BUILDINGS ENERGY EFFICIENCY CONSORTIUM

U.S. - CHINA CLEAN ENERGY RESEARCH CENTER (CERC-BEE)

Advance Ground Source Heat Pump Technology for Very Low Energy Buildings

U.S. and China Research Lead(s): Xiaobing Liu (ORNL), Jianlin Wu (CABR), Shilei Lu (TJU)

U.S. and China Industry Partner(s): ClimateMaster

YEAR 4 JOINT ANNUAL MEETING

Berkeley California

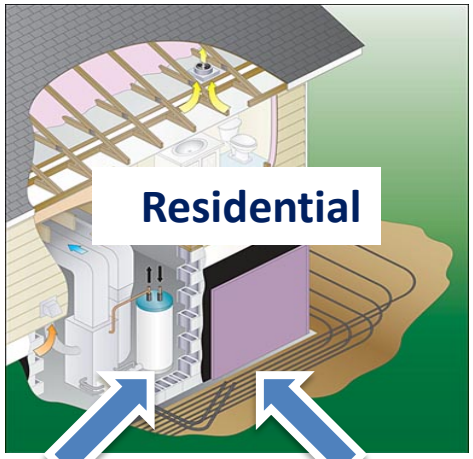
Presented By Xiaobing Liu, Ph.D.

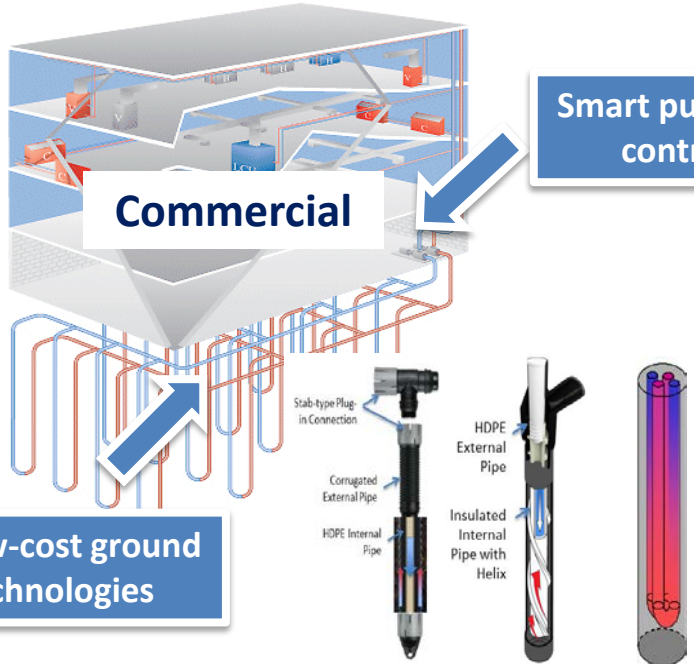
Oak Ridge National Laboratory

25, August, 2014

Purpose and Objective

- Exchange best practices of GSHP applications in US and China, and advance GSHP technology in a targeted manner to reduce cost and improve performance





Smart pumping control

Integrated heat pump with efficient hot water generation

Alternative low-cost ground coupling technologies

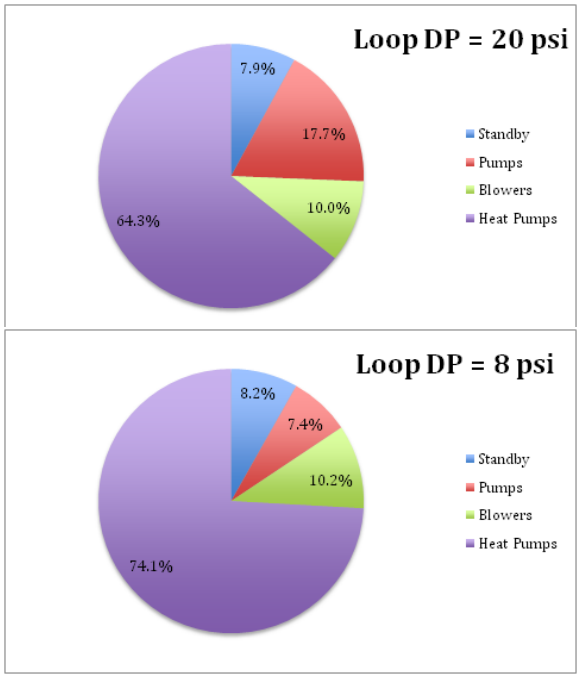
Progress and accomplishments on Year 4 Milestones, Target Outcomes

- Two invention disclosures were submitted: 1) A Virtual-Sensing-Enabled Low-cost Monitoring System for Distributed GSHP (DGSHP) Systems, and 2) Smart Pumping Control for Hydronic Distribution Systems
- Two technical papers were published
  - Liu, X., R. Beier, M. Anderson, and G. Ewbank, 2014. "Field test and evaluation of residential ground source heat pump systems using emerging ground coupling technologies", 2014 IEA Heat Pump conference, Montreal, Canada.
  - Southard, L., X. Liu, and J. Spitler, 2014. Performance of the HVAC Systems at the ASHRAE Headquarters Building, Part 1: Measured Energy Usage. ASHRAE Journal, September, 2014
- ClimateMaster GSHP units were installed and are operating at CABR demo
- A CRADA is signed with ClimateMaster for smart tank and pump control
- Test facilities are designed and under construction: 1) Apparatus for lab test of smart tank at ClimateMaster, and 2) Test bed for distributed GSHP systems at ORNL

Key Year 4 Technical Achievement

Analyzed performance of a DGSHP system at ASHRAE HQ

- Analyzed 166 sub-hourly data points for 2 years (July 2011-June 2013) in collaboration with a team at OSU
- Developed and validated a new method to determine heating/cooling outputs and associated power draws of each GSHP unit in the DGSHP system
- Calculated each end-use energy of the DGSHP system and determined the system efficiency
- Evaluated the impacts of various differential pressure (DP) setpoint on pumping power consumption

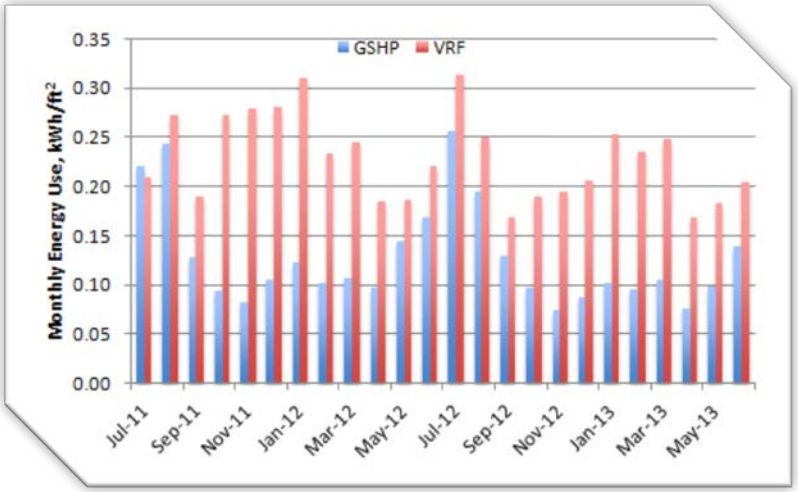


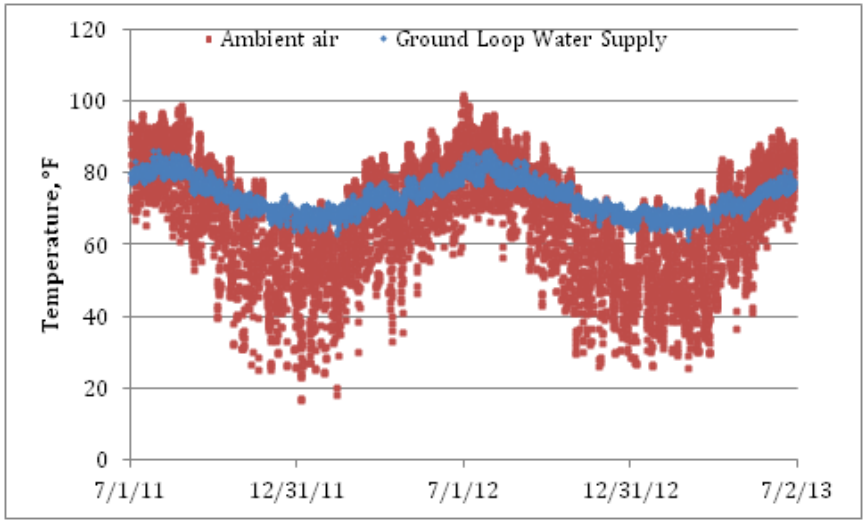
	Heating	Cooling
Heating/Cooling Provided, MWh	28.97	142.45
Power Consumed by Heat Pumps, MWh	5.66	27.66
Heat Pump COP	5.12	5.15
Heat Pump EER, Btu/Wh		17.57
Additional power for parasitic loads, pumps and blowers, MWh	2.18	12.13
System COP	3.70	3.58
System EER, Btu/Wh		12.22

Low DP reduced pumping power use by ~60%, but resulted in frozen at a heat pump due to insufficient flow in heating mode → DP needs to be optimized, or even better, adjusted automatically with varying flow rate

Key Year 4 Technical Achievement

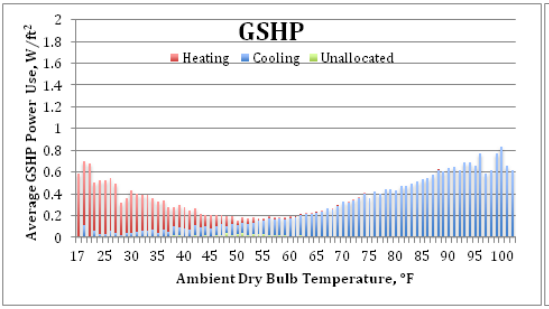
Compared performance between the GSHP and VRF systems at ASHRAE HQ

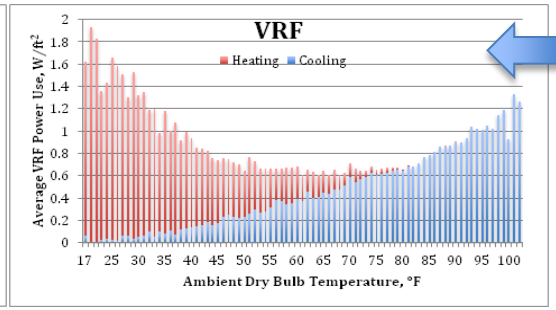




The DGSHP system used 44% less energy than the VRF system for similar building loads and room temperatures

Ground has more favorable temperature than ambient air for heat pump operation





Control strategy of the VRF system resulted in conflicting simultaneous heating and cooling in adjacent zones, which increased energy consumption

ASHRAE Journal Article

TECHNICAL FEATURE

Part One

Performance of HVAC Systems at ASHRAE HQ

BY L. E. SOUTHARD, P.E., ASSOCIATE MEMBER ASHRAE, XIAOBING LIU, PH.D., MEMBER ASHRAE AND J. D. SPITLER, PH.D., FELLOW ASHRAE

When ASHRAE headquarters in Atlanta was renovated in 2008, one goal was to create a living lab that could be accessed by members to learn about commercial building

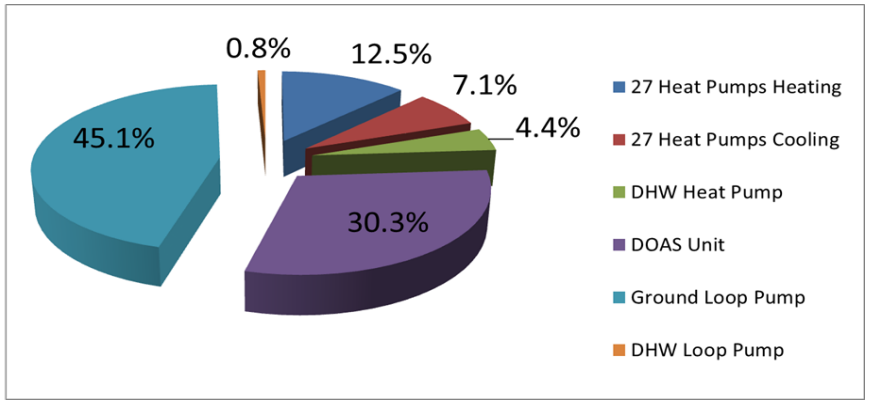
Part one is available in September 2014 issue, and one more will be in a later issue

Key Year 4 Technical Achievement

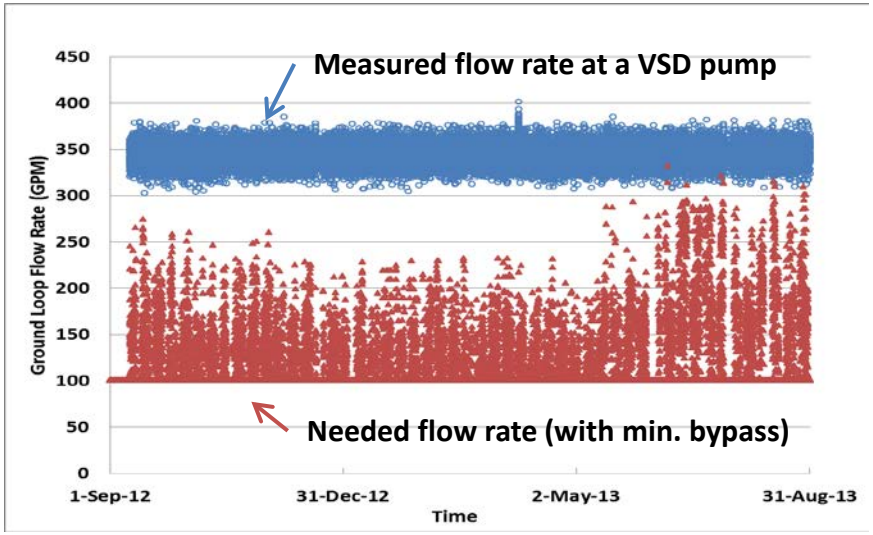
Indentified common issues in pumping control

- Pumps consume more than expected energy in many existing GSHP systems due to:
  - Continuous operation and excessive pumping, especially at low or no load conditions
  - Non-optimal and fixed DP setpoint for VSD pump control
  - Misconception in applying primary-and-secondary loop control
- Excessive pumping adds more heat to GHXs and reduces system efficiency in cooling dominated applications

Pumping power can be reduced by 50% with optimized pumping control



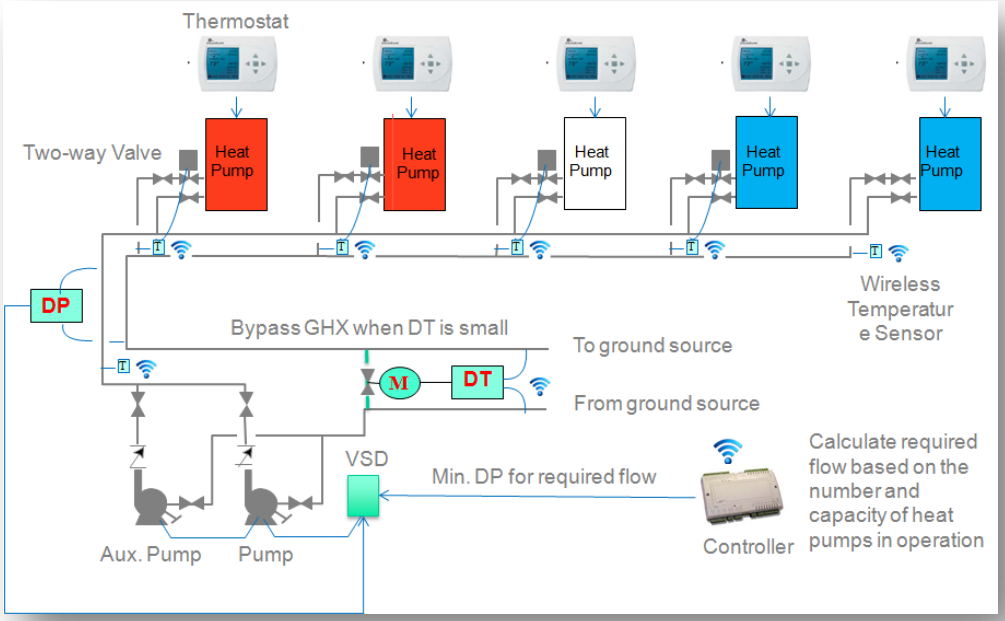
Poorly controlled VSD pumps used more power than heat pumps



Key Year 4 Technical Achievement

Developed smart pumping controls

- Optimize central pumping (for both new and existing systems)
  - Turn off or reduce flow to minimum allowable when no heat pump is on
  - Adjust DP based on flow rate demand and loop resistance characteristics
  - Enable a close-loop control with feedback of differential temperature at water coil to ensure enough water flow at each heat pump
- Apply distributed pumping (for new and small systems)



This pumping control system can be further developed to monitor system/equipment performance and perform fault detection and diagnostics

An invention disclosure for the smart pumping control has been submitted to ORNL

Estimated CO2/Energy Savings

	Technical potential for GSHP	Existing conventional HVAC
Conditioned floor space [Million SF]	4,806 [a]	11,461 [b]
Normalized pump power use [kWh/SF]	0.7 [c]	0.5 [c, d]
Annual pumping power use [Million kWh]	3,353	5,484
Percentage of reduction [%]	50% [e]	50% [e]
Annual electricity savings [Million kWh]	1,676	2,742
Annual source energy savings [Trillion BTU] f	19.3	31.5
Annual carbon emission reduction [Million Mt] f	1.3	2.1
Total annual source energy savings [Trillion BTU]	**50.8**	
Total annual carbon emission reduction [Million Mt]	**3.4**	

a) Assuming 10% of the floor space in U.S. commercial buildings (2010 Building Energy Data Book)

b) U.S. commercial buildings conditioned floor space by central VAV, central FCU, and central CAV systems (2010 Building Energy Data Book), which have pumping power consumption

c) Circulation pump energy intensity of distributed GSHP systems is estimated based on the ASHRAE HQ study and other case studies for existing GSHP systems (Liu et al. 2013, 2014)

d) Circulation pump energy intensities for central VAV and central CAV (2010 Building Energy Data Book)

e) Estimated based on the ASHRAE HQ study and other case studies for existing GSHP systems (Liu et al. 2013, 2014)

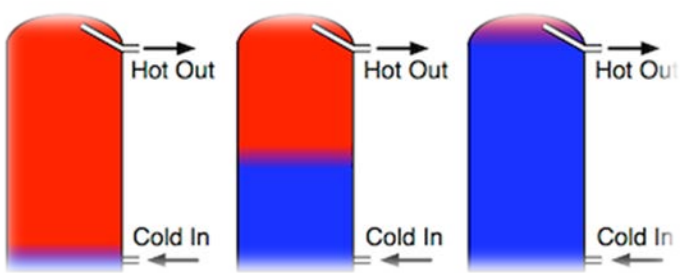
f) Calculated based on electricity savings and conversion factors presented in a NREL report (Deru and Torcellini 2007)

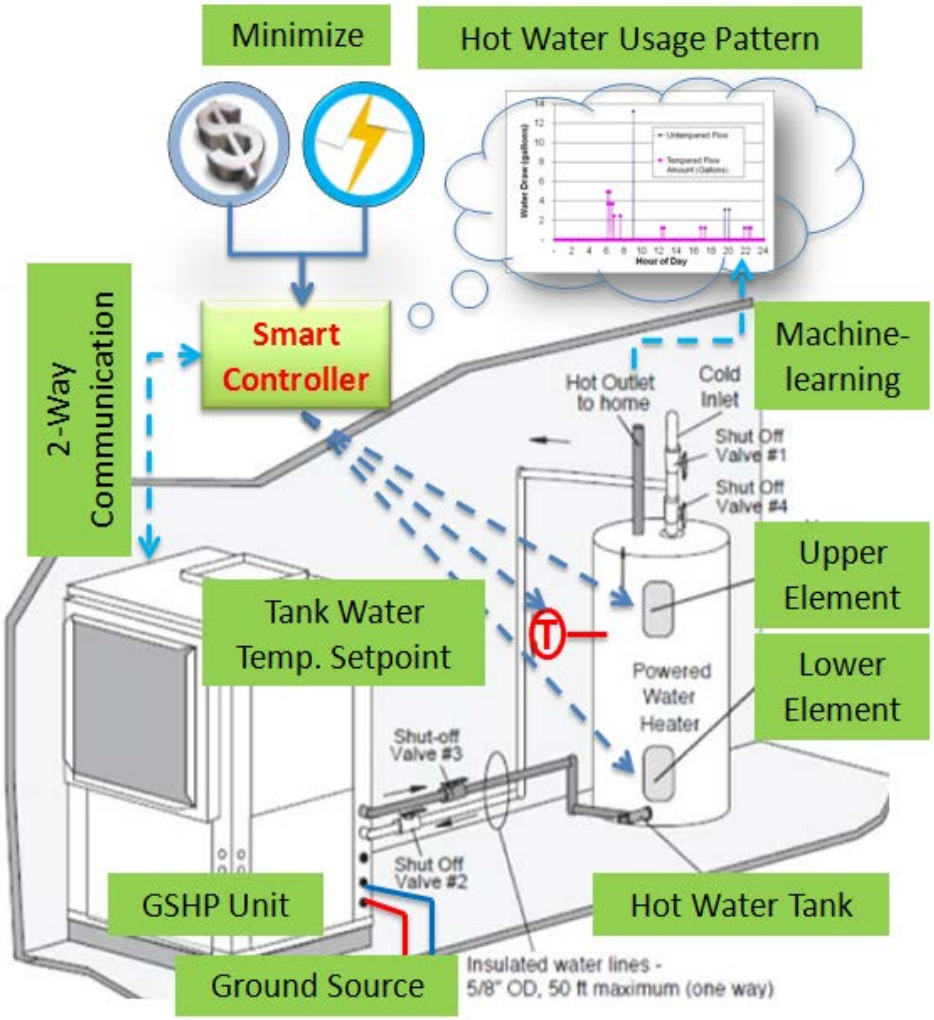
Key Year 4 Technical Achievement

Investigated controls for hot water tank

Minimize energy cost or peak electric demand while delivering needed hot water by:

- Optimizing tank water temperature schedule based on learned pattern of hot water usage
- Maximizing tank thermal stratification to improve heat pump efficiency and reduce heat loss

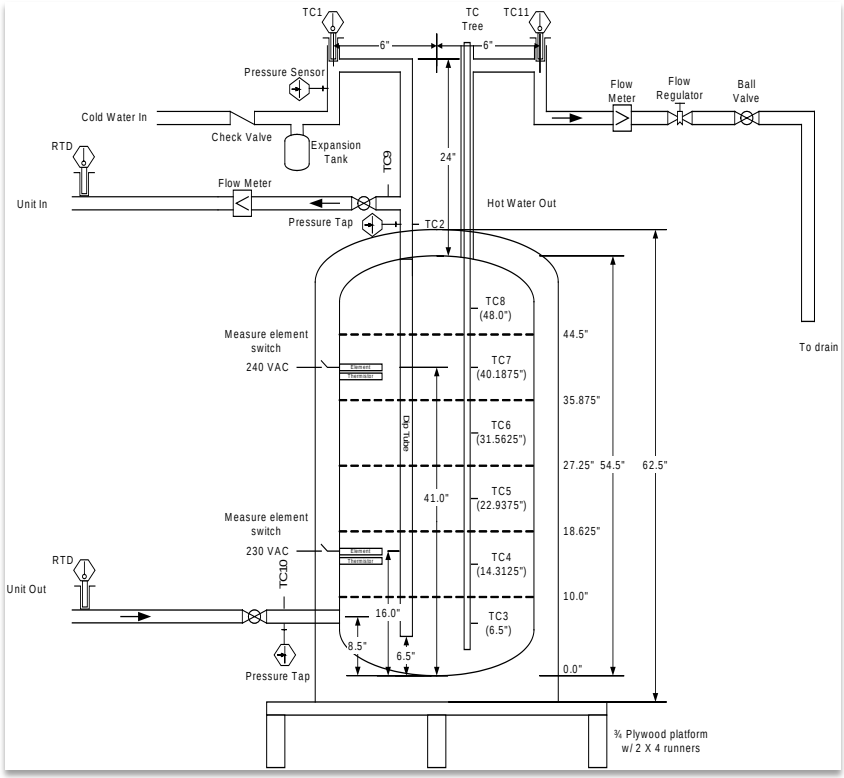




Key Year 4 Technical Achievement

Designed lab test apparatus for testing hot water tank tied with either the integrated GSHP unit (GS-IHP) or the two-stage GSHP unit (with desuperheater)

Smart tank

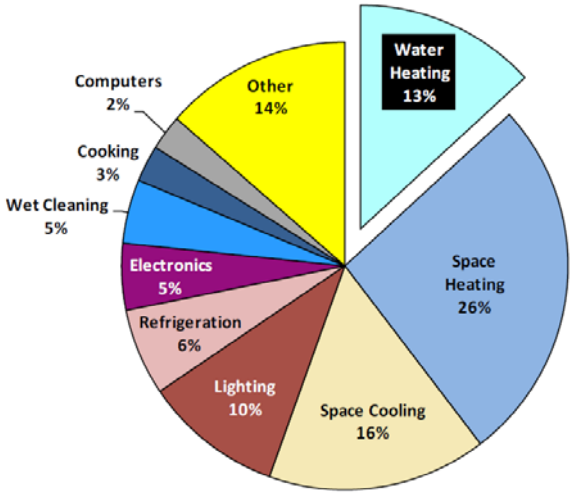


Piping connections and sensor locations for hot water tank lab test

Smart tank tied with a heat pump

Estimated CO2/Energy Savings

- Heat pump water heaters (HPWH) use 50% less power than electric water heaters, which account for ~50% current water heating market in the US
- Energy Conservation Standards for Residential Water Heaters require residential electric storage water heaters (> 55 gallons) to have an energy factor greater than 2 after April 2015
- **Estimated annual savings of 83 trillion BTU primary energy (5.5 million ton CO_2 emission reductions)** from 10% efficiency gain from smart tank (assuming HPWH replaces all electric storage water heater)



Annual power use for water heating is 1.66 Quad BTU in US (2010 Building Energy Data Book)

Table 3. Breakdown of Residential Water Heating System Shipments

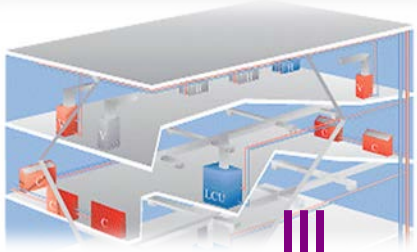
Residential	2009	2010
Gas Storage (Total)	**3,760,657**	**3,918,510**
Not E [17]*	*3,110,419*	*3,463,780*
E-qualifying [18]*	*650,238*	*454,730*
Gas Tankless (Total)[19]	**380,000**	**399,000[20]**
*Not E**	*46,987*	*14,974*
E-qualifying*	*333,013*	*384,026*
Electric Storage (Total)	**3,751,994**	**3,736,597**
Not E [21]*	*3,737,260*	*3,677,472*
E-qualifying (heat pump)[22]*	*14,734*	*59,125*

Source: R&D Roadmap for Water Heating Technologies (Navigant Consulting 2011)

Key Year 4 Technical Achievement

Designed a test bed for DGSHP systems

- First-of-a-kind facility
- Aggressively instrumented
- Multi-zone spaces
- Emulate various ground sources

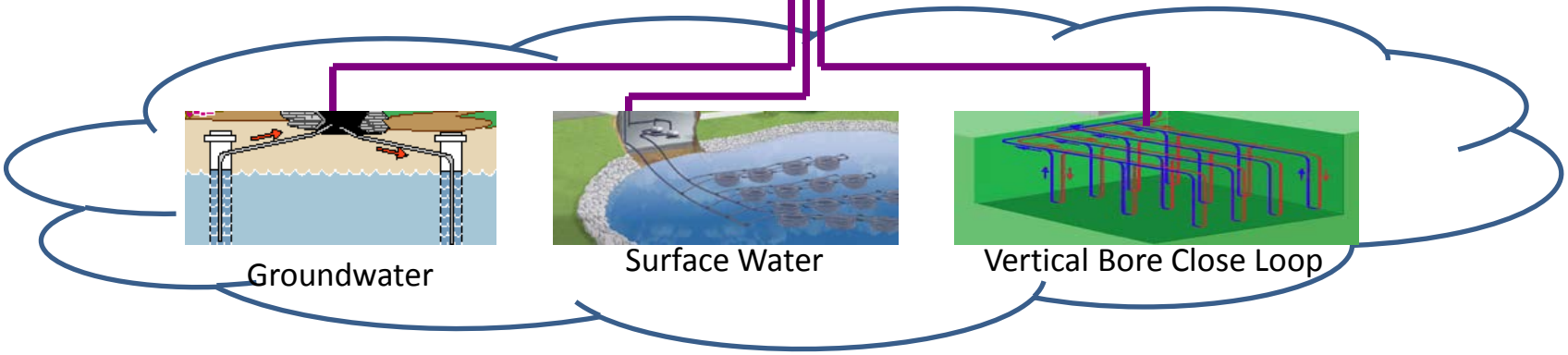


Planned Research in CY 15:

- Field test of the smart tank and pump control
- Validation of system design and simulation tool

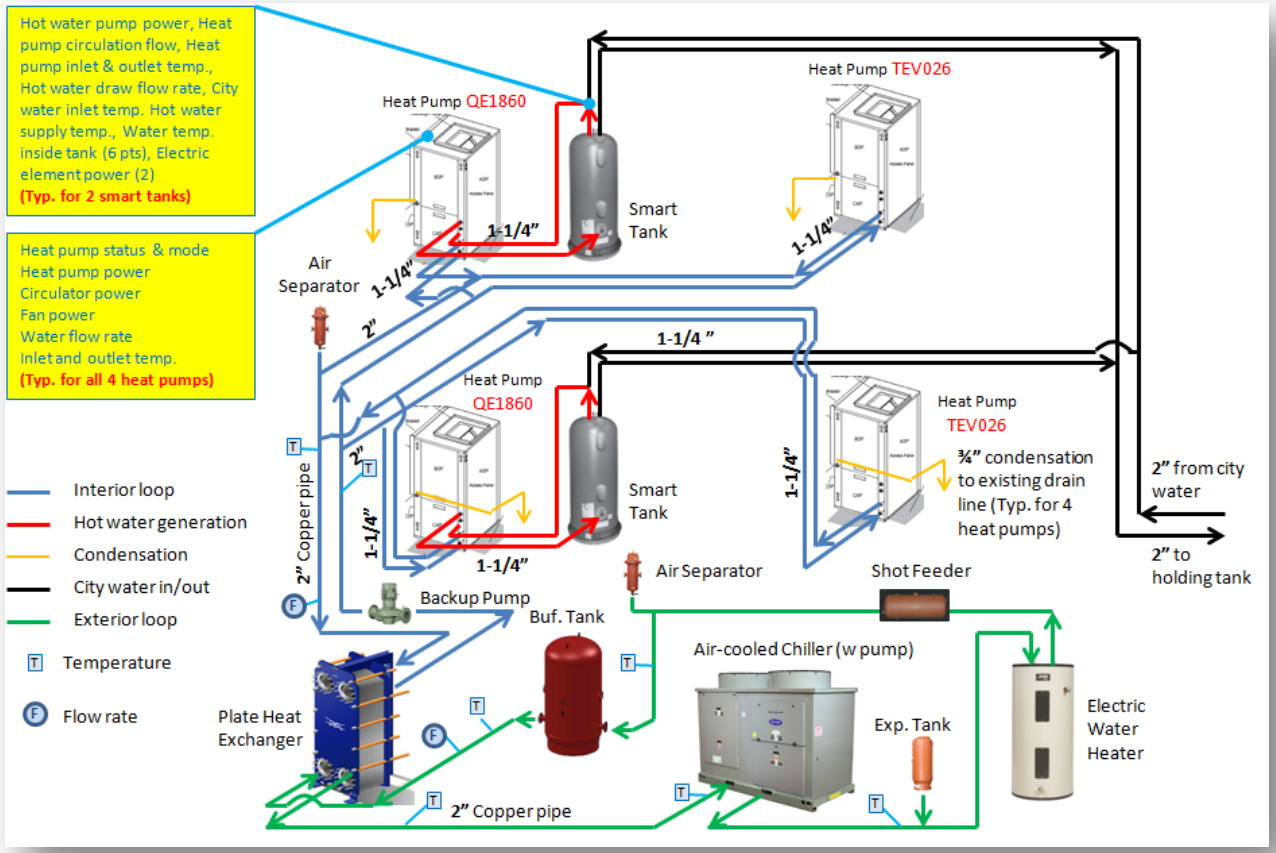
Other issues addressable:

- VRF, rooftop VAV, and GSHP side-by-side comparison
- Validate virtual sensing and energy saving calculation



Key Year 4 Technical Achievement

The test bed is under construction and will be commissioned by the end of CY14



- Equipment and sensors are ordered or have arrived
- Ductwork is nearly completed
- Hydronic piping, equipment installation, data acquisition and control are ongoing

Configuration and Data Collection of the Experimental DGSHP System at ORNL

Schedule and Budget

Schedule for completing Year 4 milestones and target outcomes

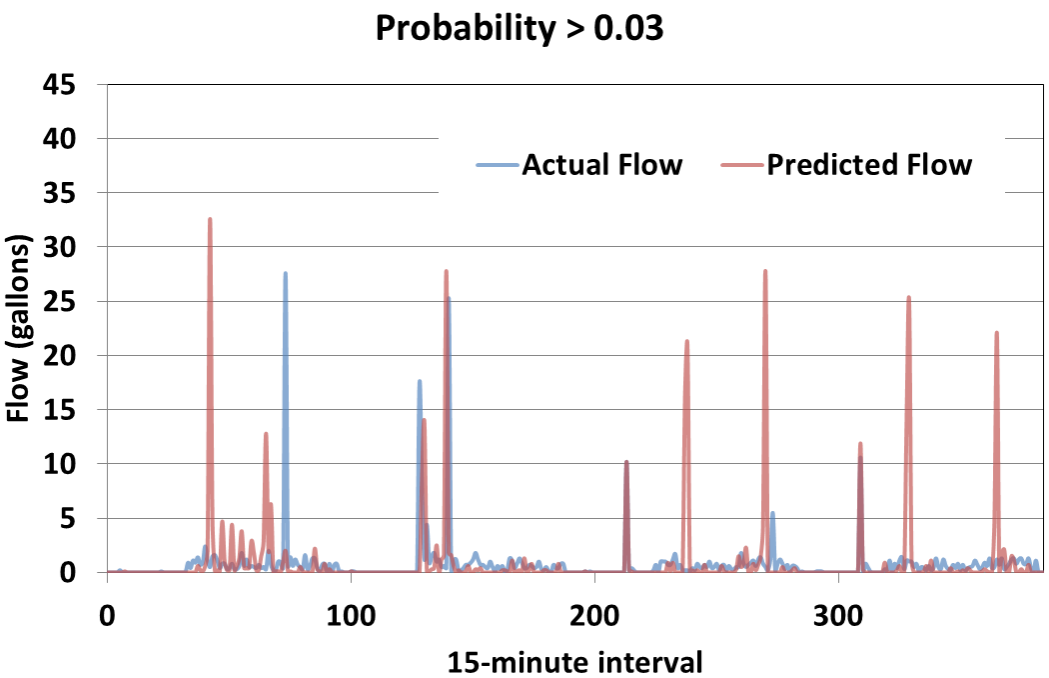
Milestones	CY14 Q1	CY14 Q2	CY14 Q3	CY14 Q4
Promising control for smart tank				
Promising controls for distributed GSHP systems				
Lab test results of smart tank				
Completed design for the test bed of DGSHP systems				
Demonstration(s) of DSHP system in China				

- Scheduled completion time
- Actual completion time
- Projected completion time

Percentage of unspent DOE funds in CY 14: 54%

Issues/risks and Abatement Plans

- Risks and abatement plans:
  - Durability and/or cost of current wireless sensors are not satisfactory for being use in the smart pumping control→ exploring other virtual sensing technologies
  - Accuracy of the existing DHW usage pattern prediction method is not good enough→ explore other machine learning technologies



Example of an existing method for predicting DHW usage pattern (Boudreaux et al. 2014)

Appendix - Proposal for Project Continuation

- Expected outcomes in CY15
  - A fully instrumented and commissioned test bed for DGSHP systems
  - One or more invention disclosures, and potential patent applications, on various aspects of DGSHP system optimal controls
  - Guidelines for improving performance of distributed GSHP systems
  - Technical papers on (1) improved control for hot water tank, (2) smart pumping controls, and (3) performance evaluation of the demonstrated GSHP technologies
- Benefits
  - Enable up to 134 Trillion BTU energy savings (and 8.9 Million Mt avoided carbon emissions) from wider adoption of GSHP systems with improved performance and economic value proposition
- Budget in CY15
  - $350K

Appendix - Budget

Project Budget: DOE/LBL total $825K CY11-14

Cost to Date: ~$658K through August 2014 (CY11-~$132K, CY12-~$175K, CY13-210K, CY14-141K)

Budget History					
CY2011– CY2013 (past)		CY2014 (current)		CY2015 (planned)	
DOE/LBL	Cost-share	DOE	Cost-share	DOE	Cost-share
$610K	$425K	$215K	$350K	$350K	$350K

Cost Share:

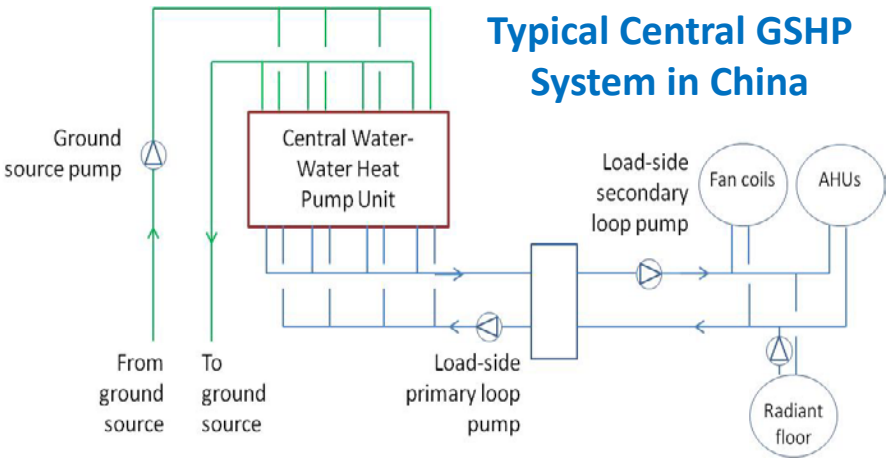
- ClimateMaster: ~$675K through August 2014 (CY11-~$100K, CY12-~$200K, CY13-~125K, CY14-~250K, expecting $350K in CY15)
- GEO: ~$100K

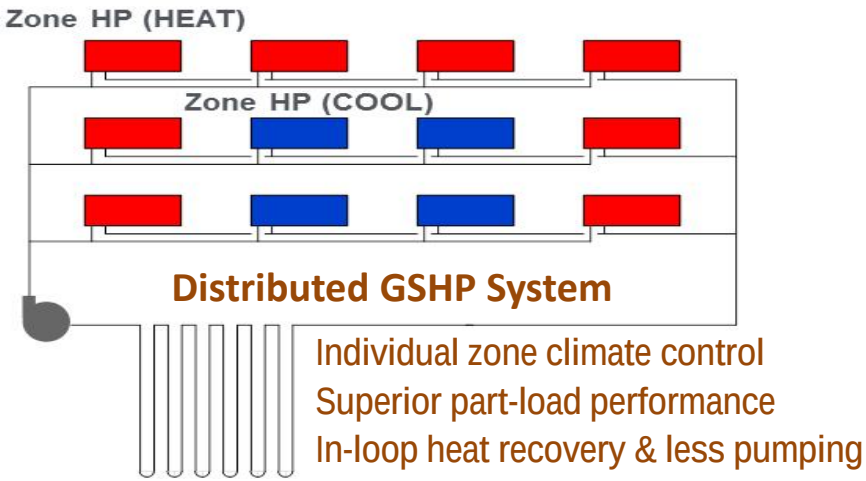
Appendix - Project Plan and Schedule (Qtly)

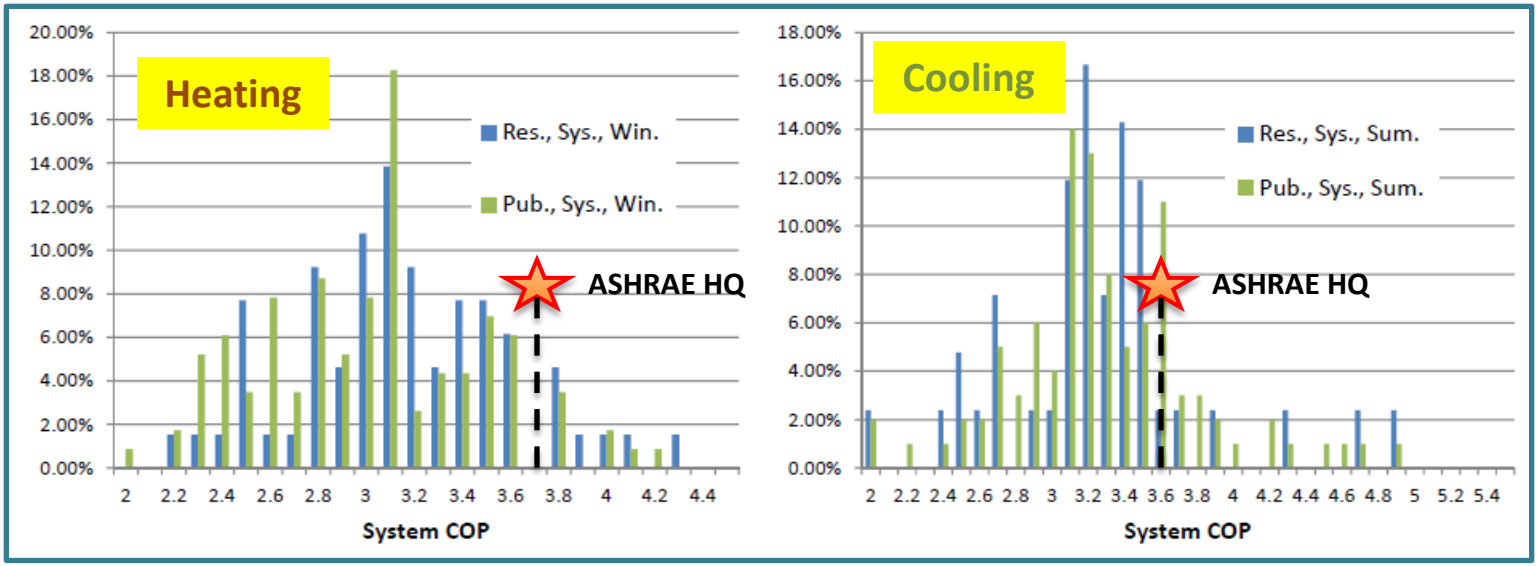
Quarter CY15	Milestones
1	Field tests for smart tank control
2	Implementation of smart pumping control
	Evaluation of GSHP technologies in CABR demo
3	Field tests for smart pumping control
4	Guidelines for improving performance of distributed GSHP systems
	Final reports

Reference Slides

GSHP System Performance Comparison between China and US



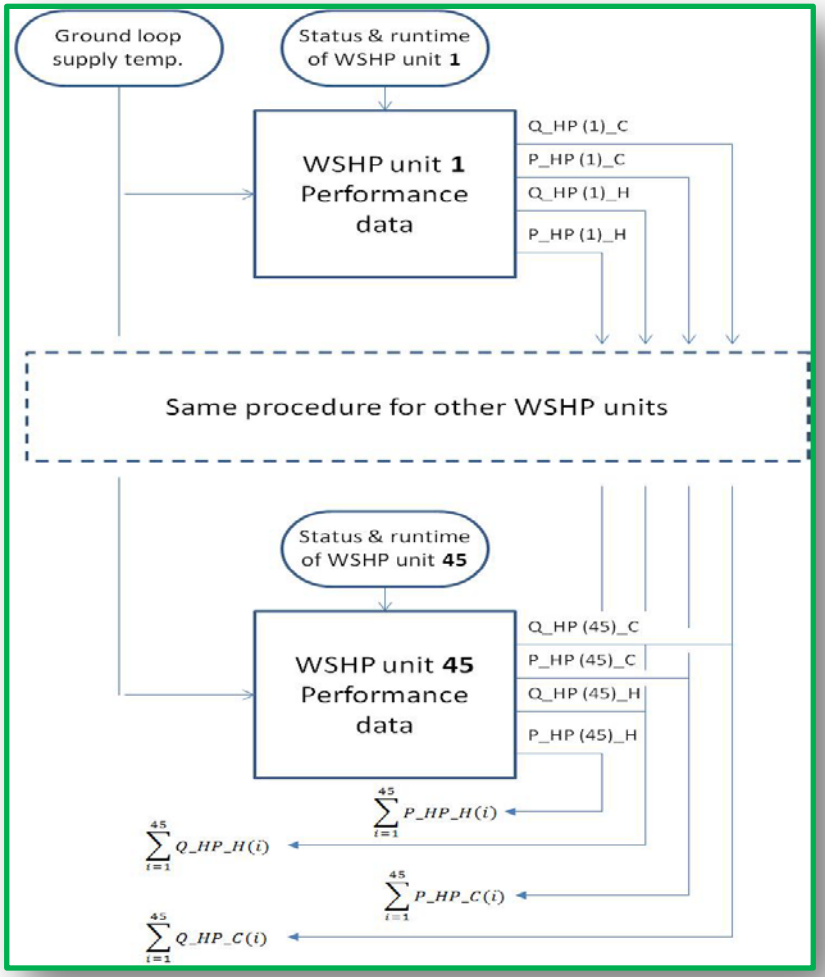




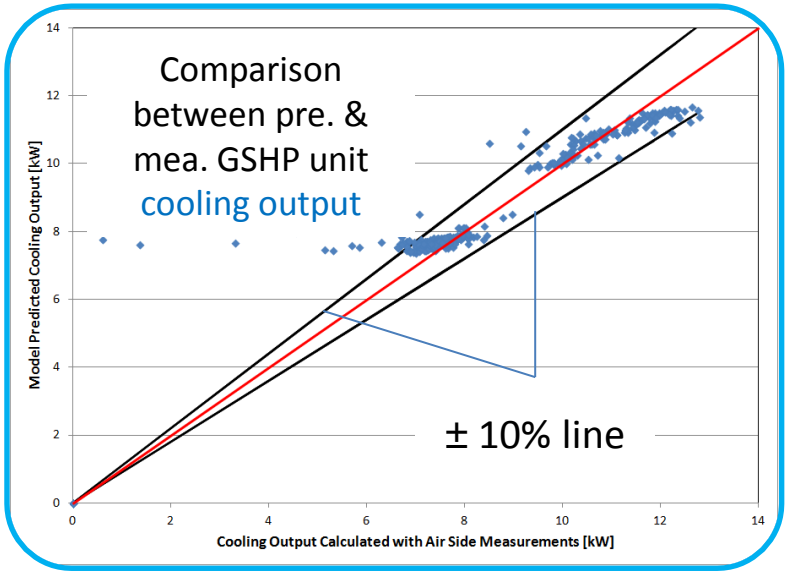
The distributed GSHP system at ASHRAE HQ is more energy efficient than most of the (central) GSHP systems in China (China-side COPs based on a few days data, likely optimistic)

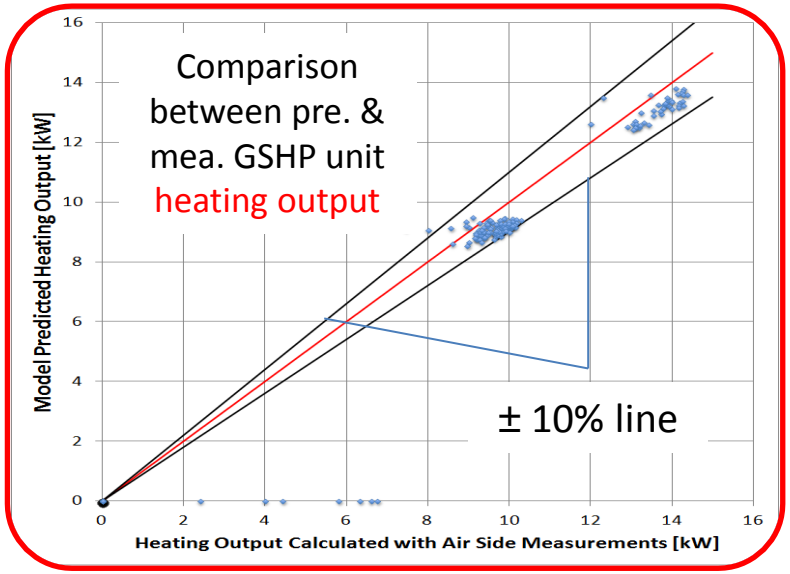
Measured Efficiencies of GSHP Systems in China (Source: Center of Science & Technology of Construction, MoHURD, China)

Virtual Sensing for Performance Monitoring

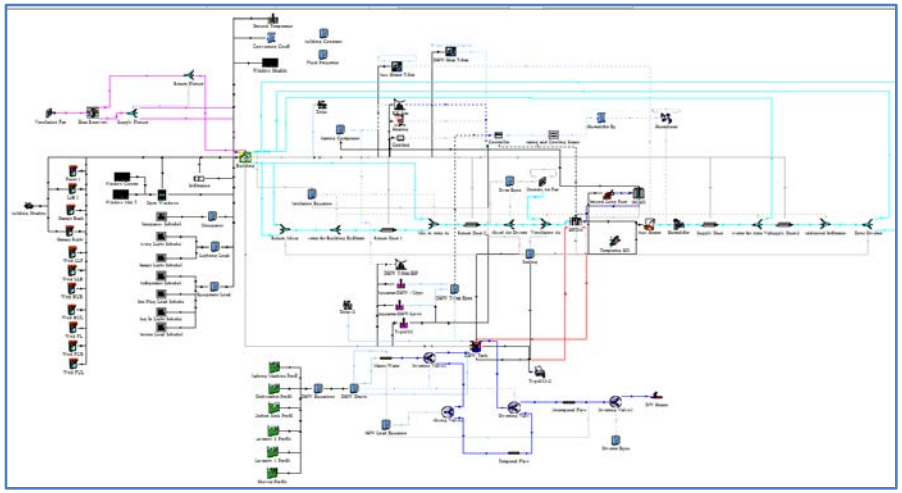


Estimate heating/cooling output and associated power usage with GSHP operation status data and performance map

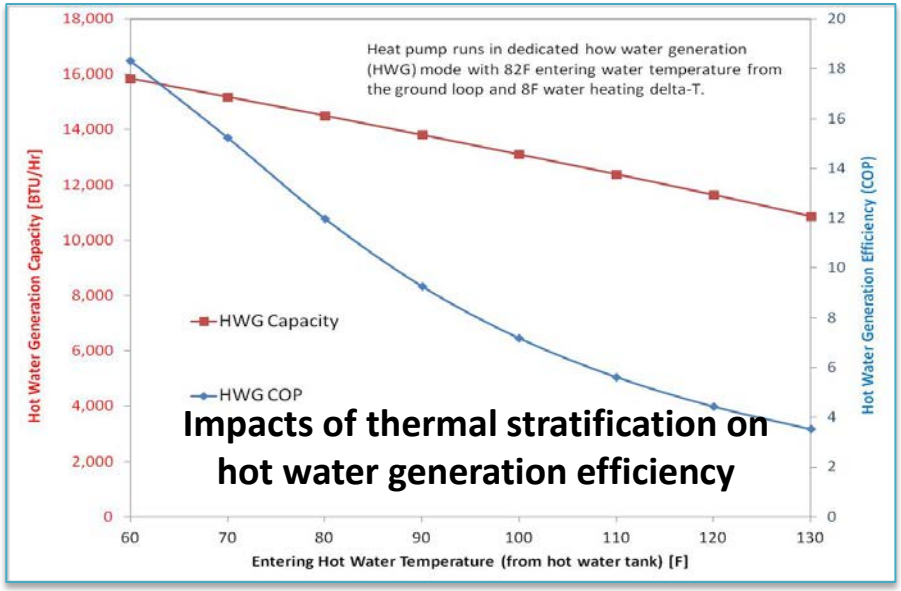




Modeling Study for Smart Tank



TRNSYS model for GS-IHP coupled with smart tank



Impacts of thermal stratification on hot water generation efficiency

- Investigated impacts of various alternative designs and controls of smart tank on the performance of hot water generation using detailed TRNSYS simulations
- Initial simulation results indicated that hot water generation efficiency can be improved up to 10% by enabling and maintaining thermal stratification in the tank