

Ground Source Heat Pump Modeling, Operation, and Participation in Electricity Markets

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Abstract—Over the last decades, Ground Source Heat Pump (GSHP) systems have grown in popularity and acceptance worldwide, having the potential to bring about significant benefits, especially if these systems participate in electricity markets through a load aggregator to optimize their operations and provide services such as load shifting and demand reduction, as proposed here. In this context, GSHP systems can be considered as an economically viable and attractive alternative to existing Heating Ventilation and Air Conditioning (HVAC) systems for space heating/cooling in buildings and houses from an aggregator point of view. Hence, this paper presents a detailed mathematical model for a GSHP with a vertical U-pipe Ground Heat eXchanger (GHX) configuration to provide residential space heating/cooling, integrating several such GSHPs into a load aggregator model. Then, a two-stage operational strategy for the GSHP price-taker aggregator participating in day-ahead and real-time electricity markets is proposed, to determine the optimal annual heating/cooling load dispatch to control the temperatures for a community of houses that minimizes the aggregator's cost. Detailed numerical studies and comparisons with HVAC systems are carried out to demonstrate the feasibility and benefits of the proposed aggregated operation of GSHPs in electricity markets.

Index Terms—Electricity markets, Ground Source Heat Pump (GSHP), Heating Ventilation and Air Conditioning (HVAC), load aggregator, modeling, optimal dispatch.

NOMENCLATURE

A. Sets and Indices

i	Index for number of houses, $i \in I$.
j	Index for the borehole section, $j \in J$.
t	Index for hours of the day, $t \in T$.

B. Parameters

$\tilde{\alpha}^P$	Heating/Cooling capability of the HVAC unit at house i [$^{\circ}\text{C}/\text{kWh}$]
Δt	Time interval in which fluid temperature passes through segment j in U-pipe borehole, [h]
Δz	Height of each segment of the borehole j [m]
$\lambda_t^{DAM/RTM}$	Energy price in DAM/RTM at hour t [$\$/\text{kWh}$]
$\hat{\lambda}^{DAM/RTM}$	Maximum energy price in DAM/RTM [$\$/\text{kWh}$]
ϕ_t	Solar radiation power [kW]
σ	Solar radiation incidence factor
c_f	Specific heat of the underground fluid [$\text{kJ}/\text{kg}^{\circ}\text{C}$]
COP_{ref}^{HP}	Rated Coefficient of Performance (COP) of GSHP
d_b	Borehole diameter [mm]
d_g	Ground node position [mm]
d_{pe}	External U-pipe diameter [mm]
d_x	Grout node position [mm]

EER_{ref}^{HP}

H_P

k_b

k_g

L_t^{DAM}

$\dot{m}_f$

$\bar{P}_i$

Q_G

R_{pp}

R_b

R_{bb}

R_g

S

$\bar{T}_i/T_i$

T_{ent}

T_{Ref}

T_{ref}^{HP}

U

v

W_{com}

$Z_{ai,t}$

C. Variables

ΔP_t

$\Delta T_{i,t}$

C_t

$COP_{i,t}^{HP}$

$EER_{i,t}^{HP}$

J_1-J_3

$p_{i,t}^{h/c}$

$p_{i,t}$

$p_{i,t}^{res}$

P_t

$Q_{in/out}$

$Q_{i,t}^{h/c}$

$Q_{i,t}$

$Q_{i,t}^{abs/ref}$

$Q_{i,t}$

$Q_{i,t}$

$Q_{i,t}$

$Q_{i,t}$

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$Q_{i,t}$

Rated Energy Efficiency Ratio (EER) of GSHP
Thermal capacitance [$\text{kJ}/^{\circ}\text{C}$]
Grout thermal conductivity [$\text{W}/\text{m}^{\circ}\text{C}$]
Ground thermal conductivity [$\text{W}/\text{m}^{\circ}\text{C}$]
Aggregated uncontrolled load at hour t [kW]
Mass flow rate of the underground fluid [kg/s]
Power capacity of a heating/cooling device in house i [kW]
House internal heat gain [kW or kJ/s]
Pipe-to-pipe thermal resistance [$^{\circ}\text{C}/\text{kW}$]
Borehole conductive thermal resistance [$^{\circ}\text{C}/\text{kW}$]
Grout-to-grout thermal resistance [$^{\circ}\text{C}/\text{kW}$]
Grout-to-ground thermal resistance [$^{\circ}\text{C}/\text{kW}$]
Shank spacing [mm]
Maximum/Minimum limits of comfortable temperature in house i [$^{\circ}\text{C}$]
Ambient temperature at hour t [$^{\circ}\text{C}$]
Reference in-house temperature [$^{\circ}\text{C}$]
GSHP's reference temperature of operation [$^{\circ}\text{C}$]
Heat transfer coefficient [$\text{kJ}/\text{m}^2^{\circ}\text{C}$]
Velocity of the underground fluid [m/s]
Compressor power consumption [kW]
GSHP operation mode (1 for heating, and 0 for cooling)

Aggregated demand deviation [kW]
In-house temperature deviation [$^{\circ}\text{C}$]
Energy procurement cost at hour t [$\$/\text{kWh}$]
COP of GSHP in heating mode
EER of GSHP in cooling mode
Objective functions of the aggregator model
Electric load of house i during heating/cooling operation at hour t [kW]
Electric load of house i from secondary thermal resistance [kW]
Total aggregated demand at hour t [kW]
House heat transfer and GHX contribution [kW]
Heat transfer heat injected to/extracted from each house i at hour t in heating/cooling mode [kW]
Heat transfer contribution of the GHX unit in each house i at hour t in heating/cooling mode [kW]

$T_{i,t,j}^b$	Borehole grout temperature of house i at hour t in segment j [$^{\circ}\text{C}$]
$T_{i,t,j}^f$	Borehole fluid temperature of house i at hour t in segment j [$^{\circ}\text{C}$]
$T_{i,t,j}^g$	Borehole ground temperature of house i at hour t in segment j [$^{\circ}\text{C}$]
$T_{i,t}$	In-house temperature of house i at hour t [$^{\circ}\text{C}$]
$T_{in/out,i,t}$	Inlet/outlet temperature at the GHX terminal of house i at hour t [$^{\circ}\text{C}$]

D. Sub- and Super-scripts

*	Variable converted to a parameter
A	External glazed surfaces
E	Building envelope
F	Forecasted
r	room
up/dn	Up/down

I. INTRODUCTION

THE total residential energy use in 2016 in Canada was 1458 PJ, of which 60% was used for space heating and cooling applications [1]. This energy is mainly supplied by electric and natural gas Heating Ventilation and Air Conditioning (HVAC) systems which add to Green House Gas (GHG) emissions. Hence, there is a need for alternative, low cost, and more efficient clean energy sources for residential and commercial heating/cooling. In this context, the development, application, and market participation of Ground Source Heat Pump (GSHP) systems could play a significant role. However, for these systems to have an impact on the grid and its associated markets, aggregation through agents, typically referred to as a load aggregators, is a good option to add flexibility to electricity markets [2], since individual customer GSHP systems are too small and not eligible to participate in wholesale electricity markets.

GSHP systems are generally preferred over other types of heat pump systems because the ground temperature remains almost constant throughout the year, being usually higher than the ambient temperature in winter and lower than the ambient in summer [3]. GSHP systems are a viable energy-efficient alternative to traditional furnaces and air conditioners, and can help reduce the energy use for heating/cooling by up to 60% [4]. These systems are categorized based on the Ground Heat eXchanger (GHX) configuration used, i.e., open loop, closed loop, or hybrid [5].

Studies on the control strategy for GSHPs to provide different services, such as peak load shifting and primary frequency control in small communities have been reported in [6], [7]. Other works present the GSHP operational performance and its advantages with respect to cost and GHG emission reductions, as compared to conventional heating systems [4]. However, most of these works do not consider detailed household thermal models and mainly focus on small-scale applications only, without considering aggregated GSHP loads in the context of bulk power grids and their associated markets.

Different bidding strategies have been proposed for load aggregator participation in electricity markets. A two-stage market framework to optimize the dispatch of flexible heating/cooling loads to minimize the aggregator's total electricity cost has been reported in [8]. Day-Ahead Market (DAM) frameworks to maximize the aggregator's short-term profit from the sale of energy and Demand Response (DR) services, while minimizing the consumption by flexible loads, such as air conditioners, dryers, and electric vehicle charging stations, are proposed in [9] and [10]. However, there are no works that examine the power consumption reduction of aggregated GSHP loads vis-à-vis conventional HVAC loads, and no models have been proposed yet for load aggregators' optimal power dispatch of heating/cooling loads with GSHP systems.

A new method is presented in [11] for the optimal design of GSHPs systems, combining financial and thermodynamic characteristics, to obtain estimates of the GSHP total costs and optimal Coefficient of Performance (COP). Studies on the long-term performance of GHX with negligible effects of groundwater movement, considering a wide range of possible field configurations and working conditions, can be found in [12]. Different numerical and analytical models have been reported in [13] and [14], which estimate the thermal behavior and monitor the operation of GHX systems, focusing on the physical configuration and geometrical characteristics of the boreholes. However, there are not works that discuss the operational performance of large-scale aggregated GSHP systems with vertical U-pipe GHX configuration, or analyze their integration with power utility operations to participate in electricity markets, for the provision of various grid services by residential customers through aggregators.

Based on the aforementioned discussion, in this paper, based on [15], a detailed GSHP model is proposed of a vertical U-pipe GHX configuration, is implemented to provide residential space heating/cooling, and the integration of several such GSHPs with a load aggregator and their combined operation is formulated, with the aggregator determining the optimal heating/cooling load dispatch of all houses to control their in-house temperatures to minimize overall costs. Therefore, the main objectives and contributions of this paper are the following:

- Develop a novel mathematical model for residential space heating/cooling of the borehole of a GSHP system with vertical U-pipe GHX configuration, not considered in [15], accounting for its thermal and geometric characteristics and integrated with the thermal model in closed-loop.
- Develop a framework, not considered in [15], in which the GSHP unit can switch between heating and cooling modes, even within the same day, thus allowing carrying out long-term simulations.
- Propose a GSHP load aggregator model for its participation in wholesale electricity markets as a price-taker participant, to provide peak load reduction and load shifting by optimally dispatching the aggregated GSHP loads with two different operating strategies: Base Case, that seeks to maximize the house comfort, and the Proposed Case, which is a two-stage operation in DAM and Real-

Time Market (RTM) to minimize the aggregator's total electricity cost.

- Introduce a mathematical model of an existing conventional HVAC system in the load aggregator model, to compare its operational performance with that of the GSHP system considering the Base and Proposed strategies.
- Carry out simulations for the whole year of 2019 considering the integration of several GSHPs/HVACs with the load aggregator and their respective optimal operation strategies in the DAM and RTM whose mathematical models have been augmented with a set of coordination equations to manage the switching between heating and cooling operations of the GSHP/HVAC systems when operating over the yearly cycle, and was not considered in [15].
- Carry out a techno-economic analysis, not included in [15], to examine the feasibility and long-term profitability for the load aggregator to invest in GSHP systems operating with the proposed strategy.

The rest of the paper is organized as follows: In Section II, the detailed mathematical model of the proposed GSHP system with a vertical U-pipe GHX configuration is presented, together with a brief description of the house thermal and HVAC models. The mathematical model of the proposed two-stage strategy and the Base Case for the load aggregator is detailed in Section III. The test system and simulation results are presented and discussed in Section IV, illustrating the advantages of the proposed models and approach. The main conclusions and contributions of this work are highlighted in Section V.

II. THERMAL LOAD MODELING

A. GSHP System and Model

The principle of operation of a GSHP unit is characterized by its ability to provide space heating and cooling [16]. In the heating cycle, shown in Fig. 1, the heat transferred from the ground to the anti-freeze solution/water in the borehole is transferred to the refrigerant solution through the evaporator, which is directed by the reversing valve to the compressor, adding pressure to the refrigerant vapour, thus increasing its temperature. The heat is transferred to the house through the condenser, and finally the expansion valve lowers the compressor pressure, with the refrigerant becoming a low-temperature liquid again. On the other hand, in the cooling cycle, the heat is pumped from the household to the ground, in the reverse direction of the heating cycle [3].

Systems with vertical U-pipe based GHX are preferred in suburban areas because their installation does not require large spaces [17], and thus these have been considered for the studies presented here. The proposed GSHP model considers the mass flow rates of the ground water circulating in the GHX and the heat pump, the power consumption of the compressor, and the heat transfer of the evaporator and condenser, based on [5].

In order to reduce the complexity of the considered heat transfer processes, while maintaining proper accuracy of the thermal load model, the following assumptions are made:

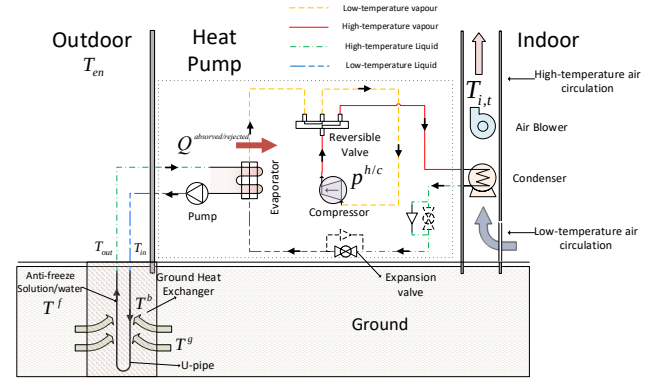


Fig. 1: Generic configuration of GSHP with the arrows depicting the heating cycle [3].

- Seasonal variation of ground temperature is not considered.
- Indoor air temperature is homogeneous, i.e., No heat loss is considered inside the house.
- Temperature of the building envelope is homogeneous.
- Thermal comfort parameters remain within the recommended limits.
- The GSHP system operates either in cooling or heating mode.
- Since the time resolution of the model is one hour, a steady-state heat exchange process is assumed to model thermal systems.

1) *Performance of the GSHP*: The COP and Energy Efficiency Ratio (EER) of the GSHP for each house i at each hour t are calculated as follows [7]:

$$COP_{i,t}^{HP} = COP_{ref}^{HP} \left[A_h + B_h \left(\frac{T_{i,t}^{out}}{T_{ref}^{HP}} \right) + C_h \left(\frac{T_{ref}^{HP}}{T_{i,t-1}} \right) \right] \quad (1)$$

$$EER_{i,t}^{HP} = EER_{ref}^{HP} \left[A_c + B_c \left(\frac{T_{i,t}^{out}}{T_{ref}^{HP}} \right) + C_c \left(\frac{T_{ref}^{HP}}{T_{i,t-1}} \right) \right] \quad (2)$$

where $COP_{i,t}^{HP}$ and $EER_{i,t}^{HP}$ are the calculated COP and EER of the GSHP, in heating and cooling mode, respectively; $A_{h/c}$, $B_{h/c}$, and $C_{h/c}$ are coefficients of a linear data-fitting obtained from the GSHP datasheets; $T_{i,t}^{out}$ is the outlet temperature at the GHX terminal; T_{ref}^{HP} is the GSHP's reference temperature of operation (283 °K); $T_{i,t}$ is the indoor air temperature; and COP_{ref}^{HP} and EER_{ref}^{HP} are the rated COP and EER of the GSHP, respectively.

2) *House Heat Transfer Balance*: The following relations represent the inter-temporal house heat transfer and the GHX contribution that affects the in-house temperature at hour t :

$$Q_{in,i,t} = (1 - \sigma)\phi_t + Q_{G,i,t} \quad (3)$$

$$Q_{out,i,t} = U_A(T_{i,t-1} - T_{en,t}^F) + U_E(T_{i,t-1} - T_{E,i,t}) \quad (4)$$

All variables and parameters in these and other equations are defined in the Nomenclature section. In (3), the first term $Q_{GHX}^{h/c}$ corresponds to the heat transfer into the house from the GHX U-pipe based system, the second term represents the solar radiation through the glazed surfaces, with the incidence factor representing the transmittance loss of the solar radiation power, which is effectively reflection [18]; and finally the internal heat gains of the house are given by the third term. In (4), the first term denotes the heat transfer from inside the house to the outside environment through the external glazed surfaces, and the second term denotes the heat transfer from inside the house through the external walls and ceiling.

3) *In-house Temperature Relation*: The inside air temperature of house i at hour t , depends on the temperature at time $t - 1$, the power consumption of the GSHP unit at time t , and the heat transfers occurring inside the house, as follows:

$$T_{i,t} = T_{i,t-1} + \frac{Q_{in,i,t} - Q_{out,i,t}}{H_{P_r}} + \frac{Q_{i,t}^h}{H_{P_r}} + \tilde{\alpha}_i^P p_{i,t}^{res} - \frac{Q_{i,t}^c}{H_{P_r}} \quad \forall i \in I, t \in T \quad (5)$$

where

$$Q_{i,t}^h = COP_{i,t}^{HP} p_{i,t}^h \quad (6)$$

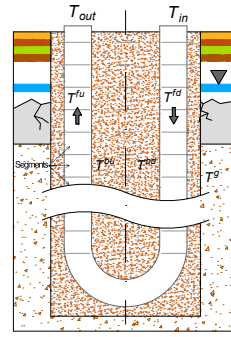
$$Q_{i,t}^c = EER_{i,t}^{HP} p_{i,t}^c \quad (7)$$

determine the heat $Q_{i,t}^h$ injected to the house or heat $Q_{i,t}^c$ extracted from the house, based on the GSHP operation mode

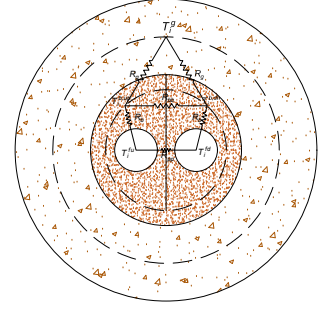
The first term in (5) represents the in-house temperature at $t - 1$. The temperature change due to inter-temporal house heat transfers, given in (3) and (4), are expressed by the second term. The third term denotes the temperature change because of heat transfer from the GSHP system operating in heating mode to the house, the fourth term represents the temperature change due to heat provided by the secondary thermal resistances $p_{i,t}^{res}$ multiplied by the factor $\tilde{\alpha}_i^P$, which are used occasionally for peak heating in severe weather conditions. The last term represents the temperature change because of heat transfer from the house to the GSHP system operating in cooling mode. In this work, the flexibility of GSHP units to switch their operation mode from heat to cooling, and vice versa, within the same day, is modeled. This capability is demonstrated in [19] and [20] based on experimental performance analyses of facilities in Germany and China, respectively.

4) *External Wall Temperature*: The temperature of the external walls of the house i at hour t depend on the solar radiation and the heat transfer between the external environment and the external walls of the house, as follows:

$$T_{Ei,t} = T_{Ei,t-1} + \frac{\sigma\phi_t + U_E(T_{Ei,t-1} - T_{en,t}^F)}{H_{P_E}} \quad \forall i \in I, t \in T \quad (8)$$



(a) Single U-pipe diagram.



(b) Cross section of a single segment of the U-pipe vertical borehole.

Fig. 2: Vertical GHX configuration [24].

5) *Comfort Limits*: The following constraints ensures that the in-house temperature is within the end-user's comfort range:

$$\underline{T}_i \leq T_{i,t} \leq \overline{T}_i \quad \forall i \in I, t \in T \quad (9)$$

6) *Cycling Constraint*: The following equation guarantees that the temperature inside a house at the end of day is the same as that of the initial temperature T_i^o for the next day:

$$T_{i,T} = T_i^o \quad \forall i \in I, t = T = 24 \quad (10)$$

7) *Borehole Thermal Model*: The borehole model is built to represent the vertical and radial heat transfer processes along its depth [7], [21]. The U-pipe is split into 50 equal segments j of height 5 meters each, as seen in Fig. 2a. Each segment j yields five different nodes, as per Fig. 2b, which represent the fluid temperature inside each leg of the U-pipe $T_{i,t,j}^{f,dn}$ and $T_{i,t,j}^{f,up}$ (one leading the fluid up and the other down), the temperatures of the grout regions $T_{i,t,j}^{b,dn}$ and $T_{i,t,j}^{b,up}$, and the temperature of the surrounding ground $T_{i,t,j}^g$. Each node has a thermal capacitance and shares a thermal resistance with every adjacent node, which can be calculated using the following equations based on GHX geometric and thermal properties [22]:

$$R_{bb} = \frac{S}{k_b(d_b - d_{pe})dz} \quad (11)$$

$$R_{pp} = \frac{S - d_{pe}}{k_b d_{pe} dz} \quad (12)$$

$$R_b = \frac{1}{\pi k_b dz} \log \left(\frac{d_x}{d_{pe} \sqrt{\frac{4S}{\pi/d_{pe}} + 1}} \right) \quad (13)$$

$$R_g = \frac{1}{\pi k_g dz} \log \left(\frac{d_g}{d_b} \right) \quad (14)$$

Finally, Lax-Wendroff finite difference approximations, as per [23], are applied to the heat-flow equations, considering that v is constant, resulting in the following expressions [24]:

$$\begin{aligned}
T_{i,t,j}^{f,dn} = & T_{i,t-1,j}^{f,dn} - \frac{v\Delta t}{2\Delta z} \left\{ [T_{i,t-1,j+1}^{f,dn} - T_{i,t-1,j-1}^{f,dn}] \right. \\
& \left. - \frac{1}{\Delta z} [T_{i,t-1,j+1}^{f,dn} - 2T_{i,t-1,j}^{f,dn} + T_{i,t-1,j-1}^{f,dn}] \right\} \\
& - \frac{\Delta t}{H_{P_f}} \left[\frac{T_{i,t-1,j}^{f,dn} - T_{i,t-1,j}^{f,up}}{R_{pp}} + \frac{T_{i,t-1,j}^{f,dn} - T_{i,t-1,j}^{b,dn}}{R_b} \right] \\
& \forall i \in I, t \in T, j \in J
\end{aligned} \tag{15}$$

$$\begin{aligned}
T_{i,t,j}^{f,up} = & T_{i,t-1,j}^{f,up} + \frac{v\Delta t}{2\Delta z} \left\{ [T_{i,t-1,j+1}^{f,up} - T_{i,t-1,j-1}^{f,up}] \right. \\
& \left. - \frac{1}{\Delta z} [T_{i,t-1,j+1}^{f,up} - 2T_{i,t-1,j}^{f,up} + T_{i,t-1,j-1}^{f,up}] \right\} \\
& - \frac{\Delta t}{H_{P_f}} \left[\frac{T_{i,t-1,j}^{f,up} - T_{i,t-1,j}^{b,up}}{R_b} - \frac{T_{i,t-1,j}^{f,dn} - T_{i,t-1,j}^{f,up}}{R_{pp}} \right] \\
& \forall i \in I, t \in T, j \in J
\end{aligned} \tag{16}$$

$$\begin{aligned}
T_{i,t,j}^{b,dn} = & T_{i,t-1,j}^{b,dn} + \frac{\Delta t}{H_{P_b}} \left\{ \frac{T_{i,t-1,j}^{f,dn} - T_{i,t-1,j}^{b,dn}}{R_b} \right. \\
& \left. + \frac{T_{i,t-1,j}^{b,dn} - T_{i,t-1,j}^{b,up}}{R_{bb}} - \frac{T_{i,t-1,j}^{b,dn} - T_{i,t-1,j}^g}{R_g} \right\} \\
& \forall i \in I, t \in T, j \in J
\end{aligned} \tag{17}$$

$$\begin{aligned}
T_{i,t,j}^{b,up} = & T_{i,t-1,j}^{b,up} + \frac{\Delta t}{H_{P_b}} \left\{ \frac{T_{i,t-1,j}^{f,up} - T_{i,t-1,j}^{b,up}}{R_b} \right. \\
& \left. - \frac{T_{i,t-1,j}^{b,dn} - T_{i,t-1,j}^{b,up}}{R_{bb}} - \frac{T_{i,t-1,j}^{b,up} - T_{i,t-1,j}^g}{R_g} \right\} \\
& \forall i \in I, t \in T, j \in J
\end{aligned} \tag{18}$$

$$\begin{aligned}
T_{i,t,j}^g = & T_{i,t-1,j}^g + \frac{\Delta t}{H_{P_g}} \left\{ \frac{T_{i,t-1,j}^{b,dn} - T_{i,t-1,j}^g}{R_g} \right. \\
& \left. + \frac{T_{i,t-1,j}^{b,up} - T_{i,t-1,j}^g}{R_g} \right\} \quad \forall i \in I, t \in T, j \in J
\end{aligned} \tag{19}$$

The inlet temperature at the terminal of the GHX borehole depends on the GSHP operation mode, cooling and heating respectively, and can be expressed as follows [7]:

$$T_{i,t}^{in} = T_{i,t-1}^{out} + \frac{Q_{i,t}^{rej}}{c_f \dot{m}_f} \tag{20}$$

$$T_{i,t}^{in} = T_{i,t-1}^{out} - \frac{Q_{i,t}^{abs}}{c_f \dot{m}_f} \tag{21}$$

where $Q_{i,t}^{rej}$ is the heat transferred to the GHX unit, and $Q_{i,t}^{abs}$ is the heat injected by the GHX unit to the household, which can be calculated as follows:

$$Q_{i,t}^{rej} = Q_{i,t}^c + p_{i,t}^c \tag{22}$$

$$Q_{i,t}^{abs} = Q_{i,t}^h - p_{i,t}^h \tag{23}$$

Equation (20) and (21) can then be written in a composite form to represent the inlet temperature:

$$T_{i,t}^{in} = T_{i,t-1}^{out} + (1 - Z_{a,i,t}) \frac{Q_{i,t}^c + p_{i,t}^c}{c_f \dot{m}_f} - Z_{a,i,t} \frac{Q_{i,t}^h - p_{i,t}^h}{c_f \dot{m}_f} \tag{24}$$

where the binary parameter $Z_{a,i,t} = \{1, 0\}$ is used to define whether the system is in heating or cooling mode, respectively.

B. HVAC Model

The indoor temperature of each house i at hour t is dependent on the temperature at time $t - 1$, the power consumption of the HVAC unit at time t , and the heat transfers in the house due to solar radiation, between the room and the environment, and between the room and the external walls of the house, and can be defined as follows:

$$\begin{aligned}
T_{i,t} = & T_{i,t-1} \pm \tilde{\alpha}_i^P p_{i,t}^{h/c} + \frac{(1 - \sigma)\phi_t + Q_{G,i,t}}{H_{P_r}} \\
& - \frac{U_A(T_{i,t-1} - T_{en,t}^F) - U_E(T_{i,t-1} - T_{E,i,t})}{H_{P_r}} \\
& \forall i \in I, t \in T
\end{aligned} \tag{25}$$

Equations (8) to (10) representing the house thermal characteristic for the external wall temperature, the house comfort limits, and the house temperature cycling constraint, respectively, are also included in the HVAC model.

III. GSHP/HVAC LOAD AGGREGATOR OPERATIONS STRATEGIES

A. Proposed Two-Stage Strategy

The objective of the GSHP/HVAC load aggregator is to determine the optimal heating/cooling load dispatch of all houses to minimize its total electricity procurement costs, while maintaining the in-house temperature of all customers within a comfortable range, considering the physical capacity of the GSHP/HVAC units, the thermal characteristics of each house and the ambient temperature. The load aggregator is assumed to collect information on the uncontrolled loads in the house, the house thermal and heating system characteristics, and the current and forecasted ambient temperature, in order to optimally schedule the GSHP/HVAC load of each house to minimize its cost of total electricity purchase from the electricity market. The following two-stage strategy for the aggregator is proposed, which interacts with the DAM and the RTM, as illustrated in Fig. 3:

- *Stage 1:* The aggregator schedules the thermal load of each house to minimize its total electricity cost using a forecast of the DAM price $\lambda_t^{DAM_F}$, while satisfying the houses' indoor temperature comfort ranges. The total scheduled load of the aggregator is submitted as a demand bid to the DAM, and it is assumed that the entire bid

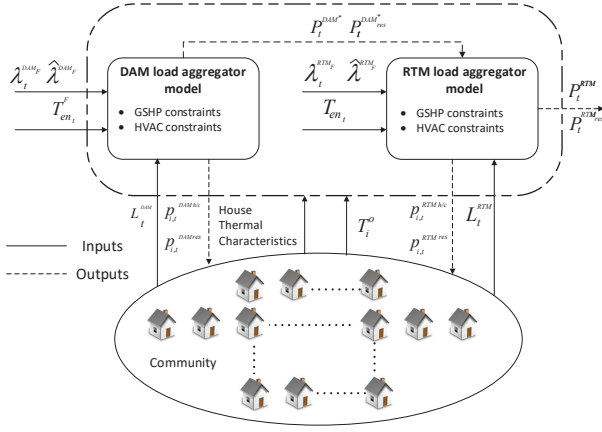


Fig. 3: Framework of the load aggregator participating in the electricity market.

quantity P_t^{DAM*} is cleared, which is then an input to the aggregator's real-time operation model.

- **Stage 2:** The load aggregator updates the forecast of local ambient temperature, RTM price forecast, and energy consumption by uncontrolled loads, and uses P_t^{DAM*} from the DAM. The aggregator then solves the real-time operation model to determine the final thermal load dispatch and other associated decision variables, assuming here that the RTM operation takes place one hour ahead.

1) Day-Ahead Load Aggregator Model:

- **Objective Function:** The aggregator seeks to minimize the total cost of purchasing electricity from the DAM, given as follows:

$$J_1 = \sum_t \left[\lambda_t^{DAMF} P_t^{DAM} + \hat{\lambda}_t^{DAMF} P_t^{DAMres} \right] \quad (26)$$

where the first term represents the load procurement cost at hour t at DAM price, and the second term denotes the total cost of serving the aggregated electrical load from the secondary thermal resistances, assuming that it is procured at the maximum DAM price [25].

- **Total Aggregated Load:** The total load procured by the aggregator at hour t is given by:

$$P_t^{DAM} = L_t^{DAM} + \sum_i p_{i,t}^{DAMh} + \sum_i p_{i,t}^{DAMc} \quad (27)$$

$\forall i \in I, t \in T$

$$P_t^{DAMres} = \sum_i p_{i,t}^{DAMres} \quad \forall i \in I, t \in T \quad (28)$$

The first term in (27) corresponds to the aggregated uncontrolled load in the community, and the second and third terms represent the aggregated GSHP/HVAC load during heating and cooling operation, respectively, with the later two terms being mutually exclusive. Equation (28) defines the aggregated load from the secondary

thermal resistances of houses.

- **Capacity Limits:** These ensure that the thermal system power consumption are within their capacity limits, as follows:

$$0 \leq p_{i,t}^{DAMh/c} \leq \overline{P_i^{h/c}} \quad \forall i \in I, t \in T \quad (29)$$

$$0 \leq p_{i,t}^{DAMres} \leq \overline{P_i^{res}} \quad \forall i \in I, t \in T \quad (30)$$

- **Operation Coordination:** The following constraints guarantee that the GSHP/HVAC unit operates either in heating or cooling mode:

$$p_{i,t}^{DAMc} \leq (1 - Z_{a,i,t})M \quad \forall i \in I, t \in T \quad (31)$$

$$p_{i,t}^{DAMh}, p_{i,t}^{DAMres} \leq Z_{a,i,t}M \quad \forall i \in I, t \in T \quad (32)$$

where M is a large number.

- **Thermal Load Modeling:** Includes the HVAC or GSHP operational constraints (3)-(25) as appropriate, formulated for DAM operation.

2) Real-time Load Aggregator Model:

- **Objective Function:** The aggregator seeks to minimize its total penalties/credits payable for any deviations in the real-time load dispatch from the DAM dispatch, at the RTM price, as follows:

$$J_2 = \sum_t \left[\lambda_t^{RTMF} \Delta P_t + \hat{\lambda}_t^{RTMF} \Delta P_t^{res} \right] \quad (33)$$

where

$$\Delta P_t = |P_t^{DAM*} - P_t^{RTM}| \quad \forall t \in T \quad (34)$$

$$\Delta P_t^{res} = |P_t^{DAM*res} - P_t^{RTMres}| \quad \forall t \in T \quad (35)$$

In (33), the first term denotes the penalties/credits paid by the aggregator for any deviation in the total aggregated load from DAM dispatch at the RTM price, and the second term denotes the total penalties/credits for deviation of the aggregated electrical load of the secondary resistances at the maximum RTM price. The model is subject to constraints (27) to (31) and the thermal load model relations (3)-(25) for either GSHP or HVAC systems, as appropriate, formulated for RTM operation.

The RTM load aggregator model presented above is non-linear because of (34) and (35), which is linearized using mutually exclusive non-negative auxiliary variables ΔP_t^+ and ΔP_t^- that represent the deviations of the aggregator's demand in RTM as compared to DAM operation, as follows [26]:

$$\Delta P_t = \Delta P_t^+ + \Delta P_t^- \quad \forall t \in T \quad (36)$$

$$\Delta P_t^+ = P_t^{RTM} - P_t^{DAM*} \quad \forall t \in T \quad (37)$$

$$\Delta P_t^- = P_t^{DAM*} - P_t^{RTM} \quad \forall t \in T \quad (38)$$

And similarly for ΔP_t^{res}

B. Base Case Strategy

The proposed strategy of the load aggregator is compared with a Base Case strategy, in which the total power consumption of the GSHP/HVAC system is determined based on maximizing the customer comfort by minimizing the deviation of the in-house temperature from a reference set point, as follows:

$$J_3 = \sum_i \sum_t |T_{i,t}^{Ref} - T_{i,t}| \quad (39)$$

This objective function is nonlinear, but can be readily linearized applying the same principle as in (36)-(38), i.e., considering mutually exclusive non-negative variables $\Delta T_{i,t}^+$ and $\Delta T_{i,t}^-$, subject to (27)-(31) and the GSHP/HVAC system constraints as appropriate.

IV. RESULTS AND DISCUSSIONS

A. Test System

The present study considers a GSHP/HVAC load aggregator in Ontario, Canada, that submits demand bids to the Independent Electric System Operator (IESO) and purchases electricity for its clients. The weather data is from 2019 [27], the solar irradiation for that year and internal heat gains in a typical house are obtained from [28] and [29], respectively. The load aggregator is assumed to provide electricity to 800 houses, as in [15], with each house assumed to have the same thermal characteristic, and all customers assumed to stay at home from 6 PM to 8 AM, for simplicity and without loss of generality.

All model parameters are presented in the following tables: Table I illustrates all the thermal parameters of the GHX model; the recommended thermal comfort ranges are presented in Table II, the parameters for the house geometric and thermal characteristics are given in Table III and the characteristics of conventional HVAC system and detailed GSHP system, obtained from [7], [8], [30], are presented in Table IV.

TABLE I: Geometric-thermal characteristics of the GHX [22]

Item	Value
Number of segments	50
Borehole depth [m]	250
Grout thermal capacitance H_{P_b} [J/°C]	537.3
Ground thermal capacitance H_{P_g} [J/°C]	2110.5
Fluid thermal capacitance H_{P_f} [J/°C]	365.7
Pipe to pipe thermal resistance R_{pp} [°C/W]	0.291
Borehole conductive thermal resistance R_b [°C/W]	0.061
Grout-to-Grout thermal resistance R_{bb} [°C/W]	0.239
Grout-to-ground thermal resistance R_g [°C/W]	0.051
Fluid specific heat c_f [J/kg °C]	4361
Fluid mass flow rate $\dot{m}_f$ [kg/s]	0.53
Velocity of the underground fluid v [m/s]	0.032

TABLE II: Household indoor temperature ranges for thermal comfort

Time	Temperature range [°C]	
	Minimum	Maximum
6 PM to 8 AM	20	22
9 AM to 5 PM	17	25

TABLE III: Household geometric and thermal characteristics [7]

Item	Value
Area [m ²]	2115
Volume [m ³]	525
Glazed surface portion [%]	9.5
R ceiling [m ² °C /W]	7.67
R external walls [m ² °C /W]	4.67

The electricity prices were obtained from [31], considering the 3h pre-dispatch price of Ontario as the DAM price forecast $\lambda_t^{DAM_F}$, and the Hourly Ontario Energy Prices (HOEPs) as the RTM price forecast $\lambda_t^{RTM_F}$. The uncontrolled loads, i.e., loads other than HVAC/GSHPs, were obtained from [32], for day-ahead profiles of operation, and the RTM load profiles for the uncontrolled loads were obtained assuming, for each hour, a normal distribution with L_t^{DAM} as mean and a standard deviation of 25% of this value, as per [33], to model a reasonable variation with respect to the DAM uncontrolled load profile.

Observe that, for cost-effectiveness, the GSHP system capacity is typically designed to provide the majority of the household's annual heating energy requirement, with the occasional peak heating load that occurs during severe weather conditions being met by a supplementary heating system, i.e., secondary thermal resistances [34]; therefore, to minimize the use of these resistances, their operation is penalized in the model by costing them at the maximum electricity price of the day.

It is assumed in this work that customers are not equipped with any Home Energy Management System (HEMS) with which they could optimize their GSHP/HVAC operation and minimize costs. Furthermore, for the case of customers with programmable thermostats, is assumed that these are not programmed, prioritizing comfort over saving. In this context, the worst case scenario is considered here for the Base Case, or business as usual, to better highlight the advantages of aggregating GSHP/HVAC flexibility, which does not require

TABLE IV: GSHP and HVAC characteristics [8], [30]

GSHP	
Model	BP030
Cooling Capacity [Btu/hr]	28500
Heating Capacity [Btu/hr]	20500
EER_{ref}^{HP}	19.4
COP_{ref}^{HP}	4.3
HVAC	
Power capacity [kW]	7
Heating/cooling capability	0.4

direct customer involvement and presents multiple advantages for electricity markets [2].

B. Study Cases

Simulations were carried out for the whole of 2019, and four sample days were specifically selected to analyze the daily operation of the GSHP/HVAC units: January 31, February 4, July 20 and September 9, since these are the coldest day in winter, the warmest day in winter, the warmest day in summer, and the coldest day in summer, respectively. Also, a comparative analysis on the performance of the GSHP model for optimal heating/cooling power dispatch as a viable alternative to existing HVAC systems from a load aggregator's perspective, was performed. Note that the GSHP optimization model is a Non-Linear Programming (NLP) problem because of (6) and (7). The mathematical models were implemented in GAMS, and solved using the MINOS solver.

The load schedules for 2019 are shown in Fig. 4 for DAM operations in the Proposed Two-Stage Strategy (the results for RTM operation yield similar conclusions) and the Base Case, for both the aggregated GSHP/HVAC technologies. Observe that in both technologies, the total power scheduled for the Base Case is slightly higher as compared to the proposed strategy. Additionally, Note in Fig. 4a that the GSHP loads scheduled in the winter months are considerable higher as compared to that scheduled in the summer. It is important to mention that the secondary thermal resistances are required only on some days within the first two months of the year during severe cold weather conditions. On the other hand, observe that the power consumption during the summer months are higher as compared to winter months with the aggregated HVAC annual dispatch, as shown in Fig. 4b. The power demand is higher in the Base Case as compared to the proposed strategy, as expected, and thus, in Fig. 5, the aggregator's daily electricity cost in the Base Case is higher than the daily cost of the proposed strategy.

The borehole inlet and outlet temperature profiles at the terminals of the U-pipe, the borehole grout temperature, and the ground temperature are shown over a one year period in Fig. 6. Note that when the GSHP operates in heating mode during the first few months of the year (typically January to March), the outlet temperature is higher than the inlet temperature, and both profiles are lower than the grout and ground temperature. This is because, as the fluid flows through the U-pipe, heat is absorbed from the surrounding ground and the borehole grout, thus increasing the difference between inlet and outlet temperatures, while the inlet and outlet temperatures decrease; note also that the grout temperature decreases, following the behavior of the fluid temperature. The ground temperature increases because it has the lowest initial temperature, but its change rate starts to decrease when all other temperatures are lower in comparison, due to their different thermal characteristics, such as thermal conductance (resistances). When the GSHP operates in cooling mode in the second part of the year (April to September), the temperature difference decreases until the inlet temperature surpasses the outlet temperature, and both profiles are higher than the grout

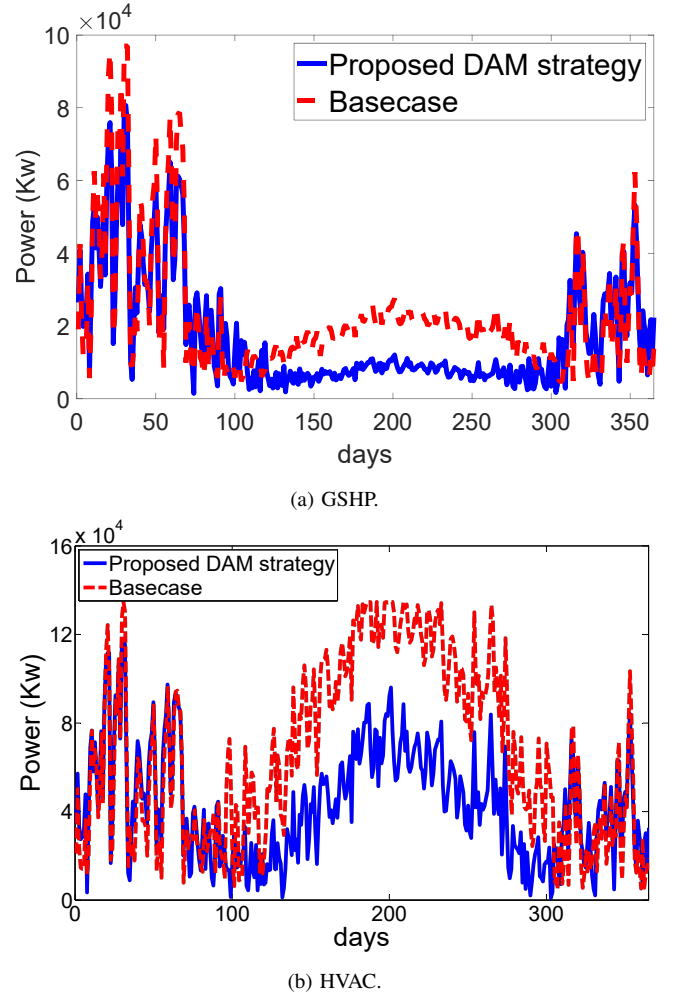


Fig. 4: Annual schedule of the aggregated GSHP/HVAC load.

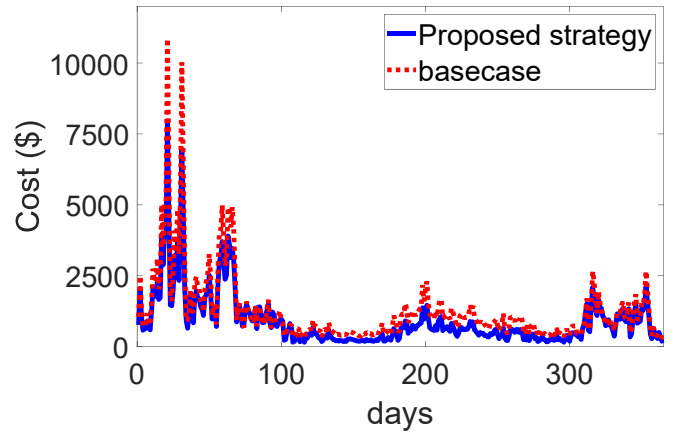


Fig. 5: GSHP aggregator total annual cost.

and ground temperature. This is because heat is transferred to the surrounding ground, and thus the temperature difference between inlet and outlet temperatures begins to increase; additionally, the grout temperature starts to decrease, along with the ground temperature, but at a lower rate of change, due to its different thermal characteristics than the other GHX thermal components. Finally, near the end of year (October

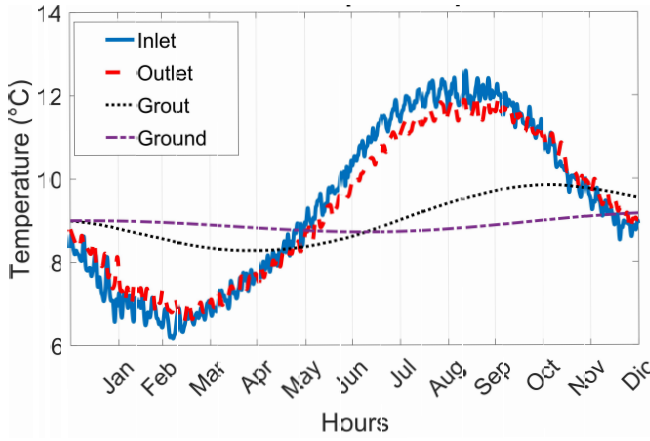


Fig. 6: Annual temperature profile of the borehole.

to December), i.e., at the start of the winter season, the GSHP returns to operate mostly in heating mode, as it was the case during the first few months of the year. Finally, the ground temperature presents the smallest variations among all temperature profiles, as expected, and the grout temperature profile is in accordance with the physical and anticipated system behavior, being lower than the ground temperature in the first half of the year, i.e., heat flowing from the ground to the grout, and vice-versa during the last 6 months.

The daily aggregated load dispatch profiles and electricity prices for the days analyzed, are shown in Figs. 7 and 9, respectively, for DAM operations in the Proposed Two-Stage Strategy (the results for RTM operations yield similar conclusions) and the Base Case, for both the aggregated GSHP/HVAC technologies. For the GSHP power dispatch, the units operate at full capacity for the entire day (see Fig. 7a) on the coldest day of the year for both strategies; on the other days, for the proposed DAM strategy, the peak heating/cooling demand occurs early in the morning (see Figs. 7b and 7c), or in the afternoon (see Fig. 7d), when the electricity prices are low. Note that for the base case, the heating/cooling peak demand coincides with hours when the electricity prices are high, usually late in the afternoon. Fig. 8 presents the dispatch of secondary thermal resistances with the GSHP unit to provide additional heating during the coldest period of the day. The peak heating/cooling demand profiles for the daily power dispatch with HVAC occurs late at night, as shown in Fig. 9b, and late in the afternoon, as illustrated in Fig. 9d. Also, note that the HVAC units operate at full capacity on the coldest and warmest days of the year, as depicted in Figs. 9a and 9c, respectively. Here, the aggregator significantly reduces the dispatch of controlled loads when the electricity price is high, to the extent that temperature constraints permit. The reduction in dispatch of controlled loads and the dispatch of thermal resistances is clearly reflected in the variation of in-house temperature and the aggregator total cost.

During winter, the GSHP is predominantly operating in heating mode, as shown in Fig. 10a, although it switches to cooling mode for a few hours on some days (see Fig. 10b). A similar operation behaviour is noticed during the warmest days in summer when the GSHP is predominantly operating

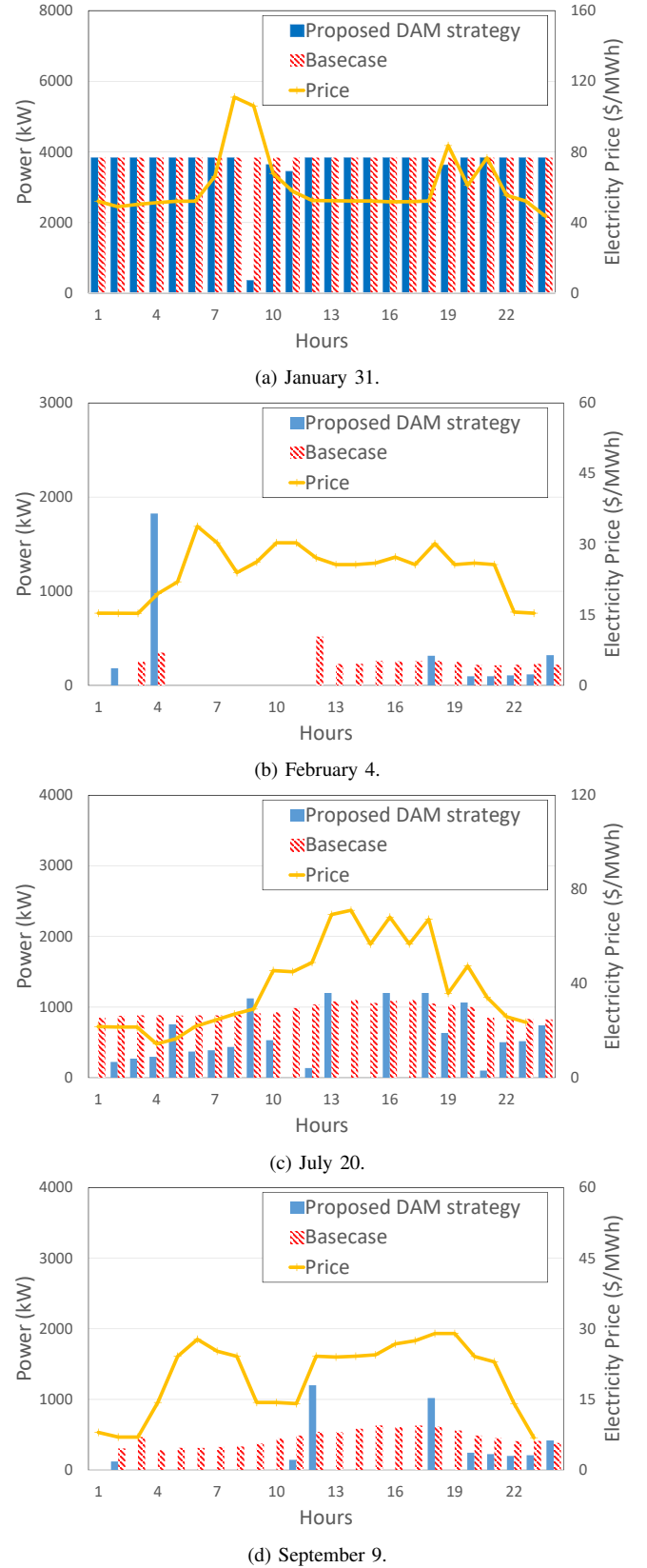


Fig. 7: Aggregated GSHP electrical load dispatch.

in cooling mode, as observed in Figs. 10c and 10d. The house temperature profiles, and the ambient temperature for each typical day (referenced with the right y-axis) are presented in

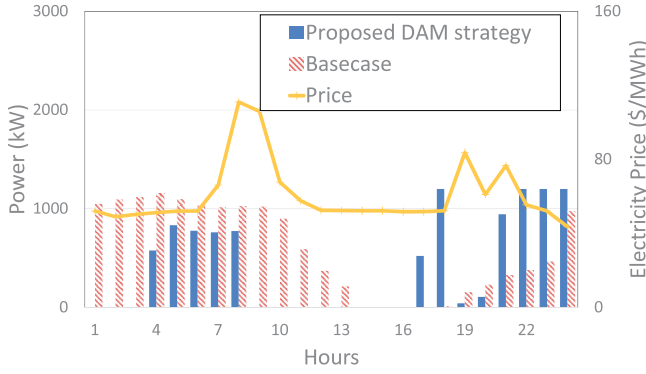


Fig. 8: GSHP secondary thermal resistance dispatch for January 31.

Figs. 11a to 11d; observe that the temperature profiles with the proposed strategy vary considerably on all these days, within the specified limits. In the Base Case, the temperature remains at the set point on all days, except on July 20 (Fig. 11c) when there is a small deviation from the set point because of the warm temperatures registered on that day. The small deviation in temperature from the set point, noted in summer months, is a consequence of the limited power capacity of the GSHP. On the other hand, in winter, such small temperature deviations from the set point in the Base Case are not observed (Fig. 11a), because of the dispatch of secondary thermal resistances.

C. Discussion

An economic impact analysis for the aggregator is carried out to examine the feasibility and long-term profitability of the proposed strategy with GSHP systems, while comparing it to existing conventional HVAC systems in the Base Case. The parameters in Table V were obtained using the historic electricity price and power demand data obtained from [31] and [35], which yield the price inflation and demand growth rated; the annual capital and operational costs of the GSHP and HVAC systems were extracted from [34]. The incremental net cash-flow diagram in Fig. 12 illustrates the total annual energy cost savings from GSHP investment as compared to an HVAC system. The investment cost will be borne by the aggregator while its accrue savings show a considerable increase in year 13 due to the avoided cost of HVAC replacement in that year.

The aforementioned models were solved for all days in 2019, yielding the results illustrated in Table VI, where the load aggregator's total electricity cost for the year decreases by 15% and 11% with the GSHP and HVAC systems, respectively, using the proposed strategy, as compared to their respective Base Cases. Furthermore, the GSHP system requires 66% less heating/cooling energy in the Base Case as compared to the HVAC, while, with the proposed strategy, the GSHP system requires 63% less heating/cooling energy than with HVAC. Finally, it is determined that the project yields an incremental Internal Rate of Return (IRR) of 7.33% that is higher than the typical Minimum Acceptable Rate of Return (MARR) of 5% to 6%, considered normally for this type of projects for a public utility [36], and is hence suitable for investment. The cost and energy savings achieved from applying the proposed strategy on GSHP systems demonstrate that these are effective

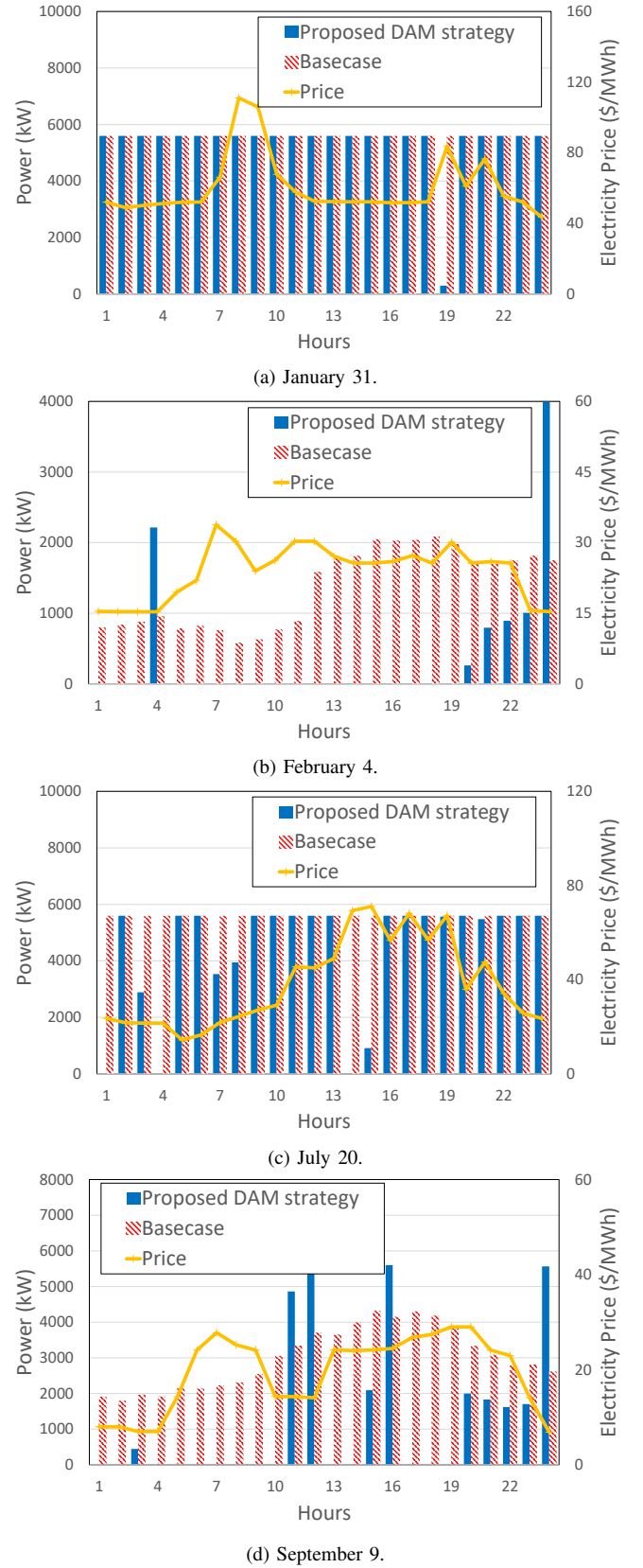


Fig. 9: Aggregated HVAC electrical load dispatch.

and economic alternatives for residential space heating/cooling applications.

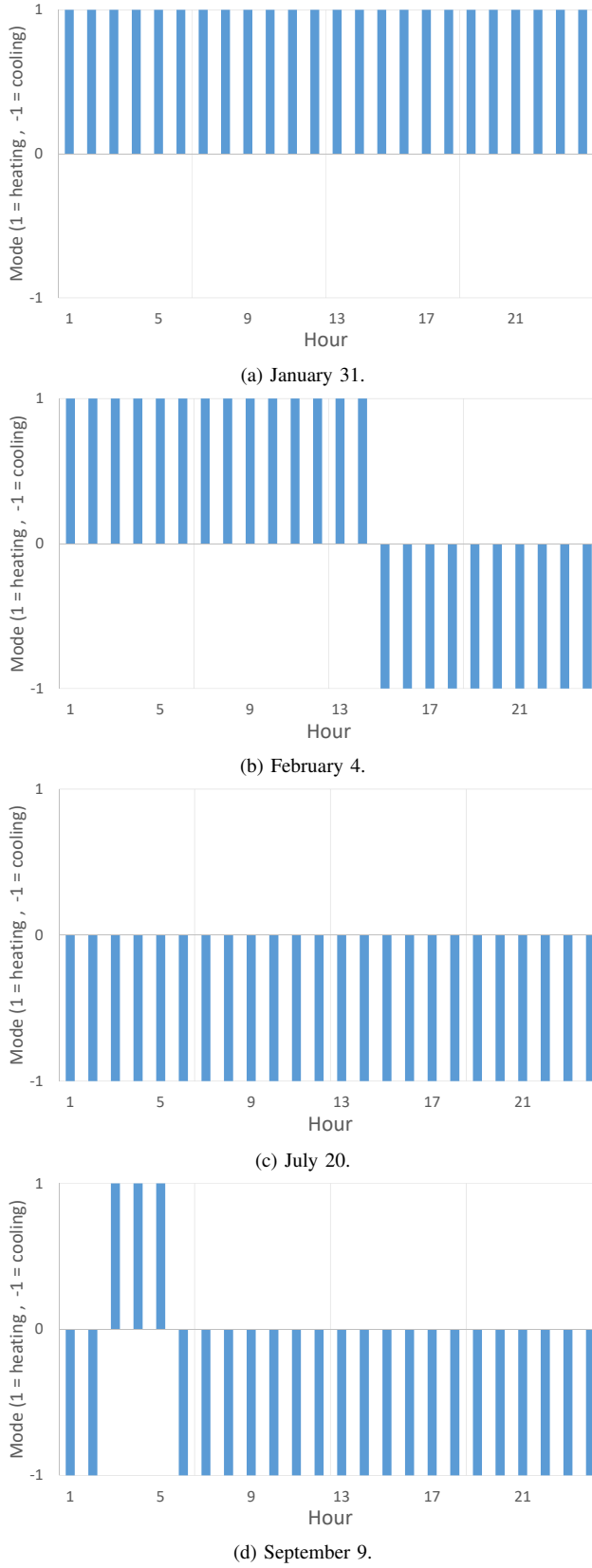


Fig. 10: GSHP operation mode, with 1 representing heating and -1 cooling.

V. CONCLUSION

Detailed mathematical model of a GSHP system with vertical U-pipe GHX configuration and a two-stage strategy for a

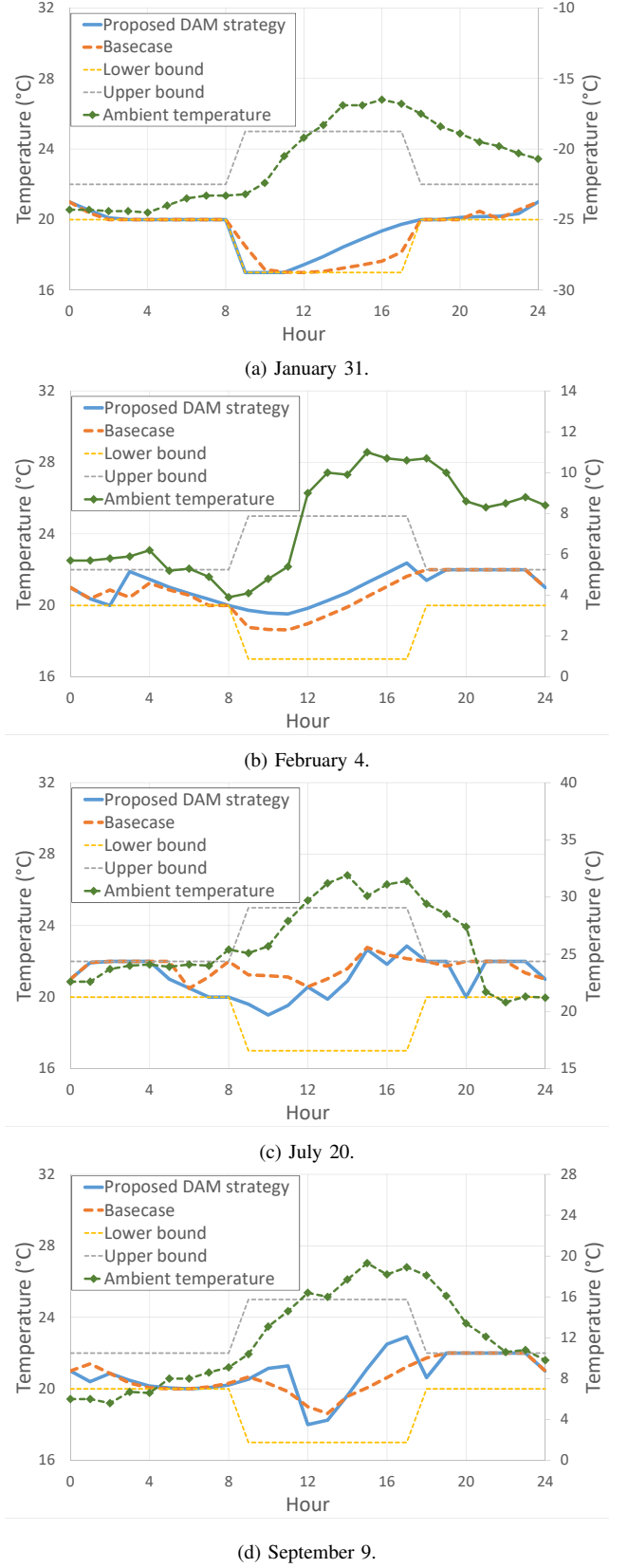


Fig. 11: Comparison of house temperature profiles.

load aggregator's have been proposed here. Thus, the thermal modeling of the residential homes, the GSHP system, and a conventional HVAC model were described first; then, DAM

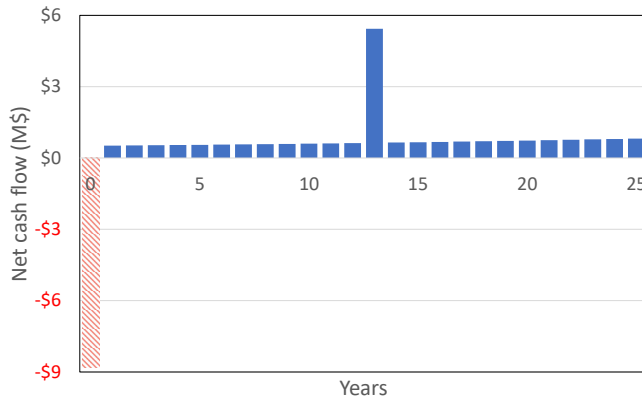


Fig. 12: Incremental net cash flow diagram of GSHP as compared with HVAC.

TABLE V: Economic parameters of GSHP/HVAC systems [31], [34], [35]

Item	GSHP	HVAC
Capital cost (\$/unit)	\$11,000	\$6,000
O&M cost (\$/unit)	\$120	\$500
Lifetime (years)	25	13
DAM/RTM price inflation	3.50%/year	
Market demand growth	0.15%/year	

TABLE VI: Comparison of GSHP versus HVAC operations

Item	GSHP		HVAC	
	Base Case	Proposed Strategy	Base Case	Proposed Strategy
Aggregator total operating cost (\$)	\$425,137 (-27%**)	\$371,157 (-15%*, -30%**)	\$585,204	\$525,881 (-11%*)
Annual heating/cooling dispatch (GWh)	6.6 (-66%**)	6.4 (-1%*, -63%**)	19.3	18.6 (-4%*)
Incremental IRR (Δ IRR)	7.33%			

* With respect to Base Case

** With respect to HVAC

and RTM aggregator models, and a base case model, were presented and discussed. A description of the test system for optimal load dispatch by an aggregator were then provided. Finally, results for different case studies were presented, analyzed, and compared in detail, demonstrating the effectiveness of the proposed two-stage strategy for optimal aggregator load dispatch of HVAC and GSHP systems, and the advantages of GSHP compared to HVAC.

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