Residential HP Modeling and Prototyping: *Phase I Report*

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1 Introduction

Increases in peak power demand and the greater penetration of non-dispatchable generating plants on the electric power system present growing challenges to electric power providers. As the gap between peak and average electricity demand widens, the average utilization levels for generating plants decrease, increasing the cost associated with maintaining the capacity required to serve peak demand periods. The addition of more renewable energy plants such as wind power onto the grid increases the percentage intermittent generation. This necessitates the ability to shift demand both to decrease peak periods and to better utilize non-dispatchable generating resources. Residential heating and cooling provide an opportunity to use the thermal mass of the home to shift power usage away from peak demand periods. In residential water heating, the water tank can serve as a thermal energy storage unit when it is preheated during low demand times.

This project proposes the use of one or more water tanks as thermal storage to provide demand response in space conditioning applications as well as residential water heating. By using two heat pumps, one to heat or cool the water tank and the other to heat or cool the home, the electric utility can shift energy consumption to times of lower wholesale cost and reduce consumption during extreme hot and cold conditions when peak demand occurs. Customer savings are achieved through the better performance of the heat pump providing air conditioning to the home and by the purchase of therms stored in the thermal mass at a rate below what they would pay for retail electricity.

An air-to-water heat pump is used to heat and cool the water tank. This heat pump would be owned and operated by the electric utility and used to charge the thermal storage unit during off-peak times and times of lower wholesale electricity costs. An air-to-water heat pump heats and cools the home within a range of temperatures set by the resident and would be owned by the customer. Thermal energy extracted from the tank by customer-side heat pump would be billed to the customer by the utility by the therm at a flat rate based on the average wholesale cost of electricity, the average coefficient of performance (COP) of the air-to-water heat pump and the standard transmission and distribution fees.

The two heat pumps operate autonomously, and their operation is predictively optimized over a sliding twenty-hour period using projected weather and wholesale pricing information. Operational set points for the heat pumps would therefore be sent to the controller at some regular interval. The performance of the system can be optimized for different objectives including minimizing utility cost, minimizing customer cost, minimizing the combined cost to both entities, minimizing energy consumption or reducing demand during peak times.

The first phase of this project saw the development of thermal models for the home and water tank, the optimization routine, a mechanical design for the system and an initial prototype of the system. Additionally, a study was performed to investigate the impact for the utility if the system were to be implemented in 10,000 single family homes and to estimate the potential savings to the customer. The following report summarizes the progress made on all of the aforementioned deliverables and details the results of this impact study.

2 Mechanical Design

The complete system is comprised of two heat pumps coupled through a thermal storage unit of one or more water tanks, which can provide load flexibility in residential heating and cooling applications. An air-to-water, utility-side heat pump is dedicated to heating and cooling the water, which then acts as a source for the smaller residential-side, water-to-air heat pump that conditions the air in the home. The thermal storage unit can be charged during times of lower wholesale electricity costs or to reduce consumption during peak periods, providing demand response to the utility while simultaneously improving the efficiency of the water source heat pump. This in turn decreases consumption during peak times and reduces customer electricity bills.

Each heat pump has an inlet/outlet at both the top and the bottom of the tank. During heating season, the utility-side heat pump extracts cold water from the bottom of the tank and returns hot water to the top while the residential-side heat pump extracts hot water from the top of the tank returning colder water to the bottom. During the cooling season, this will reverse as the utility-side heat pump now cools the tank, returning chilled water to the bottom where it will be extracted by the residential-side heat pump. This promotes stratification in the tank, maintaining a temperature gradient whereby the top of the tank always contains the warmest water, which reduces exergy losses and improves the performance of the customer-side heat pump.

Temperature sensors will be placed at the inlet and outlet points of the water tank, in the outdoor environment and in the residence to provide feedback to the control system operating the system. A flow meter will also be placed on the inlet point to the customer-side heat pump. These mass flow readings taken in conjunction with the inlet and outlet water temperature to the heat pump will measure the amount of thermal energy extracted from the water tank. This will then allow the utility to bill the customer for this energy by the therm.

3 Thermal Models

The proposed system is comprised of an insulated, rectangular volume of air representing the home, an insulated water tank as a thermal storage unit, and two heat pumps: an air-to-water heat pump and a water-to-air heat pump, each coupled to the thermal storage unit. Thermal equations to describe the behavior of the home and the thermal storage unit are given in Appendix A.

Thermal stratification in the water tank was modeled as discrete layers of equal mass with heat transfer occurring between them. Mass flow through the tank is caused by the operation of the heat pumps, and the rate of flow between the top and bottom of the tank is assumed to be the difference between the rate of water flow through each heat pump. Mass flow due to convection has been neglected for the sake of simplicity.

4 Optimized Performance

4.1 Optimization Routine

The purpose of the optimization routine is to predict the optimal operation for the heat pumps over a period of twenty-four hours. Using predicted temperatures and wholesale electricity prices, the routine generates a vector of operational set points for each heat pump in time increments of 5 or more minutes. This allows the utility-side heat pump to charge the thermal storage tank when electricity prices are low, which then improves the performance of the customer-side heat pump, thereby reducing cost to both the utility and the customer.

The thermal models of the home and storage unit are used to predict the behavior of the system over the period of optimization. Therefore, the characteristics of the actual residence and water tanks need to be input into the routine to ensure the accuracy of the optimization. Additionally, real time sensor readings of the home and water temperatures can be fed to the routine to minimize any discrepancies between the anticipated and actual performance, which might be caused by disturbances in the system.

Five optimization objectives were identified and can be selected within the optimization routine: minimize utility cost, minimize customer cost, minimize the sum cost to both entities, minimize energy usage and minimize power consumption during peak times. The primary constraints in the system are the minimum and maximum allowable temperatures in the water tank and the comfort band for the residence, which would be set by the home owner.

The optimization routine was developed in Matlab using sequential quadratic programming (SQP) and the built-in Matlab function, fmincon, which will find the minimum of a constrained, non-linear multivariable function. The function requires an initial estimate of variable vector, which is used as a starting point for the routine. Depending on the complexity of the objective function and the number of variables, the routine is susceptible to converging on a local rather than the global minimum. Therefore, it is important that this initial estimate be close to the optimal solution or that a grid is used to test multiple starting vectors across the entire range of possible solutions.

4.2 Routine Seeding

Optimizing the performance of both heat pumps over a twenty-four hour period in 5 minute increments requires that the optimization routine handle five hundred and seventy six variables, which is both computationally intensive and makes the algorithm susceptible to converging on a non-optimal solution, depending on the initial estimate passed to the routine.

A separate routine was therefore developed to generate a good initial guess for optimal vector of operational variables. The routine begins with the assumption that the customer-side heat pump will operate to heat or cool the home within the comfort band agnostic of the wholesale cost of electricity unless costs drop below zero and the objective is to minimize either utility or total cost.

The utility heat pump is then set to operate at its maximum capacity at any time the wholesale cost of electricity drops below zero. The predicted temperatures for the water tank throughout the day are then found using these two preliminary operational vectors. The boundary temperatures at the bottom and top of the tank are then tested, which triggers the operation of utility-side heat pump to operate based on a threshold temperature relative to the tank temperature constraints.

This temperature threshold is then varied with an offset temperature dictated by the cost of wholesale electricity at that time interval, normalized to the maximum cost of electricity that day. The utility-side heat pump will be operated if the boundary temperature of the tank is within this threshold of the minimum or maximum allowable tank temperature. System constraints are then tested, and the routine goes through six iterations of adjusting the operational vector to correct any violations.

If there are still constraint violations, the vector is rejected. Otherwise, the solution to the objective function using these operational points is saved. The next threshold temperature is then used until all of the threshold temperatures have been tested and the minimum solution to the objective function obtained. These operational vectors are then used to seed the optimization routine.

5 Control Architecture

5.1 Overview

The control architecture for this project was developed to support two types of system operation with set points dictated ether by the results of the optimization routine or by user inputs. These two separate functions were realised in the Main and Test Subsystems, respectively. An emergency Lockout Subsystem was also included to shut the hydronics system down if the water level in the tank drops too low. Users interact with the system through the graphical user interface (GUI) displayed on the system's touch screen panel. The user can also view many of the various system parameters on the System Information screen of the GUI.

5.2 Main Subsystem

From the Main Menu screen of the GUI, the user can start and stop the main portion of the control system. In the main subsystem, all of the operational set points will be determined by the optimization routine and the system will run normally until ether the Stop button is pressed or the float switch in the water tank indicates that the water level is too low. This will be the normal operational mode for the system once it is in place.

5.3 Test Subsystem

From the Test Menu of the GUI, the user has active control over the hydronics system including dynamic control of the mass flow rate, the piping configuration and heat pump operation. This will allow for system verification, model validation and more sophisticated plant modeling in the future.

5.4 Lockout Subsystem

Anytime that the float switch located in the storage tank indicates that the water level has dropped below the safe working level, the Lockout Subsystem is activated.

The Lockout screen is displayed on the touch screen panel and the shutdown process is initiated. During the shutdown process, the pumps are stopped, and after a designated time, the valves are closed. This is done to allow the water in the system to stop flowing before the circulation loops are closed, thus preventing unnecessary stress on the system. This same shutdown procedure is also followed any time that a user initiates a system shut down. The Lockout screen will flash a warning indicating that the water level is low until the appropriate water level is once again achieved. Once the tank's water level is again within acceptable levels, an operator must press the physical Reset button located next to the touch screen panel before the system will run again. This was included to ensure that someone be physically present to check why the system lost water before resuming operation.

6 Prototype

6.1 Heat Pump Selection

The Tranquil Compact (TC) series from ClimateMaster was chosen for the prototype for a number of reasons. The TC units are reasonably priced and use scroll compressors in their refrigeration loop. The latter is important because scroll compressors have a more consistent torque profile through a cycle of operation. This means that they are more apt at taking power in from a variable frequency drive (VFD). The TC series also has a much smaller footprint than most heat pumps with comparable capacities, which is advantageous given space constraints.

6.2 Variable Frequency Drives

Both the utility-side heat pump and the water pumps will be controlled in the prototype through variable frequency drives (VFDs). This allows for the practical approximation of variable-speed performance using smaller, single-speed units, which are more appropriate for the scale and budget of the prototype system.

The one ton unit from ClimateMaster has a scroll compressor with a rated load ampacity of 5.1 amps at 208VAC. This represents roughly a 1.5 horsepower draw. There are very few single phase output VFDs that are able to handle that kind of power flow. Ultimately we selected the SmartFan Stratus 11 model from Control Resources because of it meets the current requirements and has good controllability at a reasonable price point.

An electronic filter is required to filter switching harmonics that are produced by the VFD. The VFD manufacturer recommended a couple different options and the Corcom Q series filter was selected because of its cost and filtering profile. The Corcom 20EQ1 has strong attenuation above 100 HZ. This makes it ideal for the ResHP project since the typical operating range for the VFD will be 25 to 70Hz.

The circulation pump for the hydronic system was sized to provide one to three gallons per minute flow over the operable range with a VFD. The GS-1 Automation Direct (AD) was the natural choice for the VFD since it is designed to work with the AD PLC that was selected for the control system, making integration simple.

6.3 Plumbing Materials

Cross Linked Polyethylene (PEX) piping was used for the hydronic system. PEX is easy to work with, flexible and inexpensive. A food-grade polyethylene barrel was used for the thermal storage tank. This tank has a volumetric capacity of 55 gallons. This size was chosen since a one ton heat pump would be able to heat the entire tank by 30°F in about three hours.

Superstrut was used as the structural racking for the hydronic system of the prototype. This allows for reconfiguration and is sturdy enough to hold up to any operation and testing. ASCO Red Cap valves with solenoids were selected for the hydronic valves in the prototype. They are a well proven and reliable valve that is easily controlled with the AD PLC. WYE-strainers were added to the hydronic system to filter out large particulates that might get into the thermal storage tank. This will help to prevent flow blockage and damage to the heat exchangers in the heat pumps.

6.4 Sensors

All temperature readings for the prototype are taken using DS18B20 units. This enables the collection of many temperature readings without using up an I/O port for each sensor. Using a simple micro-controller, many temperatures can be taken and sent to the PLC. The DS18B20 has a capacitor included in the IC so it is capable of using its own store power. It can also take that power from the data line so it has no need for a separate power source of its own. The temperature response and accuracy characteristics are well within the acceptable range for this proof-of-concept prototype.

The prototype is equipped with a vertical array of temperature sensors in the thermal storage tank. This is used to track the energy stored in the tank and to characterise stratification so its effects on the overall system performance can be tracked. Temperature sensors are also at the inlet and outlet of both heat pumps. These are used to the track the actual energy flow through the system.

Simple paddle wheel flow meters were selected for the prototype because they interface nicely with the CTRIO high speed counter card of the PLC and have a high degree of accuracy for their price point.

6.5 Control Hardware

The control system hardware consists of components from the Do-More line of PLCs and C-More line of touch screens from Automation Direct. A combination of the DL-205 base and H2-DM1E CPU were selected in conjunction with various appropriate input and output modules for creating the control system while the user interface is accomplished by an 8 inch C-More panel. The DL-205 is equipped to handle MODBUS communication, allowingd2l for a standard communication for all devises used in the prototype.

7 Impact Study

7.1 Purpose of the Impact Study

The goal of implementing the dual heat pump system in customer homes is to reduce utility costs by shifting energy consumption to times of lower wholesale cost and by reducing power consumption during peak demand periods. To ensure customer buy-in it is important that the customer will also see savings from the installation of the system. The impact study was therefore conducted to quantify these potential benefits to both the utility and to the customer. Customer savings are achieved through the better performance of the customer-side (water-to-air) heat pump over resistive or air-to-air electric heating systems and by the purchase of therms stored in the thermal mass at a rate below what they would pay for retail electricity.

7.2 Home Model

The same thermal model for the home was used in developing both the benchmark and optimized system performance data. It assumes a 2,000 square foot, single family home with a thermal admittance (UA) of 400 kBtu/hr°F and 15% duct loss.

7.3 Driving Data Sets

7.3.1 Weather

Ambient temperature data for a typical Portland week in each season were taken from the typical meteorological year (TMY) from National Renewable Energy Laboratory (NREL). For the peak demand reduction study, weather data were used from the days that saw the highest annual peak demand in 2013-2014. This was December 9th, 2013 for the winter peak and August 11th, 2014 for the summer peak.

7.3.2 Wholesale Pricing

Average hourly Malin wholesale prices from 2012-2014 were used to determine utility costs for both the benchmark data and the optimized system performance.

7.4 Benchmark Data

The benchmark data for utility cost and peak reduction is based on service to 10,000 homes with 2 ton air-to-air heat pumps. The air-to-air heat pump was modeled using the capacity and COP data of a Carrier Home Comfort unit with a HSPF of 8.5 for the heating season. During the cooling season, an average COP of 3 was assumed. The same single-family home model is used in benchmarking.

7.5 System Design Assumptions

Simulations assume a 2,000 square foot, single family home with a thermal admittance (UA) of 400 kBtu/hr°F and 15% duct loss. The heat pump system was modeled using the specifications of a 3.2 ton Daikin air-to-water heat pump with a nominal COP of 4.32 and a 2 ton Trane Water Source heat pump with a nominal COP of 6.44. The thermal mass was assumed to be a 600 gallon tank of water with inlets and outlets at the top and bottom for each of the heat pumps. The utility side (air-to-water) heat pump was assumed to be installed outdoors and the customer side heat pump in the residence. The tank was modeled assuming an insulated structure with an R value of 16. Thermal stratification was assumed to exist in the tank and was modeled in four layers. The water flow through the heat pumps was set at 1 gpm.

7.6 Results

Results from the impact study are given in Tables 1 - 3 below. The first customer profile assumes resistive heating and the use of window air conditioning units totalling 1.5 tons with an average COP of 2.4. The second customer profile assumes that all heating and cooling needs are supplied by an air-to-air heat pump.

7.6.1 Optimized Daily Performance

Table 1: Optimized Performance for Minimized Utility Cost: Costs

		Benchmark Data		*Optimized Data*	
Season	**Resistive Cust. Profile**	**Heat Pump Cust. Profile**	**Utility Costs for 10,000 Homes**	**Customer Cost**	**Utility Costs for 10,000 Homes**
Winter	$910	$380	$1,200,000	$270	$1,000,000
Spring	$500	$170	$380,000	$130	$330,000
Summer	$14	$12	$31,000	$3	$6,400
Autumn	$690	$250	$770,000	$190	$700,000
Total	**$2,100**	**$810**	**$2,400,000**	**$590**	**$2,000,000**

Table 2: Optimized Performance for Minimized Utility Cost: Energy

Season	**Benchmark (kWh)**	**Optimized (kWh)**
Winter	33,000,000	29,000,000
Spring	15,000,000	14,000,000
Summer	1,000,000	300,000
Autumn	22,000,000	21,000,000
Total	**71,000,000**	**64,000,000**

7.6.2 Peak Demand Reduction

Table 3: Peak Reduction for 10,000 Homes

Season	**Benchmark (kW)**	**Optimized (kW)**
Winter	26,000	9,600
Summer	23,000	3,200

8 Future Work

Work has already been outlined for the next phase of the project, which began on September 16, 2015 and will continue until June 15, 2016. During this time, the project team will further develop the mechanical design, expand the impact study, validate the existing models, investigate options for the operations control system, perform more extensive mechanical modelling, integrate real time sensor readings into the optimization routine, and undertake use testing on the prototype.

8.1 Mechanical Models

The actual heat pump units used in the prototype will be fully characterized to predict their behavior under a complete range of operating conditions. In particular, the COP of each heat pump will be found as a function of ambient and entering water temperature and the mass flow rate.

8.2 Prototype Testing

The project team will find a suitable location for the prototype to ensure that the heat pumps are thermally isolated from one another and that there is an appropriate space for conditioning. A testing methodology will then be developed and a list of test cases created both to validate our models, verify system performance and provide proof-of-concept.

8.3 Model Validation

Sensor readings from prototype tests will be used to validate the models used in the optimization routine, including the thermal models of the home and water tank as well as the mechanical models of the heat pumps. Adjustments will be made to these models as necessary to ensure their fidelity to the actual system.

8.4 Mechanical Design

A detailed design for the system tanks will be created using lessons learned from constructing the prototype and designed to align with the project patent. A concept for expanding the prototype to a multi-tank system will be developed and considered for testing, and an in-ground solution will be explored. Finally, the team will generate cost estimates for the implementation of the final system to assist in evaluating its feasibility.

8.5 Impact Study

The impact study will be expanded to include an analysis of potential carbon emissions reduction due to the implementation of the system in 10,000 single family homes. Additionally, sensitivity analyses could be performed on a variety of system parameters, including the size of the water tank(s), the capacity of the utility-side heat pump relative to the customer-side heat pump and therm price. Finally, the benchmark data currently model the heat pump as having an average COP during the cooling season and neglect the back-up heating system during the heating season. Future work could include improving this heat pump model.

8.6 Optimization

The optimization routine will be further developed to take in real time sensor readings and compensate for any discrepancies that may occur due to unanticipated disturbances in the system.

8.7 Operations Control

The team will research options for locating the optimization routine to reduce the hardware and software costs of operating the system. Possible solutions include cloud computing or an on-board microprocessor at the system site. This may require rewriting the optimization routine in another programming language to eliminate the need for a Matlab license.

9 Conclusion

As of September 2015, sub-system testing of the dual heat pump prototype has been completed, and the project team is positioned to undertake whole-system testing moving into the fall. Once the prototype has been appropriately sited, heat pump characterization and model validation will begin, and the performance of the system can be demonstrated over a range of operating conditions.

An optimization routine has been developed to output the optimal operational set points for each heat pump over a sliding 24-hour period. This information is then fed into a control system, which regulates the heat pump operation and water flow through feedback control using a PID compensator. As whole-system testing of the prototype occurs, this optimization routine will be refined using empirical data from the system.

Potential benefits of implementing the dual heat pump were quantified in an impact study and identified customer savings of approximately $200 a year and winter peak demand reduction of roughly 16 kW per single family household. These results indicate that this dual heat pump system could realize meaningful demand response and load flexibility in the Portland region if implemented in a sufficient number of households, which could mitigate some of the challenges presented by the greater penetration of non-dispatchable renewable generation and eliminate the need for added capacity due to the peak demand periods.

Future work will see further analysis completed through this impact study and address a practical design for the water tanks, an extensible solution for hosting the optimization routine and control system, and the development of cost estimates for the system.

A Appendix: System Equations

Variables:

- A: Area
- c: Specific heat
- m: Mass
- k: Thermal conductivity
- $\dot{m}$: Mass flow rate
- T: Temperature
- Q: Thermal transfer
- P: Power
- J: Total cost
- Y: Wholesale price of electricity
- t: Time
- R: Customer rate
- C: Heat pump capacity
- CR: Capacity ratio, the ratio of heat pump demand to heat pump capacity

Subscripts

- w: Water in the storage tank
- $1in$: Inlet 1
- $1out$: Outlet 1
- $2in$: Inlet 2
- $2out$: Outlet 2
- C: Cross-sectional
- $down$: Down in tank
- env: Environment
- o: Outdoor
- i: Generic node
- S: Surface
- $tank$: Storage tank
- up: Up in the tank
- $hp1$: System-side heat pump
- $hp2$: Premise-side heat pump
- H: Customer home
- a: Air in the home
- u: Utility
- c: Customer
- t: Total
- fl: Full load
- pl: Partial load

A.1 Thermal Systems Equations

Storage Tank Interior Layer

$$\dot{T}_i = (m_w c_w)^{-1}(k_w A_C(T_{i+1} - T_i) + k_w A_C(T_{i-1} - T_i) + U_{tank} A_S(T_{env} - T_i) + \dot{m} c_w(T_{i-1} - T_i)) \tag{1}$$

Storage Tank Top Layer

$$\dot{T}_1 = (m_w c_w)^{-1}(k_w A_C(T_2 - T_1) + U_{lid} A_C(T_{env} - T_1) + U_{tank} A_S(T_{env} - T_1) \\ - \dot{m} c_w T_1 - \dot{m}_2 c_w T_1 + \dot{m}_1 c_w T_{in1}) \tag{2}$$

Storage Tank Bottom Layer

$$\dot{T}_n = (m_w c_w)^{-1}(k_w A_C(T_{n-1} - T_n) + U_{bottom} A_C(T_{env} - T_n) + U_{tank} A_S(T_{env} - T_n) \\ + \dot{m} c_w T_{n-1} - \dot{m}_1 c_w T_n + \dot{m}_2 c_w T_{in2}) \tag{3}$$

Input Water Temperature

$$T_{in1} = \frac{Q_{hp1}}{\dot{m}_1 c} + T_n \tag{4}$$

$$T_{in2} = \frac{Q_{hp2}}{\dot{m}_2 c} + T_1 \tag{5}$$

Heat Transfer Into the Customer Premise

$$\dot{T}_H = \frac{Q_{hp} + k_h(T_o - T_H)}{m_a c_a} \tag{6}$$

A.2 Optimization Equations

$$min\{J_u(P(Q_{hp1}, Y)\} \tag{7}$$

subject to $Q_{hp} \in [0, 10500]$, $T_i \in [274, 373]$

$$min\{J_c(P(Q_{hp2}, R)\} \tag{8}$$

subject to $Q_{hp} \in [0, 10500]$, $T_h \in [Min.Setpoint, Max.Setpoint]$

$$min\{J_t(P(Q_{hp1}, P(Q_{hp2}, Y, R)\} \tag{9}$$

subject to $Q_{hp} \in [0, 10500]$, $T_i \in [274, 373]$, $T_h \in [Min.Setpoint, Max.Setpoint]$

$$min\{P_t(Q_{hp1}, Q_{hp2})\} \tag{10}$$

subject to $Q_{hp} \in [0, 10500]$, $T_i \in [274, 373]$, $T_h \in [Min.Setpoint, Max.Setpoint]$

A.3 Other System Equations

System Heat Pump Coefficient of Performance

$$COP = c_1T_a^2T_w^2 + c_2T_a^2T_w + c_3T_a^2 + c_4T_aT_w^2 + c_5T_aT_w + c_6T_a + c_7T_w^2 + c_8T_w + c_9 \tag{11}$$

Heating Mode

$c_1 = -6.98 \times 10^{-6}$
$c_2 = 0.0043$
$c_3 = -0.652$
$c_4 = 0.004$
$c_5 = -2.4624$
$c_6 = 376.5558$
$c_7 = -0.5757$
$c_8 = 353.6482$
$c_9 = -5.418 \times 10^4$

Cooling Mode

$c_1 = -1.0579 \times 10^{-6}$
$c_2 = -0.0056$
$c_3 = 0.7921$
$c_4 = -0.0059$
$c_5 = 3.3670$
$c_6 = -477.9485$
$c_7 = 0.8939$
$c_8 = -507.9474$
$c_9 = 7.2051 \times 10^4$

System Heat Pump Capacity

$$C = s_1 T_a^2 T_w^2 + s_2 T_a^2 T_w + s_3 T_a^2 + s_4 T_a T_w^2 + s_5 T_a T_w + s_6 T_a + s_7 T_w^2 + s_8 T_w + s_9 \quad (12)$$

Heating Capacity

$s_1 = -3.5706 \times 10^{-5}$
$s_2 = 0.0221$
$s_3 = -3.4214$
$s_4 = 0.0203$
$s_5 = -12.5678$
$s_6 = 1.9443 \times 10^3$
$s_7 = -2.88$
$s_8 = 1.7848 \times 10^3$
$s_9 = -2.7618 \times 10^5$

Cooling Capacity

$s_1 = -1.0579 \times 10^{-5}$
$s_2 = 0.0058$
$s_3 = -0.8128$
$s_4 = 0.0060$
$s_5 = -3.3382$
$s_6 = 463.9999$
$s_7 = -0.8567$
$s_8 = 473.7564$
$s_9 = -6.5887 \times 10^4$

A.3.1 System Heat Pump Partial Load Performance

$$COP_{pl} = COP_{fl} \frac{CR}{C_d CR - C_d + 1} \quad (13)$$

$C_d = 0.9$

Customer Heat Pump Coefficient of Performance

$$COP = c_1 T_w^2 \dot{m}^2 + c_2 T_w^2 \dot{m} + c_3 T_w^2 + c_4 T_w \dot{m}^2 + c_5 T_w \dot{m} + c_6 T_w + c_7 \dot{m}^2 + c_8 \dot{m} + c_9 \quad (14)$$

Heating Mode

$c_1 = 3.3632 \times 10^{-5}$
$c_2 = -5.8993 \times 10^{-4}$
$c_3 = 0.0025$
$c_4 = -0.0204$
$c_5 = 0.3537$
$c_6 = -1.4172$
$c_7 = 3.0652$
$c_8 = -52.8087$
$c_9 = 203.8282$

Cooling Mode

$c_1 = -6.4956 \times 10^{-5}$
$c_2 = 0.0014$
$c_3 = 0.0033$
$c_4 = 0.0408$
$c_5 = -0.8722$
$c_6 = -2.1612$
$c_7 = -6.4114$
$c_8 = 136.5466$
$c_9 = 352.1723$

Customer Heat Pump Capacity

$$C = s_1 T_a^2 + s_2 T_a + s_3 \quad (15)$$

Heating Capacity

$s_1 = 0$
$s_2 = -0.0073$

$s_3 = 3.1506$

Cooling Capacity

$s_1 = 0.0014$

$s_2 = -0.7751$

$s_3 = 111.4322$

Electrical Power

$$P = \frac{Q_{hp}}{COP} \tag{16}$$

Cost Calculation

$$J = \frac{PYt}{3600} \tag{17}$$

B Appendix: User's Manual

C Graphical User Interface Operator's Manual

The following is an operator's manual. Say something better here.

C.1 Main Menu

The Main Menu is the first screen that the operator will see upon powering the system up. From this screen the operator can start and stop the system, transition to the Test Menu, view the System Information screen, as well as activate a screen saver. This screen will be used for the normal operation of the system with set points dictated by the optimization routine.

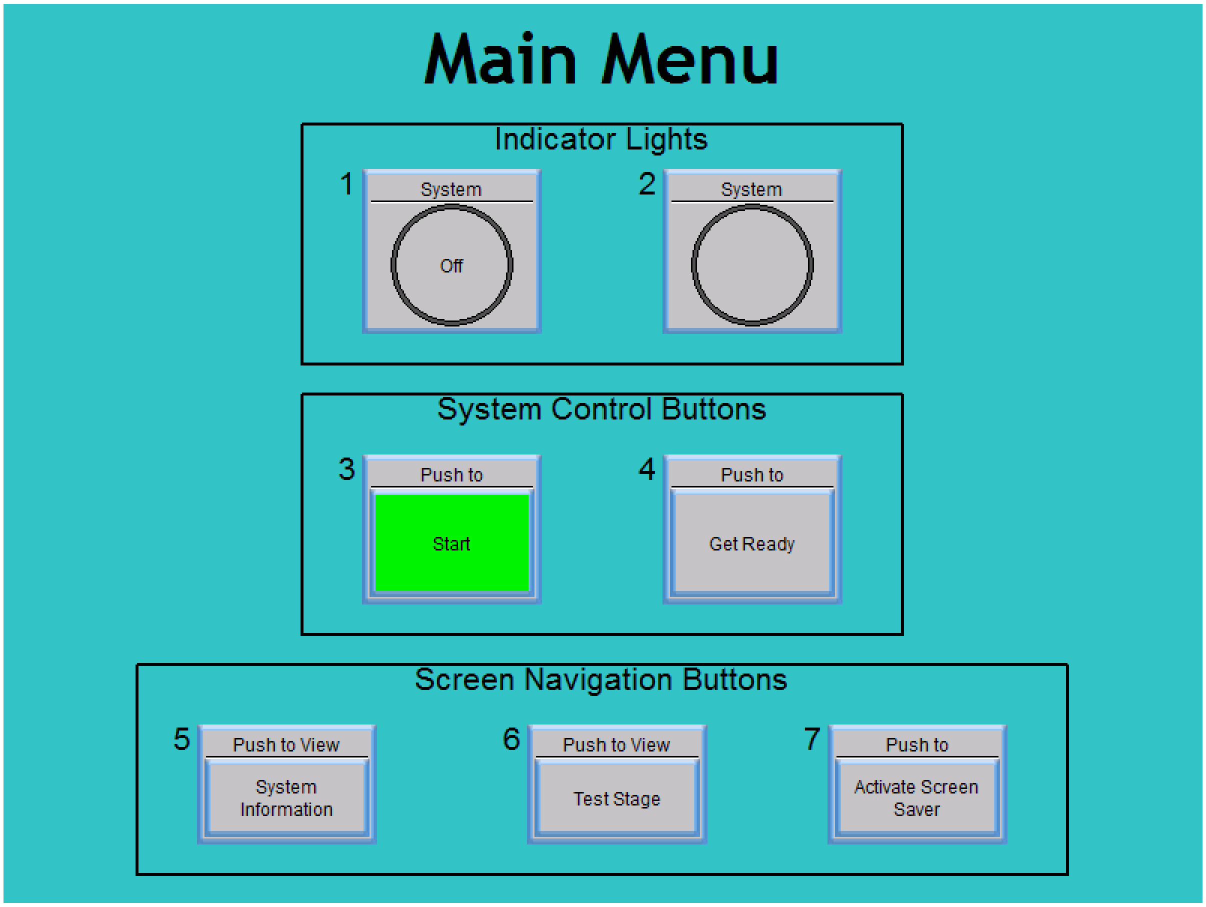

Figure 1: GUI Main Menu

1. System Running Light:
   - This light illuminates when the system is running.
2. System About to Start Light:
   - This light flashes when the system is about to start.
3. Start Button:
   - This button will start the normal operation of the system.
4. Stop Button:

- This button will safely shut the system down.
- If this button appears grey with the caption "Push to Get Ready" press it before starting the system.

5. System Information Button:
   - This button displays the System Information screen
   - Pressing this button has no effect on the operation of the system.
6. Test Menu Button:
   - This button transitions to the Test Menu.
   - This button disappears when the system is running.
7. Screen Saver Button:
   - This button activates a screen saver and should be pressed before the system is left running for any extended period of time.

C.2 Test Menu

The Test Menu allows the operator to dictate the operational set points of the system including mass flow rate (M-dot), valve configuration, and, eventually, the temperature settings on the system side heat pump. The Test Menu was designed to allow for system verification and plant modeling.

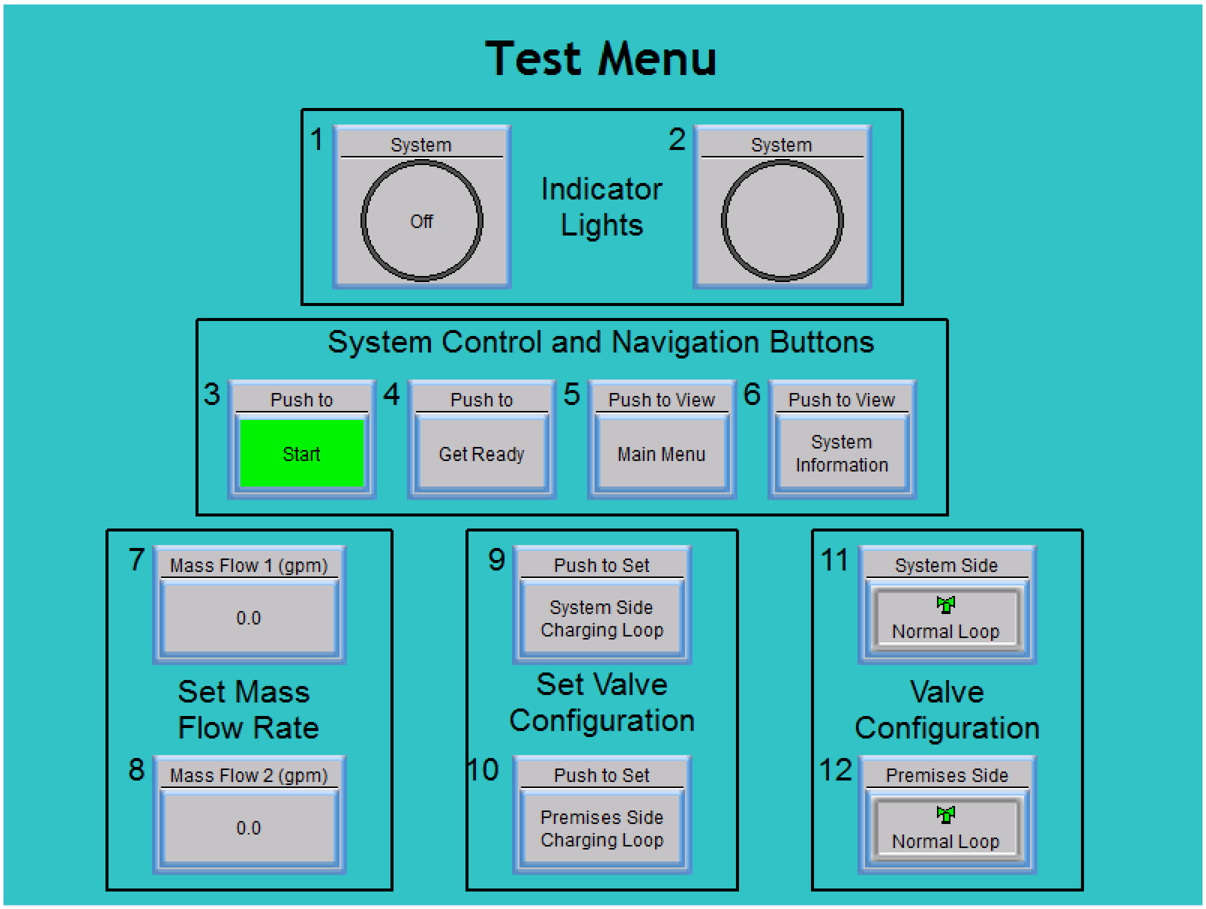

Figure 2: GUI Test Menu

1. System Running Light:
   - This light illuminates when the system is running.
2. System About to Start Light:

- This light flashes when the system is about to start.

3. Start Button:
    - This button will start the user defined operation of the system.
4. Stop Button:
    - This button will safely shut the system down.
    - If this button appears grey with the caption "Push to Get Ready" press it before starting the system.
5. Main Menu Button:
    - This button transitions to the Main Menu.
    - This button disappears when the system is running.
6. System Information Button:
    - This button displays the System Information screen
    - Pressing this button has no effect on the operation of the system.
7. M-dot Selector (Service Side):
    - This button opens a numerical entry screen that allows the user to set the mass flow rate, in gallons per minute, for the service side of the system.
8. M-dot Selector (Premises Side):
    - This button opens a numerical entry screen that allows the user to set the mass flow rate, in gallons per minute, for the service side of the system.
9. Valve Configuration Button (System Side):
    - This button changes the valve configuration of the service side of the system.
10. Valve Configuration Button (Premises Side):

- This button changes the valve configuration of the premises side of the system.

11. Valve Configuration Display (Service Side):

    - This displays the current valve configuration on the service side of the system.

12. Valve Configuration Display (Premises Side):

    - This displays the current valve configuration on the premises side of the system.

C.3 Lockout Screen

This screen is displayed when the float switch in the thermal storage tank indicates that the water level has dropped below the acceptable level. The physical system will shut down safely and not start again until the Lockout Screen is no longer visible. To exit this screen the operator must fill the thermal storage tank to the acceptable level then press the physical Reset button located next to the touch screen panel.

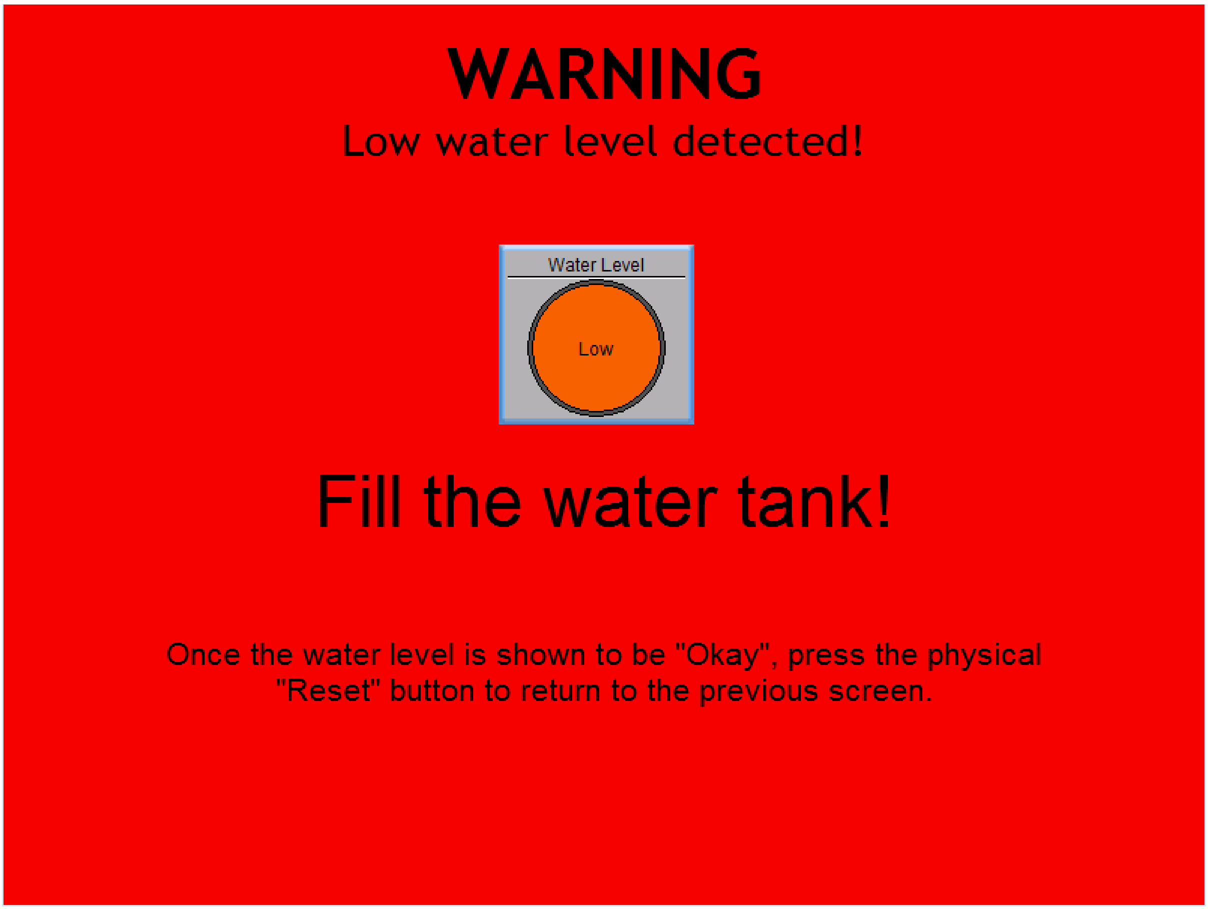

Figure 3: GUI Lockout Screen

C.4 System Information Screen with Temperature Display

This screen displays various system information and can be accessed from ether the Main or Test Menus. To transition to the previous screen press button three and to view temperature readings press button number seven. To hide the temperate readings press button seven again.

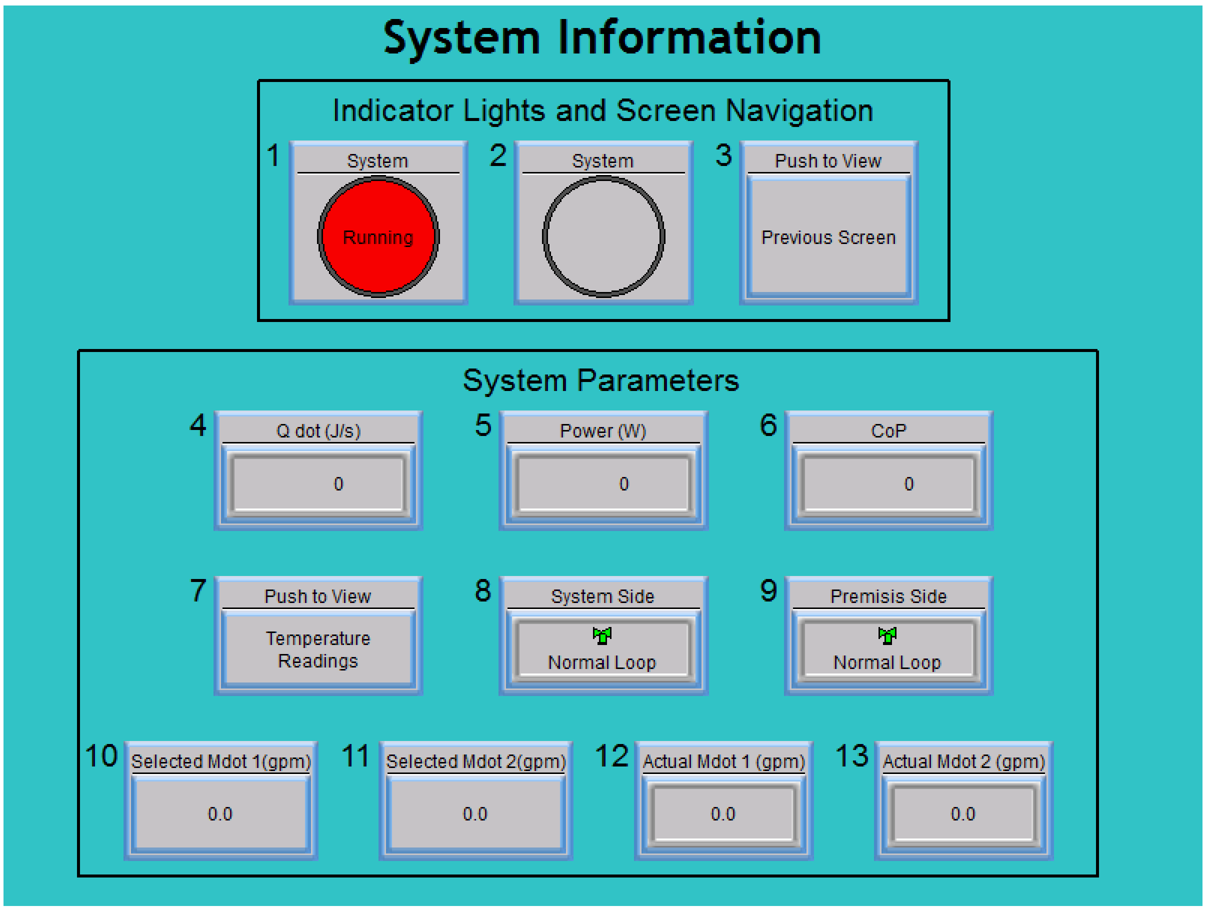

Figure 4: GUI System Information Screen

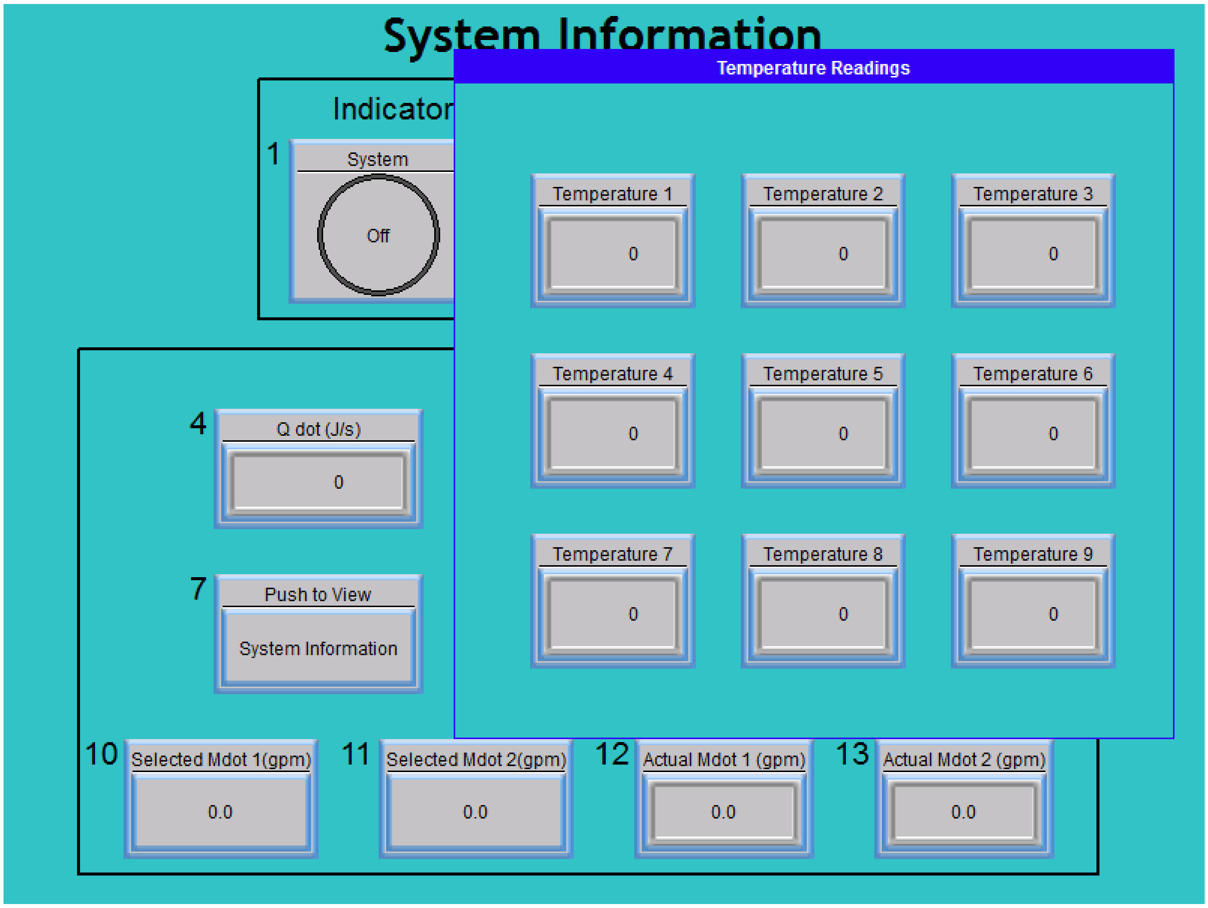

Figure 5: GUI System Information Screen with Temperature Display

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