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STRATEGIES TO OPERATE A THERMAL STORAGE DEVICE INTEGRATED INTO AN AIR-SOURCE HEAT PUMP FOR RESIDENTIAL SPACE AND WATER HEATING

Conrado Ermel
Federal University of Rio Grande do Sul - UFRGS, Brazil
conradoermel@gmail.com

Marcus V.A. Bianchi
National Renewable Energy Laboratory - NREL, USA

Paulo S. Schneider
Federal University of Rio Grande do Sul - UFRGS, Brazil

Abstract. *Thermal energy storage has been integrated into Heat Pumps (HP) in a variety of applications, including residential space heating. It is commonly used to shift the load from peak to off-peak periods, and various control strategies can be used for this purpose. This study explores different control logic for residential space heating systems consisting of air-source heat pumps integrated with a* $10\,\mathrm{kW\,h_t}$ *thermal energy storage device (TES). Computational simulations are conducted under various conditions, emulating a standard dwelling. Three control logics are explored: i) avoiding operation in cold temperatures, ii) avoiding operation during expensive electricity periods, and iii) avoiding operation when the grid* CO_2 *emission factor is high. Preliminary results indicate that energy savings are not achieved independently of the control algorithm. Additionally, compared to the standard system (without TES) economic savings of* $5.5\,\%$ *can be achieved with the second logic, while the third logic reduces emissions by* $7\,\%$ *while providing* $2\,\%$ *economic savings. Although a hybrid cost-emission algorithm proved to be the best option with improvements across all the parameters, the study emphasizes the need for further research on smart control algorithms that consider system characteristics and integrate weather, energy demand, and renewables dispatch forecasts.*

Keywords: *Thermal Energy Storage, Heat Pumps, Control Strategies, Performance Parameters.*

1. INTRODUCTION

The global movement towards decarbonization has led to a focus on electrifying buildings, as almost half of their energy demand is due to thermal loads. This has led to an increase in the use of heat pumps, which can provide heat while running on electricity from renewables. However, heat pumps have their performance compromised in very chilly weather, and their use can lead to additional demand on the grid, especially during peak-demand hours.

To overcome these issues, thermal energy storage devices have been proposed. TES can be accomplished in multiple ways, including the use of simple water tanks or phase-change materials. The method of controlling TES depends on the specific objectives of the system (Dongellini *et al.*, 2021). One common objective is to utilize TES for shifting the heating load from peak to off-peak periods (Le *et al.*, 2020). This strategy can yield benefits such as reducing the operation costs or even supporting grid resilience by managing the power demand (Farah *et al.*, 2019). The determination of the optimal algorithm for operating the TES (charging/discharging) is still pending and is contingent on several parameters. For example, when numerous heat pumps are operating at the same time, making this decision on a standalone basis may create additional problems for the grid.

In this context, this study explores different control strategies for residential space heating systems composed of air-source heat pumps integrated with thermal energy storage (ASHP-TES). A computational simulation approach is adopted to model the ASHP-TES system operating under various conditions, emulating a standard dwelling. Three different control logics, with specific objective functions, are explored:

- avoid operation in cold temperatures,
- avoid operation in periods when electricity is more expensive, and
- avoid operation when the grid CO_2 emission factor is high.

These strategies are evaluated considering energy consumption, economical aspects like levelized cost of energy, and annual carbon dioxide emission due to the system operation.

2. MATHEMATICAL MODELING

The system of Fig. 1 is used to supply the heating load of a single-family dwelling. The air-water heat pump extracts heat from the outdoor $\dot{Q}_C$, at temperature T_{air}, and transports it either to the interior, T_{indoor}, or to the thermal storage device ($\dot{Q}_H$). The term $\dot{Q}_{avoided}$ refers to the heat discharged from the TES, preventing the HP from operating in peak periods. $\dot{Q}_{load}$ stands for the dwelling thermal load. It was modeled using the Python simulation platform developed by

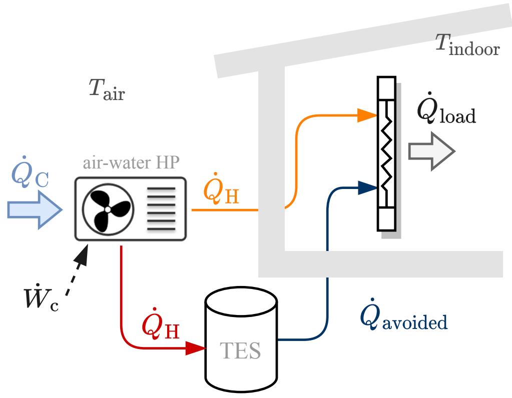


Figure 1: Air source heat pump integrated with a thermal storage device for load shifting operation.

Ermel *et al.* (2022). Each component is treated as a modular model, and the platform solves the quasi-steady state models for each time step. The mathematical model of each component is presented below, along with the adopted parameters.

2.1 Air Source Heat Pump

Due to the fact that the system under study uses a hydraulic circuit to distribute heat in the dwelling, an air-water heat pump was chosen. There are a variety of approaches to modeling such equipment. One approach is to use unified solutions that rely on regressions and generic correlations derived from experimental data. These methods allow for the determination of critical parameters such as the coefficient of performance (COP) and the heating capacity of the heat pump (Lyden, 2020).

Another approach is to use thermodynamic sub-models for each component of the heat pump. In this case, construction and operational parameters of each device are considered separately, allowing for the simulation of different models (Huang *et al.*, 2020). The vapor compression cycle was modeled by considering the four essential components: compressor, condenser, expansion device, and evaporator.

The air source heat pump was modeled using the air-water heat pump class from (Ermel, 2023), with the parameters of Tab. 1. This heat pump class was previously validated in (Ermel *et al.*, 2022). The refrigerant-air evaporator was modeled

Table 1: ASHP construction parameters

Parameter	Value	Unit
Compressor speed	3600	[rpm]
Isentropic efficiency	0.63	[-]
Volumetric efficiency	0.95	[-]
Displacement	3×10^{-5}	[m^3]
Refrigerant	R134a	[-]
Evaporator tube length	10	[m]
Evaporator # tubes	5	[-]
Evaporator tube ϕ	0.01	[m]
Evaporator fin efficiency	0.75	[-]
Evaporator fin ratio	7.2	[fin/inch]
Superheating level	8.5	[K]
Subcooling level	6.5	[K]

with the Kriging-assisted three-zone model (Huang *et al.*, 2020), while the refrigerant-water condenser was modeled using a formulation similar to the one adopted by citeWANGDynamic2017.

2.2 Thermal Storage Tank

Due to computational constraints, and because the focus of this paper is on studying different control strategies for the ASHP-TES system, we have chosen to adopt a simplified version of TES. The model, therefore, represents a device that only absorbs and releases heat, without addressing heat transfer details such as heat exchanger effectiveness or the residual energy that cannot be extracted from the device (Ma *et al.*, 2012). In other words, the heat exchange processes were assumed to be ideal. The energy balance can be written as

$$\frac{\partial Q_{\mathrm{TES}}}{\partial t} = \dot{Q}_{\mathrm{in}} - \dot{Q}_{\mathrm{out}} - \dot{Q}_{\mathrm{loss}} \tag{1}$$

where $\dot{Q}_{\mathrm{loss}}$ is due to insulation. The state of charge (SOC), given in $[\%]$, is defined as the ratio of the actual energy inside TES and the total storage capacity

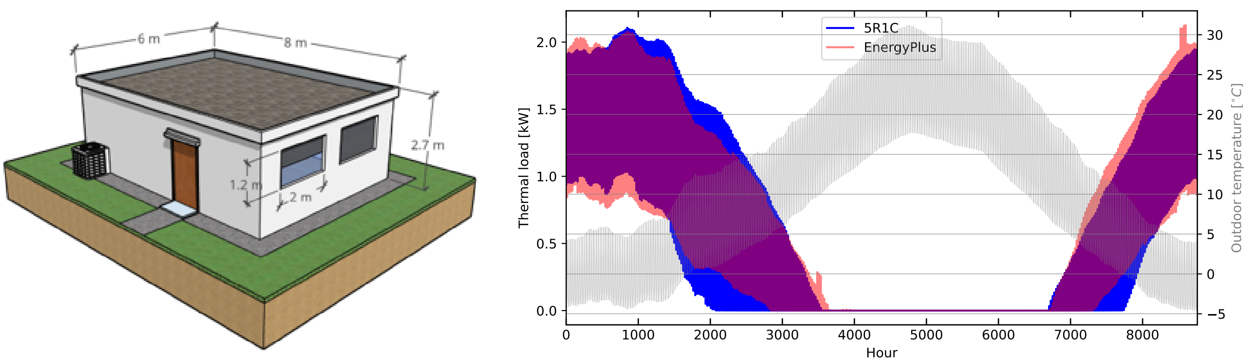
$$\mathrm{SOC} = \frac{Q_{\mathrm{TES}}}{E_{\mathrm{th}}}, \tag{2}$$

with Q_{TES} $[\mathrm{kW\,h}]$ the actual stored energy and E_{th} the storage capacity $[\mathrm{kW\,h}]$.

2.3 Thermal Load

In order to evaluate an ASHP-TES system, it becomes necessary to determine the precise amount of energy needed to maintain a conditioned space at a specific temperature. As per convention, the thermal load is considered positive when heating is necessary, whereas it is negative when cooling is required (ASHRAE, 2016).

In the simulations performed in this study we adopted a 5R1C thermal load model (Vivian *et al.*, 2017) to estimate the thermal load at each time step. This kind of approach allows one to consider relevant parameters like the building thermal inertia as a capacitance component and the heat transfer mechanisms as a function of temperatures and resistances. Thermal load simulators such as Energy Plus (DOE, 2022) offer enhanced accuracy in determining thermal loads. However, as demonstrated by (Ermel *et al.*, 2023), the 5R1C model proves sufficiently accurate for the current study while demanding minimal computational capacity.



(a)

(b)

Figure 2: a) Standard dwelling considered in the simulations. b) Predicted thermal load.

2.4 Performance Metrics

The system and the control logic were evaluated in three aspects: i) Energy consumption, ii) Operation cost, and iii) Emissions. The first is given by

$$E = \sum_{t=0}^{8760} \dot{W}_{\mathrm{HP}}(t).t_{op}, \tag{3}$$

with $\dot{W}_{\mathrm{HP}}$ the heat pump power [W] times the time interval it operated t_{op} during the times step t. The financial aspect is evaluated through the operation costs, given by

$$C_{op} = \sum_{t=0}^{8760} \dot{W}_{\mathrm{HP}}.(t).t_{op}.El_r(t), \tag{4}$$

and the Levelized Cost of Energy (LCOE). El_r is the electricity rate at the time step t.

To calculate the LCOE, we adopted the formulation of Odukomaiya *et al.* (2021), that proposed a consistent framework based on the LCOE and the levelized cost of storage (LCOS) to evaluate TES with battery storage systems. The authors defined the LCOE as the ratio between the energy expended for TES charging and the energy conserved.

$$\mathrm{LCOE} = \frac{C_\mathrm{T}}{\eta_\mathrm{S} \frac{D_\mathrm{T}\mu_\mathrm{T}}{\mathrm{COP_{av}}} \sum_{\mathrm{i=0}}^{\mathrm{L_T}} (1+r)^{-\mathrm{i}}} + \frac{p}{\eta_\mathrm{S} \frac{\mathrm{COP_{ch}}}{\mathrm{COP_{av}}}}. \tag{5}$$

The first term on the right-hand side corresponds to the system's capital expenditures, where C_T represents the capital cost of TES material calculated by the ratio between the total initial investment A_T [\$] and the thermal storage capacity of the system $E_{th,nom}$ [$\mathrm{kW\,h_t}$]. The denominator incorporates the storage efficiency η_S multiplied by an equivalent utilization term for TES, $\frac{D_\mathrm{T}\mu_\mathrm{T}}{\mathrm{COPav}}$. This term encompasses the discharge frequency μ_T [cycles/year], and the depth of charge DT [%], which represents how much the TES was discharge on average per cycle. The avoided coefficient of performance $\mathrm{COP_{av}}$ refers to the peak-hour performance of the heat pump without TES (standard ASHP). The summation term calculates the interest rate over the lifespan of the system. This equation takes into account the system's utilization factor wich depends on the

The CO_2 emissions [kg] are calculated as

$$\chi_{\mathrm{CO_2}} = \sum_{\mathrm{t=0}}^{8760} f_{\mathrm{CO_2}}(t)\dot{W}_{HP}(t)t_{op}. \tag{6}$$

The grid emission factor $f_{\mathrm{CO_2}}$ [$\mathrm{kgCO_2/kWh_e}$], i.e. the amount of carbon dioxide emitted by sources connected to the grid, is usually presented as one value representing the average over one year for a given region. For instance, the U.S. average grid emission factor in 2021 was $0.39\,\mathrm{kgCO_2/kWh}$ (EIA, 2021).

3. CONTROL ALGORITHM FOR THE ASHP-TES

Thermal storage serves various purposes, and the method of controlling it depends on the specific objectives of the system. One common objective is to utilize TES for shifting the heating load from peak to off-peak periods. However, the definition of peak periods may vary. For example, one may be interested in avoiding peak electricity prices in time-of-use (TOU) contracts Fig. 3a. Here the TES is discharged whenever the electricity rate is at its peak. Otherwise, the system could prioritize to charge the storage because the electricity is cheaper. Another form is using the ambient temperature (outdoor) as the TES discharge criterion, Fig. 3b. To mitigate the reduced performance of heat pumps in lower temperatures (Song Mengjie and Deng Shiming, 2019), a possible approach is to charge the thermal storage during warmer periods when the heat pump exhibits a higher coefficient of performance (COP). By discharging the TES during low temperature periods, one can effectively avoid operating the heat pump at a low COP.

A third parameter suitable to control a TES device is the Grid Emission Factor (GEF). This variable depends on the grid composition and the instantaneous availability of renewables. The parameter trend is illustrated in Fig. 3c.

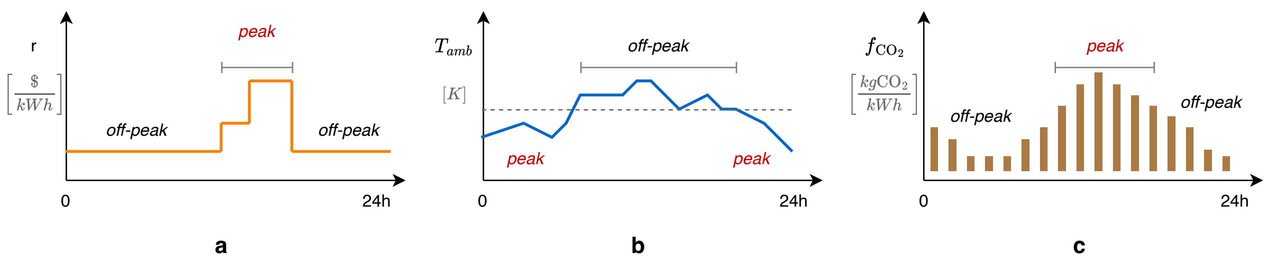


Figure 3: Possible discharge criteria: a) Electricity rate, b) Ambient (outdoor) temperature, and c) Grid emission factor.

Regardless the discharge criterion, operating an ASHP-TES requires to account for several real-life aspects. The diagram of Fig. 4 displays the operation logic adopted in this study. As presented in Fig. 1, the heat pump can either supply the thermal load through the hydraulic system or charge the TES. For each time step of one hour, if there is a thermal load ($Q_{load}[i] > 0$) the discharge criterion is checked. If true, the TES will be discharged, only if the amount of energy inside the TES is higher than the thermal load $Q_{TES}[i] > Q_{load}[i]$. In case the discharge criterion is not met, the system will either decide to simultaneously supply $Q_{load}[i]$ and charge the TES (if SOC<95 %) or only supply the heating load bypassing the thermal storage. In periods that $Q_{load}[i] < 0$ the system keeps the SOC over 95 % in order to be ready for the next discharge cycle.

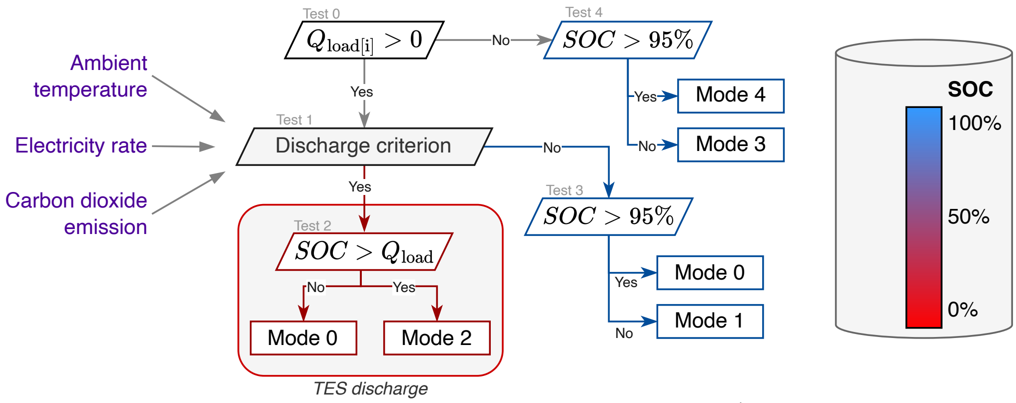


Figure 4: Control algorithm for the ASHP-TES system: **Mode 0**: HP supplying $\dot{Q}_{\mathrm{load}}$, **Mode 1**: HP charging TES and supplying $\dot{Q}_{\mathrm{load}}$, **Mode 2**: Discharging TES to supply $\dot{Q}_{\mathrm{load}}$, **Mode 3**: HP charging TES, **Mode 4**: All systems off.

4. RESULTS

In this section we present preliminary results on the assessments of the TES discharge criterion. A case study was adopted for all simulations, having the standard dwelling of Fig. 2 as the energy demand side, and the heat pump described in Tab. 1 integrated with a generic TES with $10\,\mathrm{kW\,h_{\,t}}$ storage capacity. For the discharge criterion of "Energy", it was considered that the TES is discharged whenever the ambient temperature in the outdoors is lower than $283\,\mathrm{K}$. This value was selected observing the system behavior for set points ranging from $273\,\mathrm{K}$ to $286\,\mathrm{K}$. As presented by Fig. 5, $283\,\mathrm{K}$ is the set point at which the annual energy consumption is minimal for the studied system.

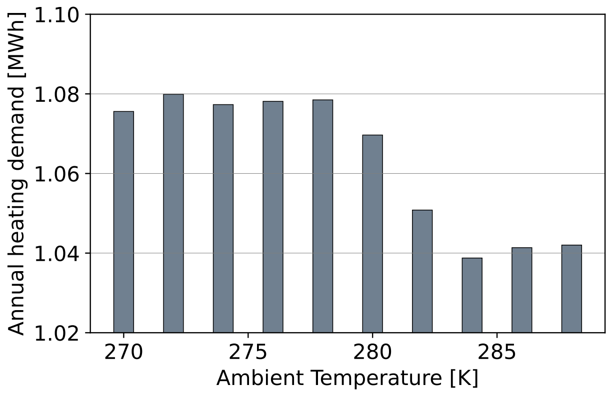


Figure 5: Energy consumption according to the discharge set point

For the criterion based on the electricity rate, the TOU structure offered by the utility for the city of Denver (XcelEnergy, 2023). During the heating season, three levels of rate are used, ranging from \$0.12/kWh to $\$0.19\,\mathrm{kW\,h_{\,e}}$, according to Figure 6. If the cost of electricity is $p > \$0.12\,\mathrm{kW^{-1}\,h^{-1}{}_{\,e}}$, the discharge of the TES is prioritized.

The grid emission factor is usually given in averaged values, however, it is directly dependent on the source of the energy that is producing at the evaluated moment. For the third discharge criterion we made the assumption that $f_{\mathrm{CO_2}}$ undergoes hourly changes, which depend on the proportion of renewables available during that specific period. Therefore, we utilized $f_{\mathrm{CO_2}}$ predictions for 2024 sourced from the Cambium database to feed the model (Gagnon *et al.*, 2023). The Cambium project offers hourly emission rates and cost data across multiple forecast scenarios. Despite the inherent uncertainties associated with future projections, we deemed the database to be a suitable source for examining the performance of the studied system. In addition to the three previous control logics, we added a hybrid version that includes both the electricity price and the GEF as discharge criteria, keeping the same conditions of TOU and grid emission factor. This approach was labeled *04-HybridCC*.

Table 2 presents the preliminary results of the comparison among the three discharge criteria: Energy, Electricity rate, and Grid emission factor. For the case study dwelling, a standard system (ASHP without TES) is expected to consume $1.033\,\mathrm{MW\,h_{\,e}}$ per year. It is interesting to highlight that no approach using TES actually provided energy savings. Even the strategy guided by the outdoor temperature was not capable of reducing the total energy consumption.

Regarding the operation costs, for both the *01-Energy* and *03-GEF* simulations the TES presented higher values than the standard system. When the control strategy is guided by the TOU rates, *02-Cost*, the operation costs were reduced by

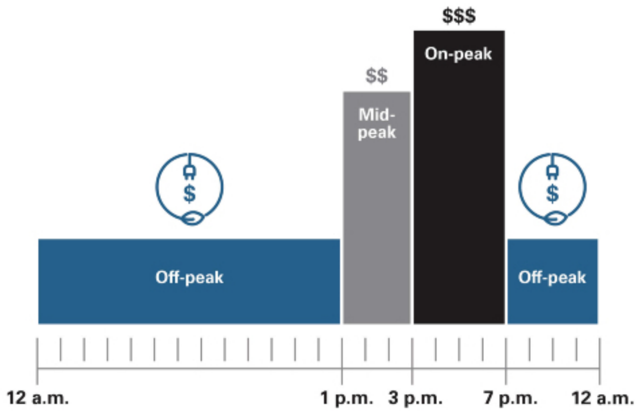


Figure 6: Time of use structure for winter season offered by (XcelEnergy, 2023). *Off-peak:* $\$0.12\,\mathrm{kW^{-1}\,h^{-1}}_{\mathrm{e}}$ | *Mid-peak:* $\$0.15\,\mathrm{kW^{-1}\,h^{-1}}_{\mathrm{e}}$ | *On-peak:* $\$0.19\,\mathrm{kW^{-1}\,h^{-1}}_{\mathrm{e}}$.

Table 2: Simulation results for the three control strategies considering one-year operation.

Parameter	*01-Energy*	*02-Cost*	*03-GEF*	*04-HybridCC*	Units
Energy consumption STD	1.033	1.033	1.033	1.033	[$\mathrm{MW\,h}_{\mathrm{e}}$]
Energy consumption TES	1.044	1.067	1.059	1.052	[$\mathrm{MW\,h}_{\mathrm{e}}$]
Energy savings	0.561	0.637	0.515	0.696	[$\mathrm{MW\,h}_{\mathrm{e}}$]
Operation cost STD	139.6	139.6	139.6	139.6	[$]
Operation cost TES	146.8	132.0	142.1	136.1	[$]
Levelized Cost Of Electricity	0.27	0.20	0.26	0.20	[$/kWh]
μ_{T} average	101	173	153	187	[cycles]
D_{T} average	0.78	0.70	0.59	0.72	[%]
COP charge	3.19	2.85	2.71	2.84	[-]
COP avoided	2.89	2.83	2.90	2.89	[-]
COP ratio	1.10	1.00	0.94	0.98	[-]
Mode 0 (std)	29.9	26.9	28.4	25.9	[%]
Mode 1 (charge/discharge)	1.3	4.8	3.6	3.9	[%]
Mode 2 (Discharge)	10.4	9.8	9.6	11.8	[%]
Mode 3 (Charge)	0.5	0.4	0.5	0.7	[%]
Mode 4 (Off)	6.3	6.4	6.3	6.2	[%]

$5.5\,\%$. The levelized cost of energy reached its minimum value, $\$0.20\,\mathrm{kW^{-1}\,h^{-1}}_{\mathrm{e}}$, in the Cost simulation. Simulation *04-HybridCC* also presented operation costs lower than the standard system (STD).

Table 2 also presents the parameters measured for all cases regarding the calculation of the LCOE. Because the discharge criterion is different, each case have a particular number off discharge cycles and average depth of charge. For the selected system, the highest COP ratio is obtained in simulation *01-Energy*. All other cases presented values lower than the unit, because they do not observe the weather conditions to decide when to discharge the TES.

An interesting trend is observed for the total CO_2 emitted over one year, Fig. 7. The standard system's emission was $397\,\mathrm{kgCO_2/kWh_e}$, the behavior of TES system changed significantly as a function of the discharge criterion. One must keep in mind that the grid emission factor was considered dynamic according to the prediction of (Gagnon *et al.*, 2023), hence, there no straightforward alignment between outside temperature, TOU rates and the grid emission factor. For the case *01-Energy*, the reduction of the emissions is attributed to the low energy consumption (compared to other control strategies) in conjunction with the grid emission factor.

The simulation observing the TOU rates presented the lowest operation cost $132, however, also generating the highest CO_2 emission $417\,\mathrm{kgCO_2/kWh_e}$. This result reveals that the peak of electricity rate and the peak of carbon emission factor are not necessarily in phase. On the other hand, when emissions was the control strategy goal, simulation *03-GEF*, the system emitted almost $7\,\%$ less CO_2 than the standard configuration.

An intermediary option was achieved with simulation *04-HybridCC*, that observes both the TOU rates and the $f_{\mathrm{CO_2}}$. This algorithm only considers constant set points values. In other words, it discharges the TES whenever $p > \$0.12\,\mathrm{kW^{-1}\,h^{-1}}_{\mathrm{e}}$

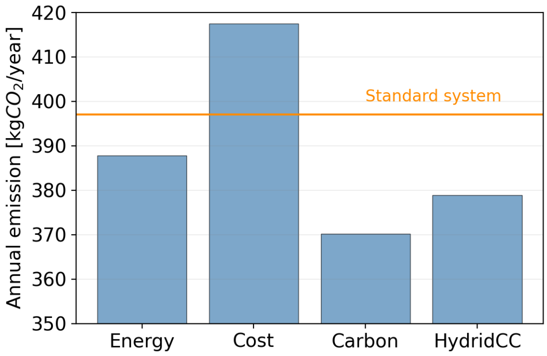


Figure 7: Carbon dioxide emission over one year.

or f_{CO_2} >0.4 – which is the average f_{CO_2} for Denver (Gagnon *et al.*, 2023). This approach led to moderate values of energy consumption $1.052\,\mathrm{MW\,h_e}$, operation cost \$136, and CO_2 emission, $379\,\mathrm{kgCO_2/kWh_e}$.

5. CONCLUSIONS

Using thermal energy storage to enhance the flexibility of residential heating systems is a current trend, and there is a variety of ways this system cab be operated. The three TES discharge criteria, evaluated in the present paper, were chosen because they represent simple forms of controlling the ASHP-TES system, not requiring advance hardware.

The first outcome from the study is the fact that introducing the storage device represented an additional energy consumption independently of the control algorithm. Even the discharge criterion design to prevent the HP of operating with low COP, *01-Energy*, required more energy than the standard one. The operation cost can be reduced by $6\,\%$ if the logic is oriented to avoid the heat pump operation during peak periods regarding the electricity rate, *02-Cost*. However, this mode increased the carbon emission by $5\,\%$ compared to the HP without TES. The control strategy *03-GEF* was able to reduce the CO_2 emission by $7\,\%$, however, compromising the system's LCOE.

The results reveal the effects of different control strategies in the system's performance. Moreover, it highlight the difficulty in accommodate parameters like energy, cost, and environmental aspects in a single control algorithm. Particularly, there is a challenge to implement such strategies without increasing the CAPEX with advance control systems. Research on smart control algorithms is required, specially focusing on approaches that integrate system characteristics with weather, energy demand, and renewables dispatch forecasts.

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