An Analytical Method to Estimate the LCOE/S of Air Source Heat Pumps Integrated with Thermal Storage

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ABSTRACT

Thermal energy storage (TES) has been considered for integration into residential heating systems with air source heat pumps (ASHP-TES) as it can bring benefits to users and the grid. There are several simulation tools that can be used to determine whether the introduction of TES is economically attractive. However, these tools are not accessible to all stakeholders in the energy market, which can hinder the deployment of such systems. In this paper. a new analytical method for estimating the economic performance of ASHP-TES systems for homes is proposed. The method uses known parameters of the heat pump, dwelling, and storage, and applies a simplified calculation procedure that can be easily implemented in spreadsheets to estimate the levelized cost of electricity and storage for specific ASHP-TES projects. The method was tested in five distinct locations in the United States. Compared to the simulation results for the levelized cost of energy (LCOE), the relative deviations ranged from 0.5 % to 3 %. Additionally, the error of the levelized cosst of storage (LCOS) calculation method was ten times smaller than the ASHP-TES system viability criterion. This indicates that the method can be used to generate initial estimates of system performance and viability. As the method eliminates the need for sophisticated tools, it could help more engineers, architects, contractors, and clients to quickly decide whether an ASHP-TES project is worth exploring further. Although the results are encouraging, the impact of the simplifications made in the method need to be further investigated.

1. INTRODUCTION

Efforts to decarbonize human activities affect all sectors. In buildings, numerous alternatives are being considered to replace combustion appliances (Vering et al., 2022). Heat pumps, as an established technology, are a good candidate to become part of this movement. However, their widespread deployment could bring additional challenges for grid operation. Air-source heat pump systems integrated with thermal energy storage (ASHP-TES) can improve the flexibility of the system and help overcome associated challenges (Moreno et al., 2014; Ma et al., 2023). As shown in Fig. 1, an example of such a system consists of an air-to-water heat pump that covers the heating load of the home, Q_{load}, and charges a thermal storage device. At peak periods, the heat pump is deactivated while the thermal energy storage is discharged to supply Q_{load}. This process is known as load-shifting, and can be used to balance the intermittence of renewable energy sources and reduce operating costs to the end users (Le et al., 2020).

The deployment of thermal energy storage systems is increasing rapidly. According to the IRENA innovation outlook on TES published in 2020, the global TES market will triple within a decade (IRENA, 2020). It is also likely that residential TES deployment will increase as customers gain more flexibility to manage their loads according to the time-of-use (TOU) structures practiced by utilities. However, the adoption of TES is not always cost-effective due to several factors, including the initial investment, TOU structure, system utilization, and weather conditions at the desired location. The decision to invest in such systems must therefore be carefully considered.

Research on ASHP-TES has increased in recent years, and computater simulation is a preferred tool for simulating

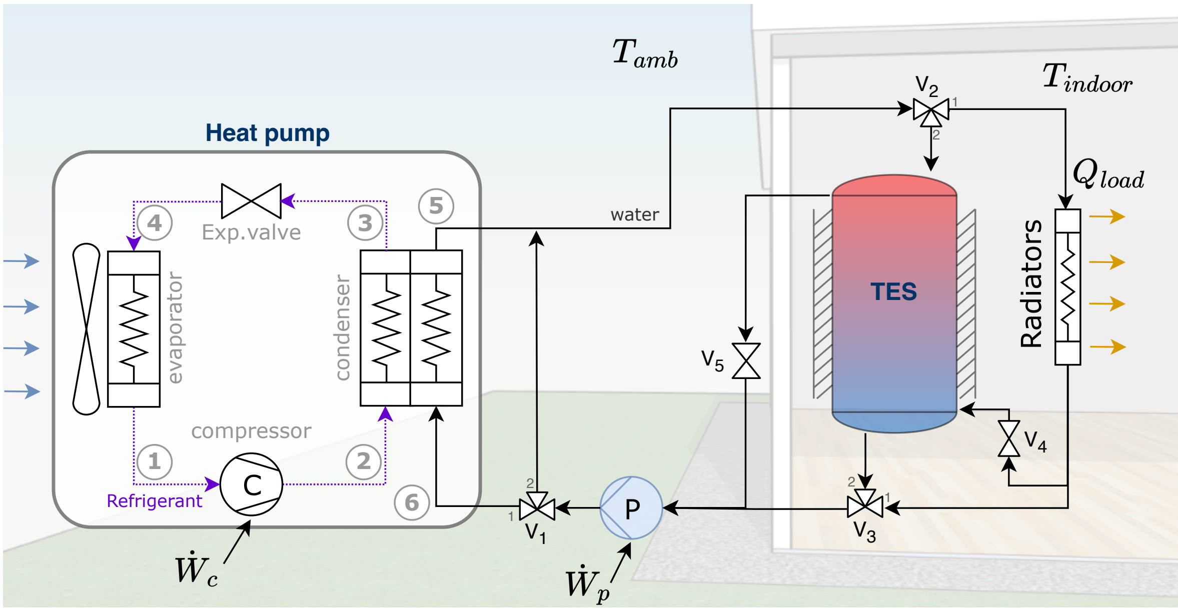


Figure 1: System scheme - Thermal energy storage integrated to air-air heat pump.

the operation of the system and determining its performance and viability (Ermel et al., 2022a). The simulation tools use complex calculations to determine how ASHP-TES interacts with the heating load of the dwelling, environmental conditions, and the price of electricity. These calculations often require powerful software or advanced knowledge. Palomba et al. (2019), for instance, modeled hybrid sorption-compression systems in Modelica using the commercial software Dymola®. Le et al. (2020) used TRNSYS® to demonstrate how a sensible thermal storage system can reduce the operating costs of a domestic cascade heat pump by using time-of-Use electricity rates. In both studies, very detailed models were used to assess system performance in specific cases.

Detailed simulations are likely to provide the best results when the goal of the simulation is to determine the performance of a specific system in a given location. These simulations can also estimate the viability of adopting a TES device. However, they require dedicated software and trained personnel, which makes them inaccessible to many stakeholders.

In response to this situation, Stalinski and Duquette (2021) proposed a simplified method to calculate the optimal storage capacity of hot water tanks integrated with heat pumps. The authors utilized TRNSYS® models coupled with a MATLAB® routine to develop an analytical method to size TES. This allows users to quickly estimate the optimal size of the water tank without resorting to complex calculations.

For end-users, determining whether to add a thermal energy storage system to their residential heating system is not a simple task. Accessing programs like the ones mentioned above is not always possible. In part because of this problem, this paper proposes a new simplified method to generate an initial estimate of the feasibility of integrating a TES into an air-source heat pump. The method was tested in various locations and the influence of system parameters is analyzed.

2. LEVELIZED COST OF ASHP-TES SYSTEMS

The performance of a heat pump system can be evaluated on the basis of energy, environmental, or economic metrics. Economic metrics are typically used to determine the system's viability, which ultimately determines whether the project will be implemented. There are several economic metrics to consider. Among them, the levelized cost of energy (LCOE) has received special attention. This metric expresses the cost per unit of energy $\left[\frac{US\$}{kWh}\right]$ when all expenses are considered over the lifetime of the system. It can be applied to electrical systems, heat, and even energy storage and is particularly useful for comparing different technologies (Short et al., 1995).

Odukomaiya et al., 2021 defined the levelized cost of energy for thermal storage systems over its lifetime *LT* as the ratio of TES cost to the value of discharging it during peak periods

$$\text{LCOE} = \frac{\text{Cost}_{\text{LT}}}{\text{Value}_{\text{LT}}}. \tag{1}$$

The system cost is the summation of the initial investment A_T and the operation cost:

$$\text{Cost}_{\text{LT}} = A_{\text{T}} + \sum_{\text{i=1}}^{\text{LT}} (1+r)^{-i} \sum_{\text{j=1}}^{8760} W_{\text{c[i,j]}} \cdot p_{\text{[i,j]}} \Big|_{\text{off}}, \tag{2}$$

where $W_{\text{c[i,j]}}$ is the heat pump energy, $p_{\text{[i,j]}}$ the hourly electricity rate, and r the annual interest rate. The value is the total energy avoided during peak hours calculated as

$$\text{Value}_{\text{LT}} = \sum_{\text{i=1}}^{\text{LT}} (1+r)^{-i} \sum_{\text{j=1}}^{8760} W_{\text{av[i,j]}} \Big|_{\text{on}}. \tag{3}$$

Odukomaiya et al., 2021 rearranged Eq.1 in a simplified form:

$$\text{LCOE} = \frac{C_{\text{T}}}{\eta_{\text{S}} \frac{D_{\text{T}}\mu_{\text{T}}}{\text{COP}_{\text{av}}} \sum_{\text{i=1}}^{\text{LT}} (1+r)^{-\text{i}}} + \frac{p}{\eta_{\text{S}} \frac{\text{COP}_{\text{ch}}}{\text{COP}_{\text{av}}}}. \tag{4}$$

This equation still represents the cost of charging the TES at off-peak tives versusthe energy avoided in peak periods. However, in this framework all parameters are averaged values. The first term on the right-hand side considers the capital expenditures. C_{T} is the capital cost of the TES material [$/kWh], i.e. the ratio between the total initial investment A_{T} [$] and the system storage capacity $E_{th,nom}$ [kWh_{t}]. In the denominator, η_{S} stands for the storage efficiency, and COP_{av} is the avoided COP, which is interpreted as the coefficient of performance of a heat pump operating without a TES device. In this framework, the authors have used the terms $D_{\text{T}}\mu_{\text{T}}$ to characterize the utilization of the TES device. In other words, μ_{T} indicates how many times the TES was discharged within a year [cycles/year], and D_{T} is the average depth of charge for all cycles. The summation term calculates the interest rate over the service life of the system. The last term on the right-hand side refers to the operating costs, where the electricity rate p [$/kWh] is divided by a dimensionless ratio of the COPs during charging (COP_{ch}) and discharging (COP_{av}).

The viability of ASHP-TES systems can be estimated using the levelized cost of storage (LCOS), which is defined as

$$\text{LCOS} = \text{LCOE} - p_{\text{off}}. \tag{5}$$

The LCOS represents the costs that are added to the base electricity costs p_{off}. So, if the LCOS is less than $< (p_{\text{on}} - p_{\text{off}})$, the user pays less when using the storage system. Otherwise, it makes more sense to pay for the electricity at its peak price.

3. AN ANALYTICAL METHOD TO DETERMINE THE LCOE PARAMETERS

Equation 4 provides a precise method for evaluating the economic performance of an ASHP-TES system. Odukomaiya et al. (2021) used this approach to generate trend maps by varying the parameters within realistic ranges. However, calculating the LCOE/S of specific projects with this equation can be challenging. The user must input averaged parameters of the system that are not found in tables or correlations and must be determined using simulation tools. As mentioned above, the use of such simulations can limit the versatility of the equation and make it inaccessible to some stakeholders in the thermal storage market. To overcome this limitation, in this section we present a new analytical method to determine the input parameters of Eq. 4. This method eliminates the need for detailed simulation tools and can be implemented in spreadsheets, making this tool more accessible. Provides the user with an initial estimate of the performance and viability of residential ASHP-TES.

3.1 Method Description

To apply the method, the user must enter the annual hourly temperature of the desired location, set the storage capacity of the TES device, and specify a COP correlation for the heat pump. This information can be found in the operating instructions for the device.

The system discussed here, Fig. 1, charges the TES when the electricity price is lower off-peak (p_{off}), and turns off the HP to discharge the TES when the electricity is more expensive p_{on}. A similar approach was employed by Olympios et al. (2022), focusing on the ASHP-TES control strategy. The system State of Charge (SOC) represents the percentage amount of energy stored. The depth of charge can be calculated as $D_{\text{T}} = 100\% - \text{SOC}$. The system operation is displayed in Fig. 2, considering the Time-of-Use rate structure represented in yellow.

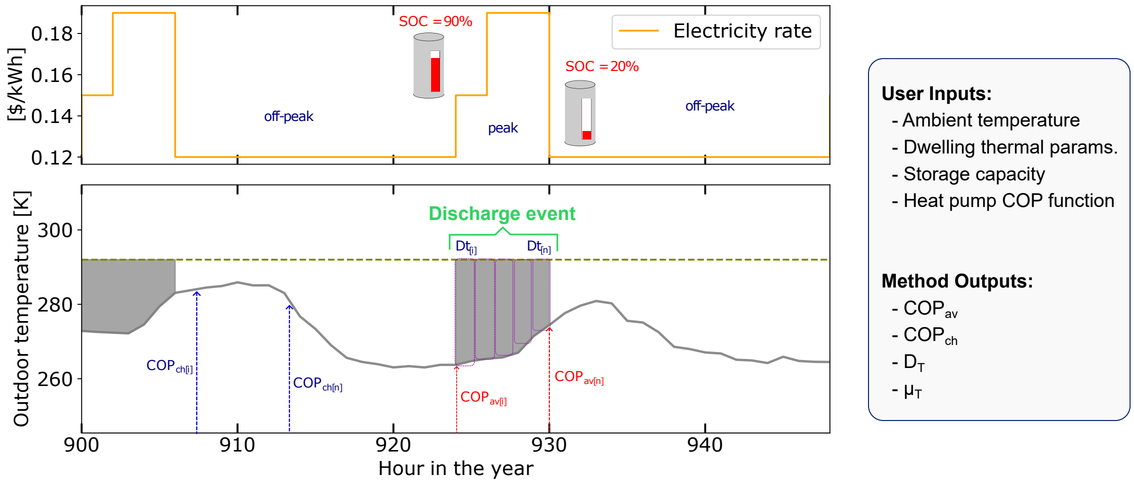


Figure 2: ASHP-TES operation based on TOU rates, and considering hourly temperature data over one year.

The method, as shown in Fig. 3, utilizes simplification hypotheses in the HP and TES operation to estimate the mean values of COP_{av}, COP_{ch}, and $D_{\text{t}}\mu_{\text{t}}$. These values are then used in the levelized cost equation, Eq. 4. For an annual weather data file with hourly outdoor temperatures $T_{\text{air[j]}}$, the method assumes that there is a thermal load $Q_{\text{load[j]}}$ if the outdoor temperature falls below the set point for the indoor temperature. For each hour [j], if the electricity price is off-peak, p_{off}, the charging $\text{COP}_{\text{ch[j]}}$ is calculated, otherwise, the system calculates $\text{COP}_{\text{av[j]}}$. The next parameter to be determined is the depth of charge $D_{\text{t[j]}}$, which is the amount of energy discharged in a given hour j. The method assumes that $D_{\text{t[j]}} = Q_{\text{load[j]}}$ and it uses a simple $UA\Delta T$ relation to estimate the heating load.

$$D_{\text{t[j]}} = Q_{\text{load[j]}} \simeq U_{\text{d}} A_{\text{d}} \left(T_{\text{air[j]}} - T_{\text{SP}} \right) \Delta t, \tag{6}$$

where U_{d} and A_{d} are the dwelling envelope heat transfer coefficient [$\text{W}\,\text{m}^{-2}\,\text{K}$] and area [$\text{m}^2$], respectively. They must first be determined using simulation tools or relations like ISO, 2006 or ASHRAE, 2005. This approach neglects several phenomena like air infiltration, solar gains and internal heat sources. Nonetheless, it can be used to estimate the heating demands for specific assessments that do not require high accuracy (ASHRAE, 2005).

The upper box in Fig. 3 shows how the method calculates the depth of charge. First, the events must be identified and counted as shown in Fig. 2. The total number of events in one year is μ_{t}. Then, for each i event, the depth of charge $D_{\text{T[i]}}$ is calculated as the total energy discharged divided by the storage capacity. Finally, COP_{av}, COP_{ch}, and $D_{\text{t}}\mu_{\text{t}}$ are averaged to be used in the LCOE equation.

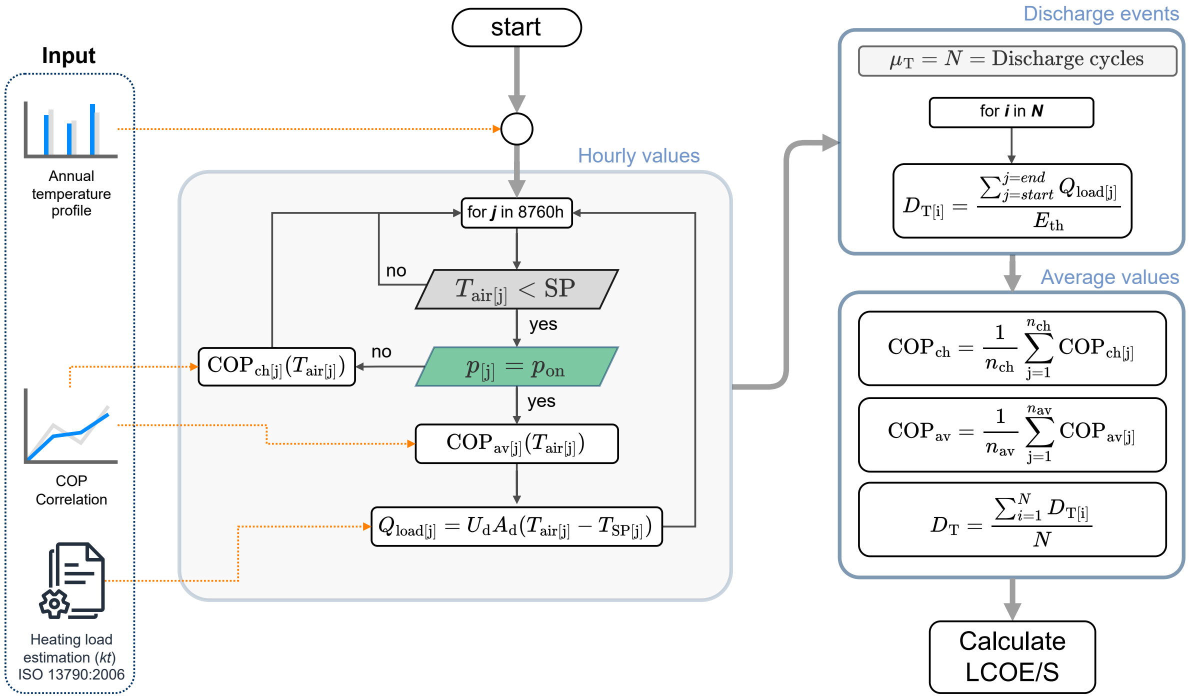


Figure 3: Analytical method to determine the input parameters of the LCOE equation without simulation tools. D_T: Depth of charge [%], μ_T: discharge cycles [cycles/year], COP_{av}: avoided COP, COP_{ch}: charging COP. $U_d A_d$: analytical expression to estimate the thermal load, obtained from (ASHRAE, 2005; ISO, 2006), for instance.

4. MODELING

4.1 Heat Pump and Thermal Storage Models

To explore the capabilities and limitations of the method, we compared it with results from simulations. The system of Fig. 1 was modeled using a Python library developed by Ermel et al. (2022b). The selected heat pump has similar parameters to the one studied by Ermel et al. (2022c), and considering a constant charging temperature of 328 K for the thermal storage, the following 2nd-order polynomial regression was obtained:

$$COP_{reg} = -7 \times 10^{-5}\, T_{air}^2 + 0.0745\, T_{air} - 12.36, \tag{7}$$

The TES device was modeled as a generic 15 kW h storage, i.e. it was treated as an ideal energy storage system. Heat transfer phenomena such as the geometric characteristics, PCM glide, heat transfer intensification, were not considered. The operation logic follows a TOU structure adapted from XcelEnergy (2023): On-peak: $0.19/kWh (1-7 p.m.), and in the remaining hours off-peak: $0.12/kWh. The system is designed to maintain the SOC > 95 %, and to discharge the TES during peak hours, according to the thermal load.

Five U.S. locations were simulated to represent the system operation in different weather conditions: Denver-CO, Baltimore-MD, Seattle-WA, Boston-MA, and Chicago-IL. The parameters obtained from the simulation were used as reference values, to be compare with those obtained from the analytical method.

5. RESULTS

Three approaches to calculating the LCOE were compared: i) simulation using the Python platform (Ermel, 2023), ii) the framework proposed by Odukomaiya et al. (2021), and iii) the method proposed in section 3 of this paper. The simulation calculates the LCOE directly through Eq. 1. The input parameters of the second approach, Eq. 4, were obtained from the simulation.

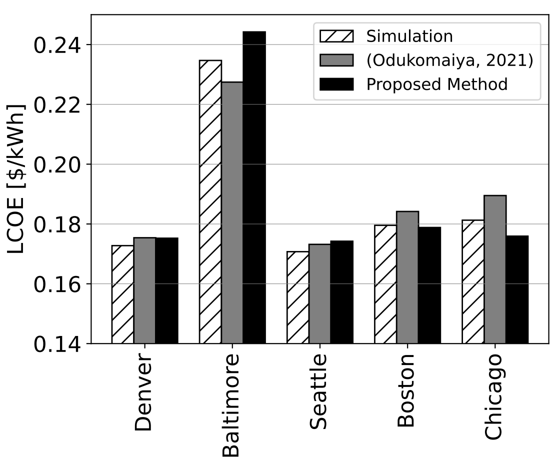
Table 1 shows the results of the input parameters for the LCO equation extracted from the simulations and those estimated by the proposed method. The coefficient of performance calculated with the proposed method was similar to

Table 1: Results for the LCOE input parameters obtained from the simulation, the framework proposed by Odukomaiya et al. (2021), and the proposed method.

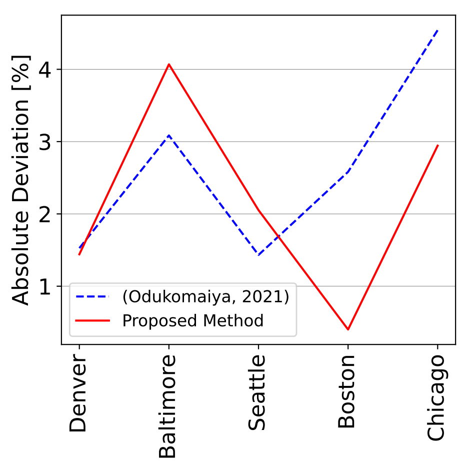
Parameter	Denver	Baltimore	Seattle	Boston	Chicago
Framework of Odukomaiya et al. (2021)					
D_T	0.50	0.28	0.53	0.48	0.51
μ_T	170	152	177	171	158
COP_{ch}	2.83	2.97	2.82	2.78	2.66
COP_{av}	2.83	2.96	2.87	2.91	2.88
COP_r	1.00	1.01	0.98	0.96	0.92
LCOE	0.1754	0.2274	0.1732	0.1842	0.1895
Proposed method					
D_T	0.48	0.22	0.49	0.49	0.48
μ_T	177	174	177	177	177
COP_{ch}	2.85	2.98	2.89	2.86	2.86
COP_{av}	2.84	3.02	2.87	2.92	2.86
COP_r	1.00	0.99	1.01	0.98	1.00
LCOE	0.1752	0.2442	0.1742	0.1788	0.1759

the simulation results in all cases, both for the COP_{ch} and for the COP_{AV}. Moreover, the COP ratio remained within the range of 8 % deviation. Interesting trends were observed with regard to TES use. While the proposed method assumes that the TES is discharged whenever a peak-period occurs, the simulation also monitors the TES state of charge. If SOC is not sufficient to supply the thermal load in a given period the heat pump will work, even in a peak-period. As a consequence, the method considers that for most cases the TES was discharged 177 times over a year. As the simulation provides more precise information about when a discharge cycle occurs, small deviations are observed at the various locations. The depth of charge predicted by the present method followed the same trend calculated by the simulation, but deviations from 2 % to 21 % were observed. Although the numerical values appear to be significant, the key metrics (LCOE and LCOS) were not affected to the same extent.

The LCOE predicted by Odukomaiyas' method and the present method were compared with the simulation results in Fig. 4a. In general, the three method produced similar results in almost all locations, with relative deviations in the



(a) LCOE



(b) Deviation

Figure 4: Comparison of the LCOE obtained from the simulation, calculated by the framework of Odukomaiya et al. (2021), and the proposed method.

range of 0.5 % to 3 %. Only for Baltimore and Chicago did the results differ by up to 4.6 %. The viability criterion, Eq. 5, for the simulated cases is $p_{\mathrm{on}} - p_{\mathrm{off}}$ = US$ 0.7, while the deviation revolved around US$ 0.01. This result indicates that the method is able to provide initial estimates on the viability of ASHP-TES.

6. CONCLUSIONS

Determining the LCOE/S is crucial for assessing the performance and economic viability of ASHP-TES systems. In this paper, an analytical method for estimating the economic performance of ASHP-TES systems was first proposed. The method determines the input parameters of the LCOE/S equations based on the characteristics of the dwelling, the heat pump, and the annual temperature profile of the desired location. By applying simplification hypotheses for the calculation of the heating load and storage utilization, the method offers a significant advantage by dispensing complex simulation tools, making it accessible to a wider range of stakeholders. The method was developed to provide initial estimates of the ASHP-TES viability, and this can be accomplished using spreadsheets and without resorting to complex simulation tools. We conducted an assessment at five different locations in the US, compared the results of our method with a benchmark simulation. The method results followed the same trend as the simulation for all the studied sites. Despite the adoption of robust simplification hypotheses, the outcomes remained consistent in all scenarios.

When looking at the levelized cost of electricity and storage calculated with the method, the deviations ranged from 0.5 % to 3 %. This is an interesting result that indicates the validity of the proposed method. The deviation found for the LCOS is 10 times smaller than the economic viability criterion for ASHP-TES systems. In other words, the error of the method had no significant effect on the results when the LCOS was used to determine the profitability of the system.

Although the results are promising, one must keep in mind that the strong simplification hypotheses may lead to larger errors in specific scenarios. Despite the encouraging results, further research is needed to better understand the limitations of the method. Nonetheless, we believe that our method provides a valuable initial estimation tool for evaluating ASHP-TES system performance and viability. This preliminary estimate can help users decide whether further investigation and investment in thermal energy storage systems are warranted, emphasizing its practical relevance to the decision-making process for residential ASHP-TES systems.

NOMENCLATURE

Latin Symbols		
A	Area	(m^2)
C	Cost of investment	(US$)
D_T	Depth of charge	(%)
p	Electricity rate	($/kW h)
$\dot{Q}$	Heat transfer rate	(W)
r	Interest rate	(%)
T	Temperature	(K)
U_d	Overall heat transfer coefficient	($\mathrm{W\,m^{-2}\,K^{-1}}$)
$\dot{W}$	Power	(W)
Greek Symbols		
η_S	Storage efficiency	(%)
μ_T	TES utilization	(cycles/year)
Subscripts		
amb	Ambient	
av	Avoided	
c	Compressor	
ch	Charge	
i,j	Year and hour counting	
LT	Life time	
off	Off-peak period	
on	On-peak period	

p	Pump
reg	Regression
SP	Set-point
T	Total

REFERENCES

ASHRAE (2005). *2005 ASHRAE Handbook—Fundamentals (SI)*. ASHRAE, Atlanta, GA, USA.

Ermel, C. (2023). ASHP_TES - Air source heat pump integrated with thermal storage simulation library. https://github.com/conradoermel/ASHP_TES.git.

Ermel, C., Bianchi, M. V., Cardoso, A. P., and Schneider, P. S. (2022a). Thermal storage integrated into air-source heat pumps to leverage building electrification: A systematic literature review. *Applied Thermal Engineering*, 215:118975.

Ermel, C., Bianchi, M. V. A., and Schneider, P. S. (2022b). Energy model of an air source heat pump to explore performance improvements under cold conditions: A python framework. In *7th International High Performance Buildings Conference at Purdue*.

Ermel, C., Bianchi, M. V. A., and Schneider, P. S. (2022c). Energy Model to Evaluate Thermal Energy Storage Integrated with Air Source Heat Pumps. In *ASHRAE 2022 Buildings XV International Conference*, Clearwater, FL.

IRENA (2020). Innovation Outlook: Thermal Energy Storage. Technical report, International Renewable Energy Agency, Abu Dhabi.

ISO (2006). ISO/FDIS 13790:2006(E) Energy performance of buildings — Calculation of energy use for space heating and cooling - Draft for comments by CEN and ISO WG.

Le, K. X., Huang, M. J., Wilson, C., Shah, N. N., and Hewitt, N. J. (2020). Tariff-based load shifting for domestic cascade heat pump with enhanced system energy efficiency and reduced wind power curtailment. *Applied Energy*, 257.

Ma, Z., Awan, M. B., Lu, M., Li, S., Aziz, M. S., Zhou, X., Du, H., Sha, X., and Li, Y. (2023). An Overview of Emerging and Sustainable Technologies for Increased Energy Efficiency and Carbon Emission Mitigation in Buildings. *Buildings*, 13(10):2658.

Moreno, P., Sole, C., Castell, A., and Cabeza, L. F. (2014). The use of phase change materials in domestic heat pump and air-conditioning systems for short term storage: A review. *Renewable & sustainable energy reviews*, 39:1–13.

Odukomaiya, A., Woods, J., James, N., Kaur, S., Gluesenkamp, K. R., Kumar, N., Mumme, S., Jackson, R., and Prasher, R. (2021). Addressing energy storage needs at lower cost via on-site thermal energy storage in buildings. *Energy & Environmental Science*, 14(10):5315–5329.

Olympios, A. V., Sapin, P., Freeman, J., Olkis, C., and Markides, C. N. (2022). Operational optimisation of an air-source heat pump system with thermal energy storage for domestic applications. *Energy Conversion and Management*, 273:116426.

Palomba, V., Varvagiannis, E., Karellas, S., and Frazzica, A. (2019). Hybrid adsorption-compression systems for air conditioning in efficient buildings: Design through validated dynamic models. *Energies*, 12(6).

Short, W., Packey, D. J., and Holt, T. (1995). A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies. Technical Report NREL/TP-462-5173, National Renewable Energy Laboratory, Golden, CO.

Stalinski, D. and Duquette, J. (2021). Development of a simplified method for optimally sizing hot water storage tanks subject to short-term intermittent charge/discharge cycles. *Journal of Energy Storage*, 37:102463.

Vering, C., Maier, L., Breuer, K., Krützfeldt, H., Streblow, R., and Müller, D. (2022). Evaluating heat pump system design methods towards a sustainable heat supply in residential buildings. *Applied Energy*, 308(October 2021):118204.

XcelEnergy (2023). Time of Use (TOU). https://co.my.xcelenergy.com/s/billing-payment/residential-rates/time-of-use-pricing.

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