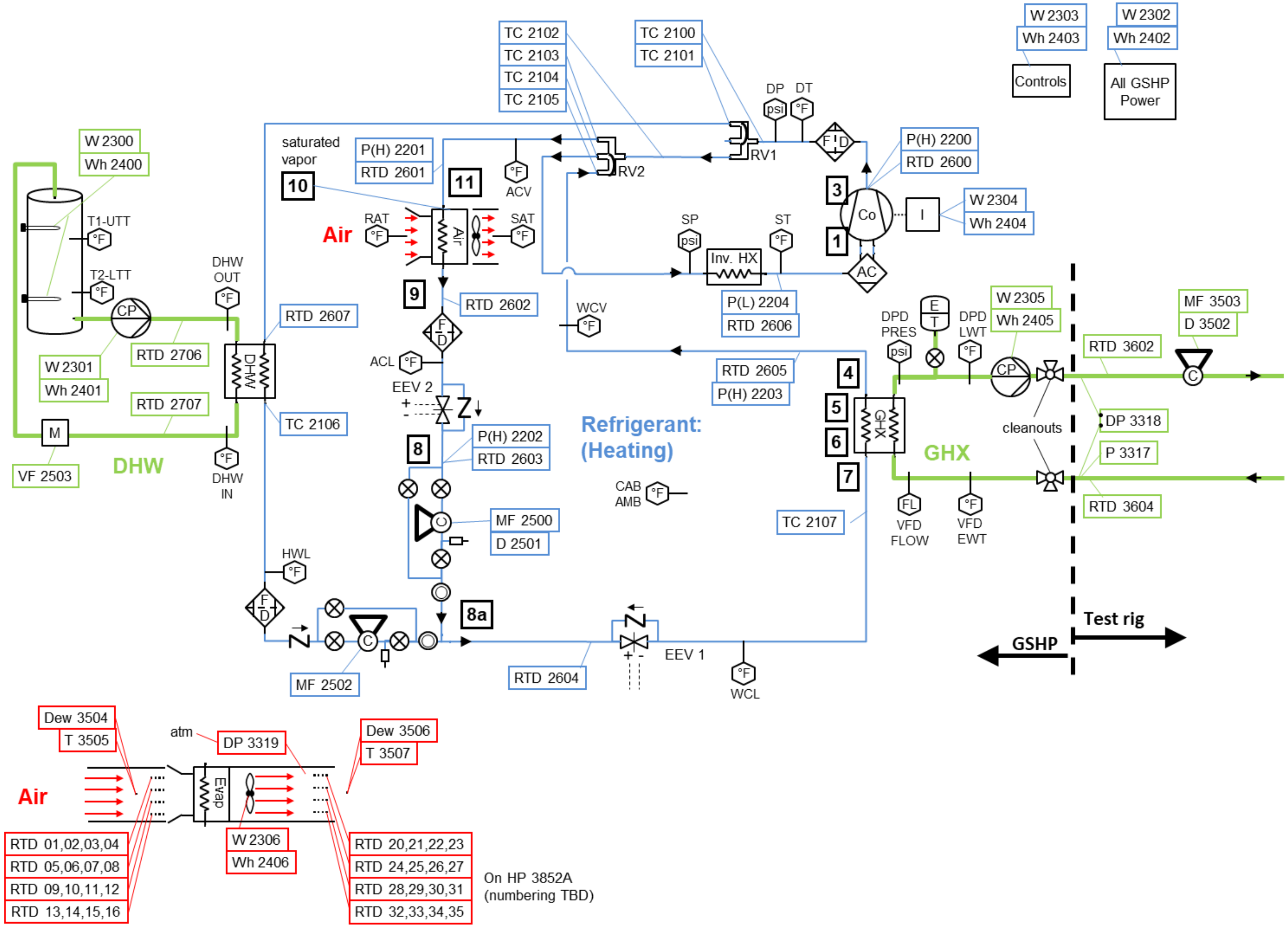
Laboratory Tests

- Currently constructing DHW test facility



GS-IHP Measurements

- Extensive measurements for refrigerant, GHX antifreeze, DHW, air



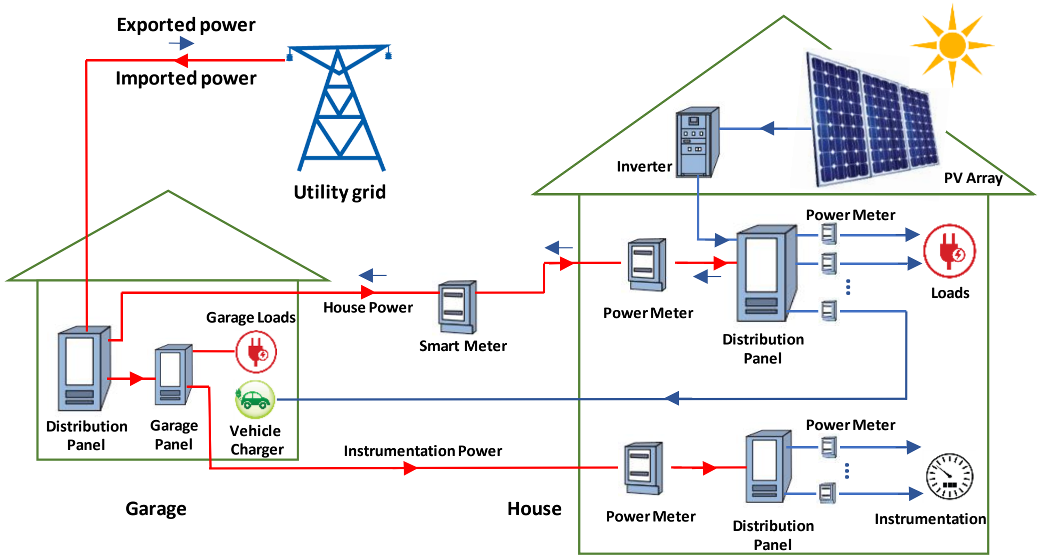
TRNSYS Model: Overview

Purpose

1. Useful for extrapolating lab & field tests to alternate climates.
2. Useful for system sizing & design.

Methods

1. Simulation of Net-zero house in TRNSYS platform.
2. Include multiple modes and variable-speed operation.
3. Performance data based on laboratory tests.
4. Verification by 12-months NZ house field testing.



TRNSYS Model

Model Details[5-9]

Envelope

- Walls: R-7.9 (US R-45)
- Windows: R-0.9 (US R-5.3)
- Roof: R-12.7 (US R-72)

HVAC

- Heat pump
- GSHX (DST model[10])
- Dehumidification
- Mechanical ventilation

Occupants

- Simulated family of 4
- Sensible & latent loads

Hot Water

- Solar hot water
- Heat pump water heater

Weather

- TMY2 - hourly averages[11]
- Drybulb, Dewpoint, Insolation, Wind

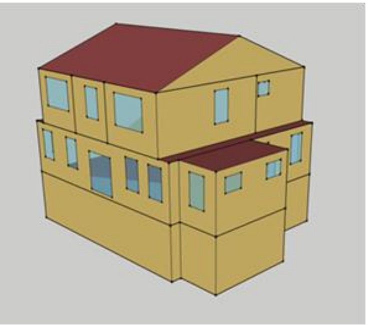
Time

- 1-minute timestep
- 1 year (ASHP)
- 10 years (GSHP)

<u>Area</u>

- Main: 251 m^2 (2701 ft^2)
- Basement: 135 m^2 (1450 ft^2)

NIST NZ house

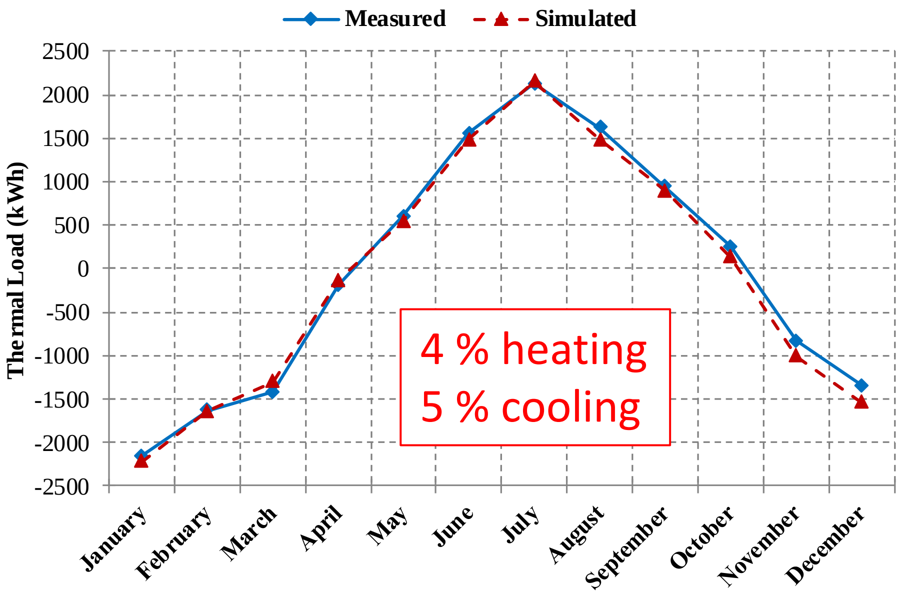


Model

TRNSYS Model: Verification

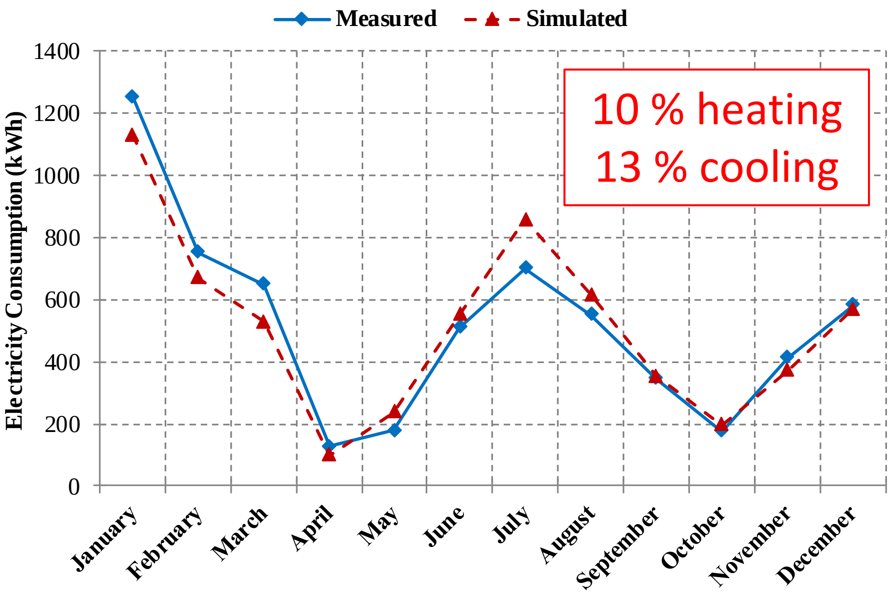
- Model validated using 1 year of data[1,5,7,12] from NIST NZ house in Gaithersburg MD

Validation of building model



monthly building loads

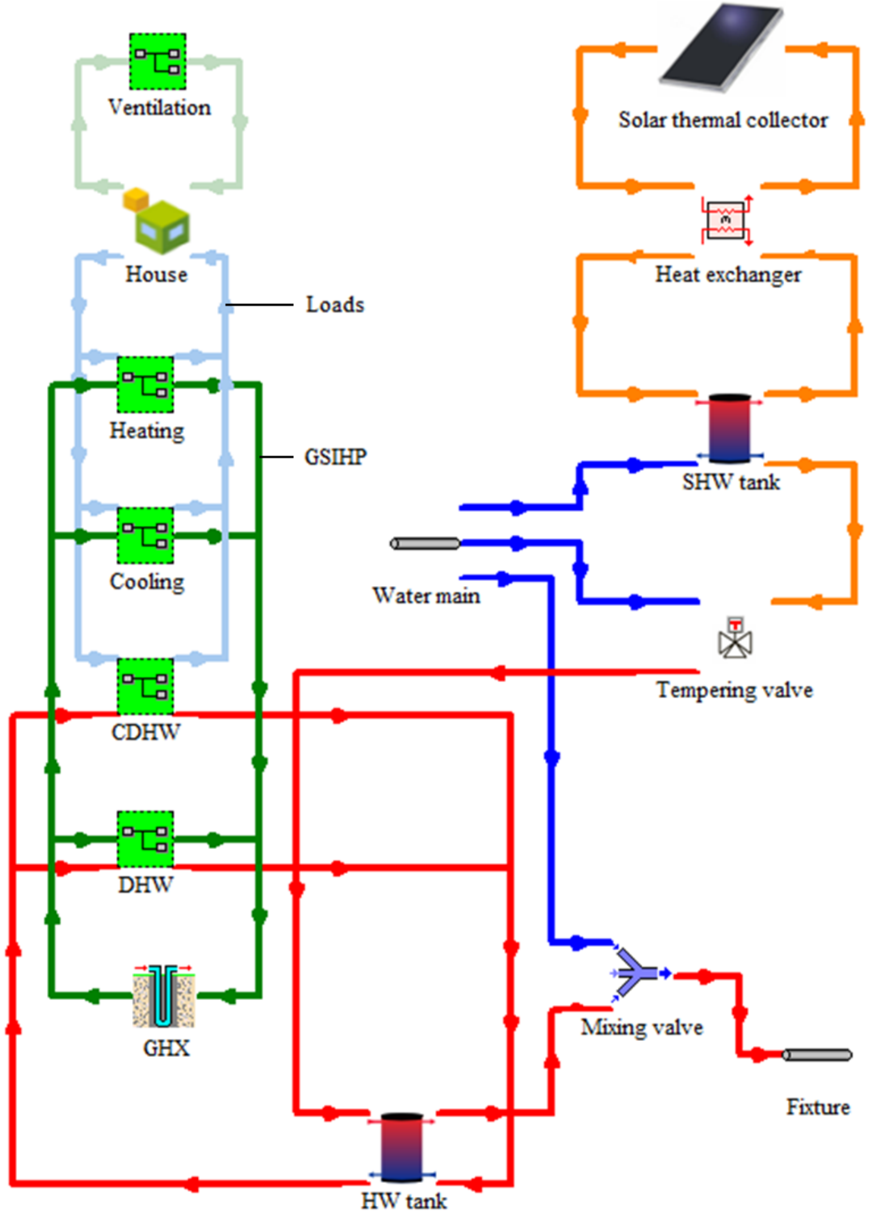
Validation of ASHP model



monthly ASHP electricity

Building Simulations: TRNSYS

(Transient Systems Simulation Tool)



Subsystem	Component	TRNSYS type	Main parameters
Building	Building	Type 56	Living area: 251 m^2 basement area: 135 m^2
	Infiltration	Type 932	Effective leakage area: 244 cm^2
PV	PV array	Type 194b	Module area: 32 × 1.472 m^2 orientation: south Tilt angle: 18.4° maximum power: 10.24 kW DC
HRV	Heat recovery	Type 667b	Outdoor air: 195 $m^3\ h^{-1}$ defrost temperature trigger: −10 °C Sensible effectiveness: 0.72 latent effectiveness: 0.01
GSIHP	Heating Performance map	Type 581b	Input: $T_{a,in}$, $T_{liq,in}$, Q Output: $T_{liq,out}$, m_{liq}, P
	Cooling Performance map	Type 581b	Input: $T_{a,in}$, $T_{liq,in}$, Q Output: $T_{liq,out}$, m_{liq}, Q_{sen}, P
	CDHW Performance map	Type 581b	Input: $T_{a,in}$, $T_{liq,in}$, Q Output: $T_{liq,out}$, m_{liq}, Q_{sen}, P
	DHW Performance map	Type 581c	Input: $T_{liq,source,in}$, $T_{liq,load,in}$ Output: $T_{liq,source,out}$, $T_{liq,load,out}$, Q_{source}, Q_{load}, P
	HW tank	Type 534	Volume: 0.189 m^3 height: 1.454 m Loss coefficient: 0.6 W $m^{-2}\ K^{-1}$
SHW	Solar collector	Type 1b	Collector area: 2.1 m^2 intercept efficiency: 0.744 1st order efficiency coefficient: 3.6707 W $m^{-2}\ K^{-1}$ 2nd order efficiency coefficient: 0.00543 W $m^{-2}\ K^{-1}$
	SHW tank	Type 534	Volume: 0.2953 m^3 height: 1.5939 m Loss coefficient: 1 W $m^{-2}\ K^{-1}$
	Heat exchanger	Type 91	Heat exchanger effectiveness: 0.44
	Pump	Type 114	Rated flow rate: 196 kg h^{-1} glycol, 999 kg h^{-1} water Rated power: 80 W glycol, 80 W water
Ground loop	GHX	Type 557	Number of bores: 2 Effective borehole radius: 4.88 cm borehole depth: 45 m borehole spacing: 6.4 m tube center to center: 6.83 cm Tube diameter: 2.54 cm inner, 3.30 cm outer Tube conductivity: 0.45 W $m^{-1}\ K^{-1}$ Soil conductivity: 2.43 W $m^{-1}\ K^{-1}$ Soil heat capacity: 2549 kJ $m^{-3}\ K^{-1}$ Fill conductivity: 0.727 W $m^{-1}\ K^{-1}$ Fluid density: 980.7 kg m^{-3} Fluid specific heat: 4.396 kJ $kg^{-1}\ K^{-1}$

Testing GS-IHP in NIST Net-zero house

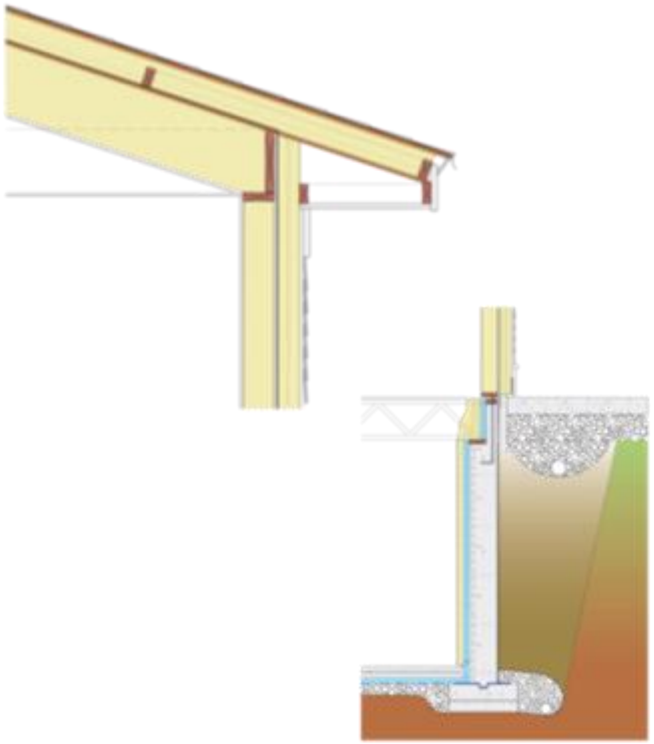
- GS-IHP testing for 12 months in NZ house
- GS-IHP will provide all heating, cooling, and water heating
- Data used to tune & verify TRNSYS model

Testing GS-IHP in NIST Net-zero house

House: by the numbers

- Type: Single-Family
- Stories: 2
- Bedrooms: 4
- Baths: 3
- Floor Area: 251 m^2
- Basement Area: 135 m^2
- Smart Grid Ready
- Electric Vehicle Ready
- Four-Member Family (emulated)

Testing GS-IHP in NIST Net-zero house



Basement Wall Cross Section

Enclosure Design

- Roof Insulation R-12.7 (Typical R-6.7)
- Walls R-7.9 (Typical R-2.3)
- Windows R-0.9 (Typical R-0.5)
- Rim Joist Area R-6.2 (Typical R-2.3)
- Basement Walls R-4.1 (Typical R-2.3)
- Basement Slab R-1.8 (Typical R-1.8 Two Foot In from Perimeter)

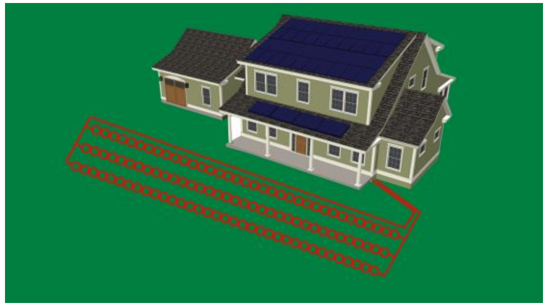
Typical values taken from 2009 International Energy Conservation Code Climate Zone 4

Testing GS-IHP in NIST Net-zero house

Vertical borehole

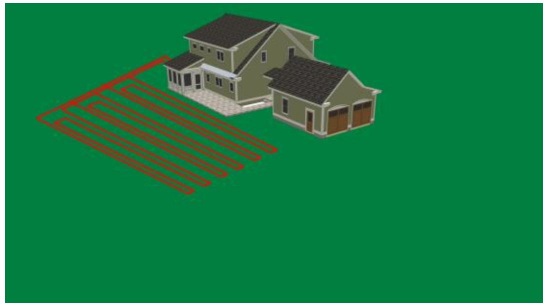
3 parallel circuits
6.1 m spacing
45.1 m deep

Horizontal slinky



3 parallel circuits
Trenches are 1.5 m wide and deep
3 m spacing, 1.8 m loop pitch
39.6 m length per trench

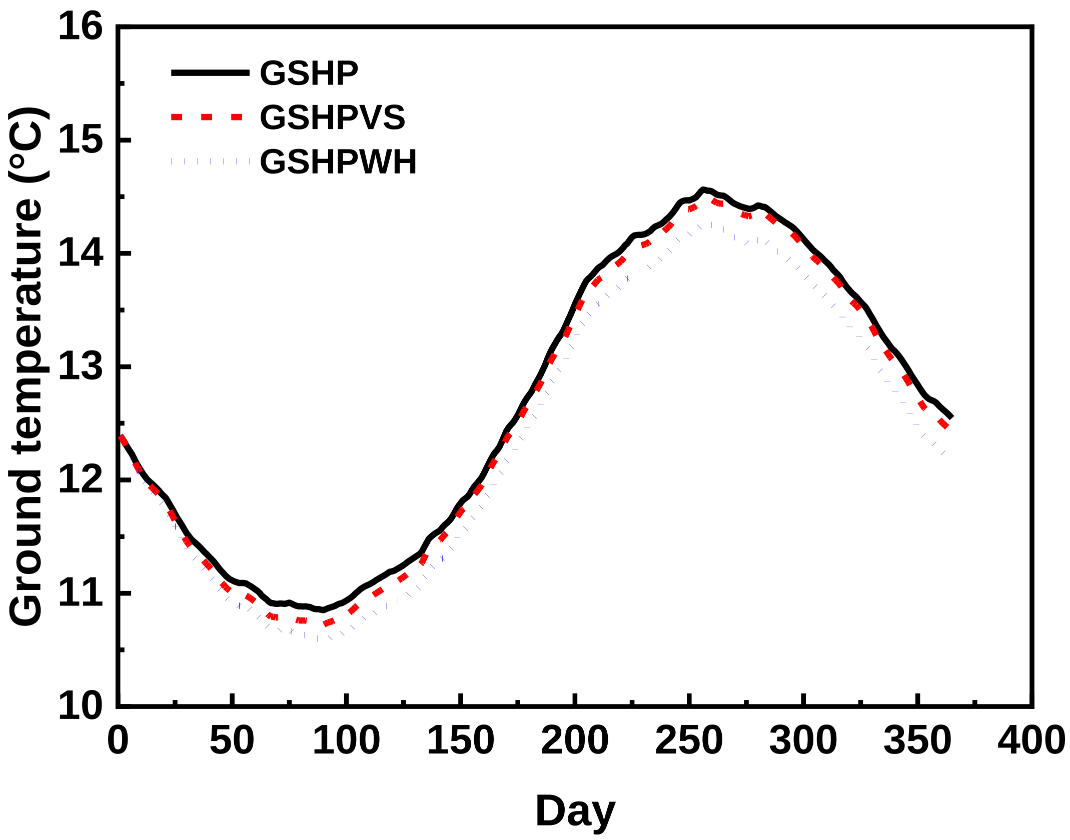
Horizontal U-tube



3 parallel circuits
Each circuit uses 2 trenches
Trenches are 34.1 m long and 1.8 m deep
3 m spacing between loops

Results: Ground Temperature

- GS-IHP shows lower ground temperature due to more utilization of ground source for both space heating and DHW.



GSIHP Control Logic

Mode	Setpoint (°C)	Deadband (°C)	Capacity (%)	Cutout offset (°C)	Cutout capacity (%)
Heating	20.5	0.2 1.1 (aux)	30	0.6	90
Cooling	23.9	0.2	30	0.6	100
CDHW	23.9 (cooling) 48.9 (DHW)	0.2 (cooling) 8.3 (DHW)	30	–	–
DHW	48.9	8.3	> 70 (high) ≤ 70 (low)	–	–

Energy Consumption – GSHP Options

Item	GSHP	GSHPVS	GSIHP
Heating (kWh)	2432	2007	1840
Heating standby (kWh)	156	123	115
Cooling (kWh)	570	354	378
CDHW (kWh)	0	0	81
Dehumidification (kWh)	1454	1154	1054
Cooling standby (kWh)	74	66	56
Total heating (kWh)	2587	2130	1955
Total cooling (kWh)	2098	1575	1569
Total heat pump (kWh)	4685	3705	3524
Annual COP	3.16	4.08	4.15

Item	GSHP	GSHPVS	GSIHP
DHW (kWh)	1684	1687	748
Heat pump (kWh)	4685	3705	3524
Ventilation (kWh)	450	450	450
Lighting + plug + appliance (kWh)	4801	4801	4801
Total consumption (kWh)	11620	10643	9523
PV generation (kWh)	14142	14142	14142
Net generation (kWh)	2522	3500	4619

Energy Consumption – GHX Design

Item	L = 30 m	L = 35 m	L = 40 m	L = 45.1 m	L = 50 m	L = 55 m	L = 60 m
Heating (kWh)	2047	1957	1890	1840	1802	1770	1745
Heating standby (kWh)	115	115	115	115	115	115	115
Cooling (kWh)	520	452	407	378	356	338	323
CDHW (kWh)	82	81	83	81	81	81	81
Dehumidification (kWh)	1177	1122	1087	1054	1035	1020	1010
Cooling standby (kWh)	55	56	56	56	57	57	57
Total heating (kWh)	2162	2071	2005	1955	1917	1885	1860
Total cooling (kWh)	1835	1710	1634	1569	1528	1496	1471
Total heat pump (kWh)	3997	3782	3639	3524	3444	3381	3331
Annual COP	3.63	3.85	4.01	4.15	4.25	4.34	4.41

Item	L = 30 m	L = 35 m	L = 40 m	L = 45.1 m	L = 50 m	L = 55 m	L = 60 m
DHW (kWh)	804	780	760	748	738	730	724
Heat pump (kWh)	3997	3782	3639	3524	3444	3381	3331
Ventilation (kWh)	450	450	450	450	450	450	450
Lighting + plug + appliance (kWh)	4801	4801	4801	4801	4801	4801	4801
Total consumption (kWh)	10051	9812	9649	9523	9433	9362	9306
PV generation (kWh)	14142	14142	14142	14142	14142	14142	14142
Net generation (kWh)	4091	4330	4493	4619	4709	4780	4836