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The impact of a demand-side management strategy in operating a hybrid geo-district energy system for a high-rise mixed-use residential building in Toronto, Canada

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ABSTRACT

In Ontario, Canada, the building thermal energy market is largely driven by the low cost of natural gas as a heating fuel source, with natural gas rates being approximately five times less per unit energy than electricity. The hybridization of geo-exchange with conventional building energy systems is a well-established means of optimizing the economics of geo-exchange and accelerating the adoption of this technology as a standard building thermal energy system. Demand-side management (DSM) is a mechanism which can be utilized in Ontario's electricity market (or others with similar demand charge structures) to manipulate a user's overall electricity cost. This case study presents the results of a project currently under development in Ontario for a hybrid geo-exchange system, comprised of an in-house Ground-Source Heat-Pump (GSHP) supplemented by a hot/chilled water district energy system. Utilizing the GSHP as a flexible load, the heat-pump is deactivated during the electrical grid's peak periods, shifting the building's demand to the district system. Transferring the load to the district results in a reduction in the high-rise building's contribution to the electrical grid's peak power demand, and consequently a reduction in the building's blended annual electricity rate. This case study illustrates the potential to reduce a high-rise building's blended annual electricity rate by up to 52%, impacting both the building's plug load and geo-exchange operating costs, proportionally. The simulated results indicate a potential geo-heating and geo-cooling operational cost savings of 14% and 67%, respectively.

INTRODUCTION

In the face of climate change, there is a prominent need for the adoption of low-carbon technology to displace our current dependence on fossil fuel-based building energy systems. According to the U.S Energy Information Administration, the building sector consumed 47.6% of total energy used in the United States (EIA 2012). In Canada the building sector contributed to 17% of the national carbon emissions by economic sector (NRCan 2017). With space heating/cooling requirements typically accounting for 50% of a building's annual energy usage, the integration of high efficiency low-carbon solutions present the potential for significant reductions in both energy consumption and green-house gas emissions.

Ontario's Energy Market

In recent years Ontario's Heating Ventilation and Air-Conditioning (HVAC) market has been predominantly driven by the "spark-spread" between natural gas and electricity, representing the costs differential present between these

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commodities. As it stands, the spark-spread is significant with natural gas costing approximately five times less than electricity, on a per unit energy basis (OEB 2018). The result of this imbalance has guided the HVAC market in the direction of combustion-based heating systems, which has proven to be a difficult hurdle to overcome for GSHP technology.

The environmental benefits of utilizing a GSHP as a building energy provider is dependent on the carbon intensity of the local distribution network powering the mechanical systems. From an emissions perspective, Ontario's electrical grid provides a clean source of low-carbon power, generating less than 5% of energy from gas/oil (IESO 2018); standing among the top five provinces in country with the cleanest electrical grid (NRCan 2017). Through the electrification of building energy systems, significant emissions reductions can be realized. In Ontario, this benefit has been identified and supported with capital subsidies for single family dwelling retrofit programs for GSHPs; however, no funding programs have been established for commercial, institutional, or mixed-use high-rise developments.

For large developments like mixed-use high-rise, commercial, and institutional facilities, the provincial power grid imposes a demand charge mechanism used to cover the cost of providing generation capacity and conservation programs in Ontario. This demand charge mechanism is referred to as Global Adjustment (GA), which is the difference between the hourly provincial electricity price and the regulated price on generation. The GA component of an average customers blended electricity rate can be greater than 50% (IESO 2018). The province allows lager consumers, defined as a customer with monthly average peak power draw of > 1 MW_e, to opt-into a designation referred to as a "Class A Customer". Class A customers are provided the flexibility to manage their grid electrical demand, as GA fees are apportioned based on the customer's percentage contribution to the five provincial peak hours during the previous year. Which would otherwise be administered on a cost per unit energy consumption basis for Class B customers. Through proactively avoiding peak contribution to the provincial grid, Class A customers can strategically manipulate greater than 50% of their blended electricity rate to manage building operating costs.

The Building

This paper introduces the results of a case study for a new development located in Toronto's downtown core. The building is a 70 – storey mixed-use high-rise; its occupancy is predominately residential, with commercial and institutional usage located in the building's 10 – storeys of podium. This development will deliver 63,000 m^2 of gross floor area to the newly developed precinct.

The base case mechanical system for the building would consist of a central penthouse plant with natural gas boilers and electric chillers; in-building forced-air distribution is accomplished via a four-pipe fan coil system. Due to the city's energy efficiency standard imposed on new developments, the base case mechanical design was insufficient in meeting the minimum threshold. However, the city's energy efficiency criteria provides an optional compliance path by incorporating an onsite GSHP system sized to meet a minimum of 20% of total building energy.

The System

To assist the new mixed-use high-rise in meeting their energy efficiency targets while providing a financially viable solution, a hybrid GSHP system was developed. The system consists of an in-building GSHP, an electric boiler, and a hot/chilled/domestic hot water Energy Transfer Stations (ETS). Table 1 provides a summary of the system's equipment selections.

Table 1. Hybrid geo-district equipment specifications

Unit	Specification	Duty
Heat Recovery Chiller	Trane – RTWD	878 kW_{th}
Electric Boiler	Clever Brooks – CR	563 kW_{th}
Chilled Water ETS	Alfa Laval – Gasketed Plat and Frame Heat Exchanger	2,975 kW_{th}
Hot Water ETS	Alfa Laval – Gasketed Plat and Frame Heat Exchanger	4,799 kW_{th}
Domestic Hot Water ETS	Alfa Laval – Double Walled Braised Plat and Frame Heat Exchanger	682 kW_{th}

The in-building GSHP was sized to meet 20% of the building's total energy consumption, translating to a system operated to meet 24% of the peak cooling and 6% of peak heating. With the GSHP operating as a baseload provider, the capacity deficiency is supplemented by the precincts low-temperature district hot and chilled water systems.

Figure 1 provides a schematic representation of the hybrid geo-district system. The proposed system employs a Trane RTWD heat pump to reclaim heat from the building chilled water distribution system (dark/light blue CW S/R circuit) and reject it to the building hot water distribution system (orange/yellow HW S/R circuit). Under simultaneous heating and cooling conditions, the heat recovery chiller allows for waste heat to be reclaimed within the building, sustaining its own internal demand before relying on external sources such as the Ground Heat Exchanger (GHX) or the district ETS. The building chilled water system utilizes the heat recovery chiller and district chilled water ETS piped in a parallel configuration to meet the building's design cooling demand; the heat recovery chiller operates as a GSHP base load provider in cooling only demand scenarios, with the building hot water circuit operating in GHX switch over mode by drawing fluid from the bore-field (dark/light green GHX S/R circuit). The building hot water system utilizes the heat recovery chiller and hot water ETS in a series arrangement. With a cascading arrangement the output of the heat recovery chiller can be polished to the design supply temperature via the district hot water ETS; cascading operation will occur under high demand (>1,100 kW_{th}) and in scenarios where the heat recovery chiller's condenser outlet temperature is below the design hot water supply temperature. The heat recovery chiller will operate as a GSHP base load provider in heating only demand scenarios, with the building chilled water circuit operating in GHX switch over mode by drawing fluid from the bore-field (dark/light green GHX S/R circuit). The hybrid geo-district system utilizes an electric boiler connected in parallel to the building's Domestic Hot Water (DHW) ETS. The electric boiler's primary function is to act as a false electrical load, used to artificially inflate the building's average monthly peak electricity demand to meet the Class A 1 MW_e threshold; with a secondary function of providing DHW heating redundancy with high output temperature capabilities.

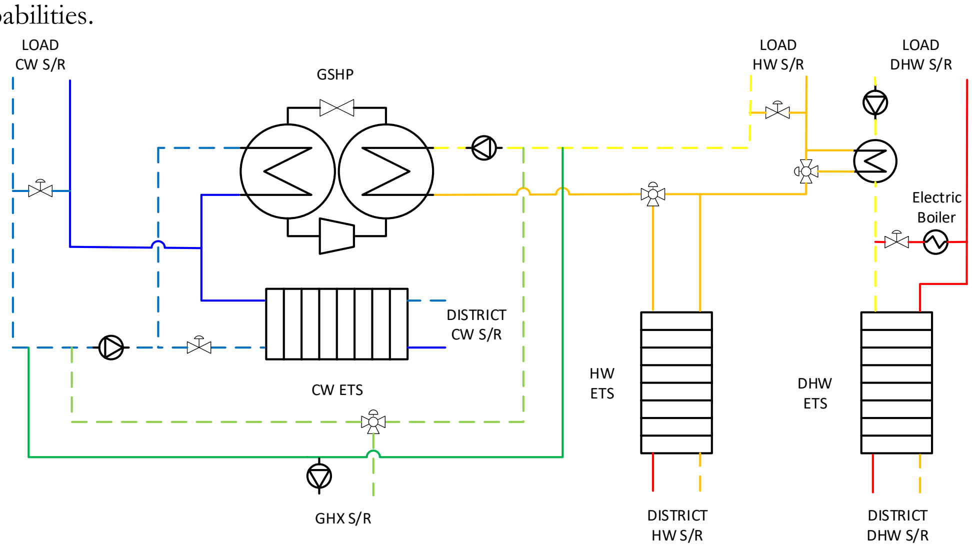

Figure 1 Process flow schematic of the hybrid geo-district energy system

The Control Strategy

The hybrid geo-district energy system for the proposed building case utilizes a DSM control strategy to manipulate the building's blended electricity rate; applicable in any electricity market that has a demand-based rate structure, like Ontario. DSM control strategies for hybrid GSHP plants have shown strong potential in all sectors, academia and industry alike (Carvalho *et. al* 2015; Jassen *et. al* 2015). In Ontario's market, GA drives a significant portion of an end-user's electricity rate. Operating costs of electrical loads can be intelligently managed to provide significant cost savings to an end-user, under the condition they are able to opt-into a Class A rate structure (average monthly peak power demand >1 MW_e).

The hybrid geo-district system was conceived to provide the building with the capability to meet the Class A GA designation, while reserving the flexibility to shift the building's central plant electricity demand to the district energy system. The hybrid geo-district system operates in a manner that is consistant with conventional hybrid GSHP control logic. The GSHP operates as a based load thermal energy provider for the building, with the district energy system being dispatched to provide supplementary heating and cooling under high demand conditions. The proposed DSM strategy introduces two unique operational sequences in addition to the conventional hybrid control logic: (1) artificial monthly peak inflation and (2) grid peak contribution avoidance. The monthly peak inflation sequence is introduced to elevate the building's base case monthly peak power draw to a degree which satisfies the GA Class A, 1 MW_e threshold. The monthly peak inflation is realized through the operation of the electric boiler; when the building experiences its monthly peak demand, the electric boiler (connected in paralled to the DHW ETS in Figure 1) is activated for a maximum of one utility meter sampling cycle, inflating the building's apparent peak power demand.
The grid peak avoidance sequence is a critical element to the success of the DSM strategy, as it has a direct impact on the resulting blended electricity rate. This sequence occurs only 5-hours a year, during the provincial grid's five peak demand hours; under these states, the on-site GSHP and electric boiler are deactivated, and all thermal demand is placed on the district energy system. The result of the grid peak avoidance sequence is a significant reduction in the build's grid power draw and associated Peak Demand Factor (PDF), the ratio the building's peak demand contribution to the provincial grid's demand during the province's five peak demand hours. The DSM strategy targets a maximum reduction in the PDF as this is the critical variable in the GA cost allocation for Class A customers; with the maximum reduction in the PDF, and end-user can minimize their blended electricity rate.

METHODOLOGY

This study consisted of a three-part process in evaluating the implications of the DSM control strategy on the proposed hybrid geo-district energy system. First, a building energy model was developed to establish the building's annual hourly thermal and electrical load profiles. The output of the building energy model was used as an input to numerical simulation of the hybrid geo-district system. Finally, a financial model was developed to assess the economic impact the proposed hybrid system and operational strategy have on the building's blended electricity rate and heating/cooling operational costs.

Building Energy Model

Using eQuest 3-65 (DOE 2009) building energy modelling software, a simulation was conducted for the proposed building to develop annually hourly thermal and electrical load profiles. The simulated profiles were used as inputs to the numerical model of the hybrid geo-district system. Table 2 provides a summary of the simulated thermal and electrical energy requirement for the proposed building. As indicated in Table 2, there is a significant thermal imbalance in the building's demand, with approximately four times more heating required than cooling. With this thermal imbalance, a hybrid GSHP solution provides the necessary flexibility in both design and system operation, allowing the GHX economics to be managed and risk of ground thermal saturation to be mitigated.

Table 2. Summary of thermal and electrical energy requirements

Unit	Demand	Consumption
Space Heating	4,799 kW_{th}	7,790,927 kWh_{th}
Space Cooling	2,975 kW_{th}	2,437,612 kWh_{th}
DHW	682 kW_{th}	1,882,429 kWh_{th}
Electrical Plug Load	383 kW_e	2,627,562 kWh_e

Hybrid Geo-District Numerical Simulation

A numerical simulation of the proposed hybrid system was conducted utilizing the modelling platform Ground-Loop Design (GLD) 2016 Premier (Gaia Geothermal 2016); with a numerical time-step of one hour, simulated for a 20-year period. Table 3 presents a summary of the numerical model assumptions used in the GLD simulations.

Table 3. Summary of numerical model assumptions

Input	Assumption	Unit
GHX Design Flow Rate – Heating Mode	0.06	LPS/kW
GHX Working Fluid	Water – Propylene Glycol (12.9% by Weight)	-
Undisturbed Ground Temperature	10	°C
Soil Thermal Conductivity	2.34	W/m*K
Soil Thermal Diffusivity	0.074	m^2/day
Borehole Thermal Resistance	0.118	m*K/W
Nominal Pipe Size	40	mm
Pipe Type	SDR11	-
GHX Flow Type	Turbulent	-
Borehole Diameter	108	mm
Grout Thermal Conductivity	2.09	W/m*K
Borehole Grid Pattern	12 X 5	-
Borehole Spacing Centre-to-Centre	5	m
Borehole Depth	229	m
Annual Average Load EWT, Cooling	13.3	°C
Annual Average Load EWT, Heating	40.6	°C

Table 4 presents a summary of the GSHP's performance over the 20-year simulation period. The simulated minimum/maximum Entering and Leaving Water Temperatures (EWT and LWT) are reflective of the design day operational peak hour over the 20-year period. The maximum operating capacity in heating and cooling mode represent the GSHP's controlled thermal output to ensure ground thermal loading is seasonally balanced, mitigating the risk of ground thermal saturation. As a result, the GSHP is operated to 24% of peak cooling and 6% of peak heating, meeting 66% and 24% of cooling and heating energy, respectively.

Table 4. Summary of the simulation results

Output	Result	Unit
	GSHP Cooling Performance	
Maximum Sink EWT	28.7	°C
Maximum Sink LWT	33.8	°C
Maximum Operating Capacity	714.1	kW
Design Day COP	5.5	-
Seasonal COP	7.4	-
	GSHP Heating Performance	
Minimum Source EWT	4.2	°C
Minimum Source LWT	2.9	°C
Maximum Operating Capacity	319.5	kW
Design Day COP	3.1	-
Seasonal COP	3.5	-

RESULTS AND DISCUSSION

In this study, the proposed DSM control strategy's impact on the building's hybrid geo-district system operational cost is evaluated. Figure 2 presents the building's hourly grid power demand including the hybrid geo-district plant operation. In Figure 2, the building's power demand (green profile) represents the actual power required to operate the building's various electrical loads. The artificial building power demand (red profile) represents the demand induced on the grid during the building's monthly peak demand hour, through strategically operating the 563 kW_{th} electric boiler to inflate the hourly grid power draw. This strategy allows the 1 MW_e threshold of the Class A designation to be satisfied, providing the building the flexibility of managing the GA operating costs by avoiding the peak contribution during the provincial grid's five peak demand hours.

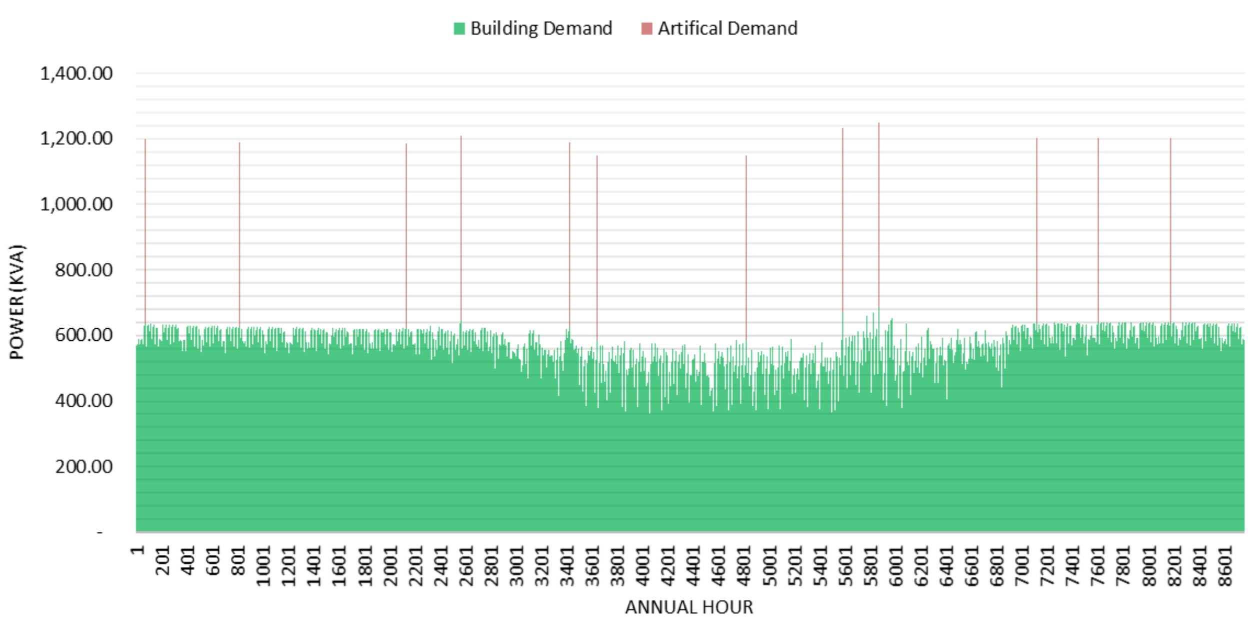

Figure 2 The building annual hourly grid power demand

Three scenarios have been evaluated, the base case Class B (GA cost administered by consumption on a $/kWh basis), Class A with conventional hybrid GSHP system operation, and Class A with GA avoidance (all plant electrical loads deactivated during the five hours of the provincial grid's peak demand). Table 5 presents a summary of the Class A operating scenarios' (regular and avoided GA) PDF. In Table 5, the building peak contribution in kW represents the sum of the building's peak electrical demand during the grid's five peak demand hours, and the provincial grid peak represents the sum of the grid peak power demand during the province's five peak demand hours. The resulting PDF characterises the ratio of the building's peak contribution to the grid's provincial peaks, representing the portion of GA cost paid by a connected customer. As illustrated in Table 5, the avoided GA control strategy reduces the PDF by 47% when compared to a Class A customer operating irrespective of the grid's peak demand hours.

Table 5. Summary of Class A peak demand factor results

Operation Case	Building Peak Contribution (kW)	Provincial Grid Peak (MW)	PDF
Regular	1,796	111,575	0.00001610
Avoided GA	852	111,575	0.00000764

Figure 3 illustrates the building's average monthly blended electricity rate for all three hybrid geo-district system operating scenarios. In Figure 3, the stacked column plots represent the operationally independent cost components of the building's blended electricity rate; the line plots represent the cost of GA for the three proposed operational cases; the scatter plot represents the total blended electricity rate, being the sum of the stacked column and line plot for each operational scenario. As indicated in Figure 3, the results indicate significant financial savings attributed to proposed operational strategy. The base case scenario of the building operating under a Class B rate structure indicates an average annual blended rate of $ 0.156/kWh. When the building's demand is artificially inflated (through dispatching the electric boiler) and operated under a Class A rate structure, the building experiences an average annual blended rate of $ 0.103/kWh, a 34% reduction compared to the base case scenario. Through implementing the proposed DSM control strategy (avoiding the central plant peak power contribution to the grid's five peak demand hours) the building experiences and average annual blended rate of $ 0.074/kWh, a 52% reduction compared to the base case scenario.

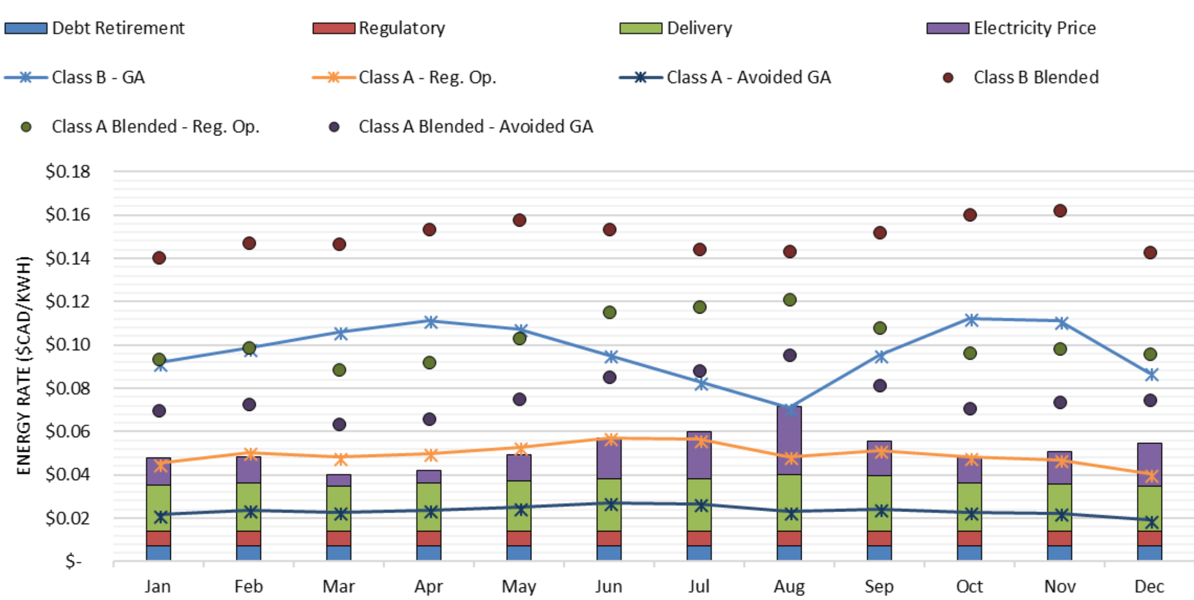

Figure 3 The building's monthly electrical energy rate components and average blended rates

With the proposed DSM operating strategy, the spark-spread between natural gas and electricity has been reduced, allowing geo-heating to become more economical than a natural gas-based solution. The Class A GA avoidance scenario produced a heating and cooling operational cost of \$ 0.038/kWh_{th} and \$ 0.018/kWh_{th}, respectively. When compared to the base case central plant alternative, the GA avoidance scenario reduces the heating and cooling rates by 14% and 67%, respectively.

The integration of the GSHP into the proposed building's district energy based mechanical system provides the means to satisfy the development's energy efficiency and sustainablility targets imposed by the city. Without the hybridization of the building's district energy-based system with a GSHP, the afromentioned operation cost savings would not have been realized. The on-site GSHP and electric boiler combination provide the critical electical load to elevate the building from a Class B to Class A customer designation. The GSHP is an instrumental asset to the proposed building, which makes the use of the DSM control strategy capable of manipulating the building's blended electricity rate, significantly improving the operational economics of the GSHP system in Ontario's challenging energy market.

CONCLUSION

In this study, a DSM control strategy is proposed for a hybrid geo-district energy system, serving a mixed-use high-rise development in Toronto, Canada. The effect of the DSM control strategy on the building's blended annual electricity rate and heating/cooling operating costs were investigated. The proposed DSM strategy has shown strong potential for improving the business case of a hybrid GSHP system in Ontario's energy market and others with similar demand charge structures, even when facing a prominent spark-spread.

The proposed hybrid geo-district system was studied under two electrical rate structures with three operational strategies. Scenario one examined the system under a Class B rate structure (average monthly demand of $< 1\ MW_e$) and a conventional hybrid GSHP control strategy; results indicated an average annual blended rate of \$ 0.156/kWh. Scenario two evaluated the system under a Class A rate structure (average monthly demand $> 1\ MW_e$) and a conventional hybrid GSHP control strategy; results indicated an average annual blended rate of \$ 0.103/kWh, a 34% reduction compared to scenario one. Scenario three investigated the system under a Class A rate structure and a DSM control strategy; results revealed an average annual blended rate of \$ 0.074/kWh, a 52% reduction compared to scenario one, while reducing the building heating and cooling rates by 14% and 67%, respectively.

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