Feasibility Analysis for Retrofitted Air-Conditioners Using Thermal Energy Storage (TES) in High Ambient Temperature (HAT) Countries

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Acknowledgements

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Building Technologies Office Award Number DE-EE0009681. The views expressed herein do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

This work was also funded in part by the Modeling and Optimization Consortium at the University of Maryland.

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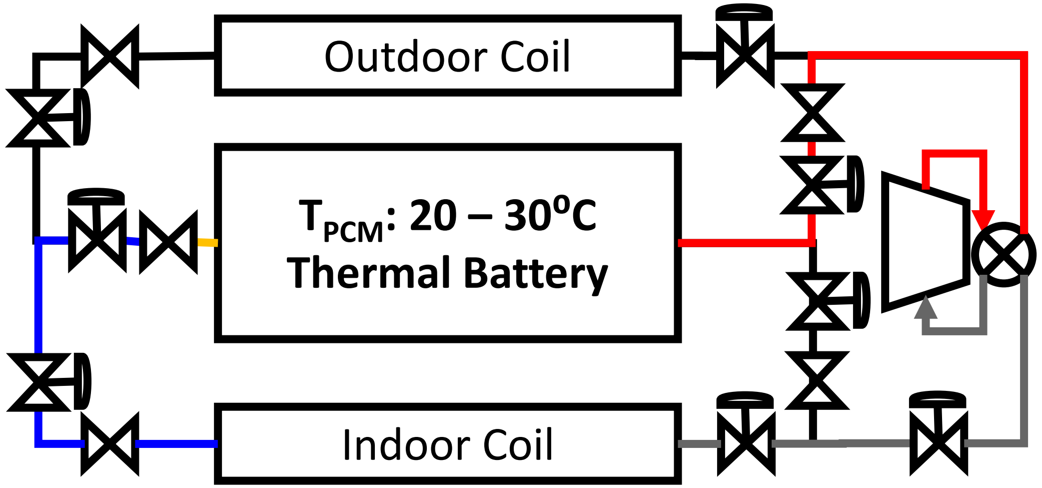
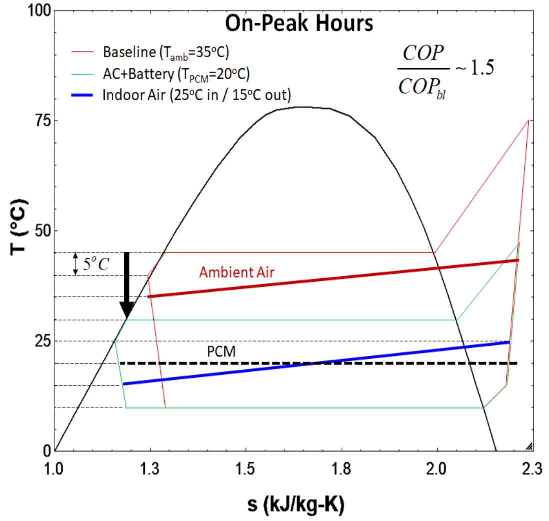
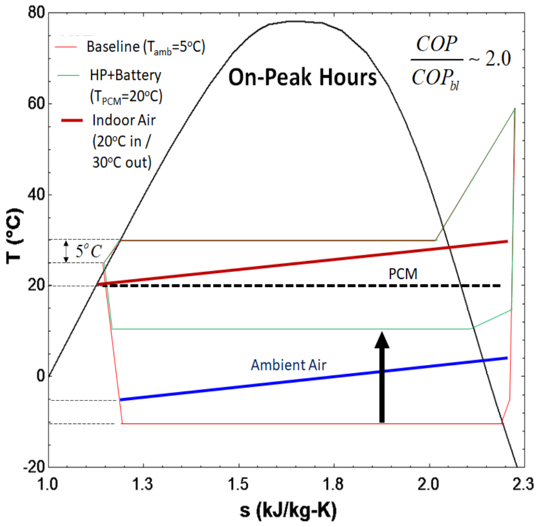
Proposed Technology Description

- Dual-purpose (heating and cooling) thermal battery with room temperature storage integrated in a commercial heat pump
- The battery absorbs heat when operating as condenser in cooling mode or rejects heat when operating as evaporator in heating mode

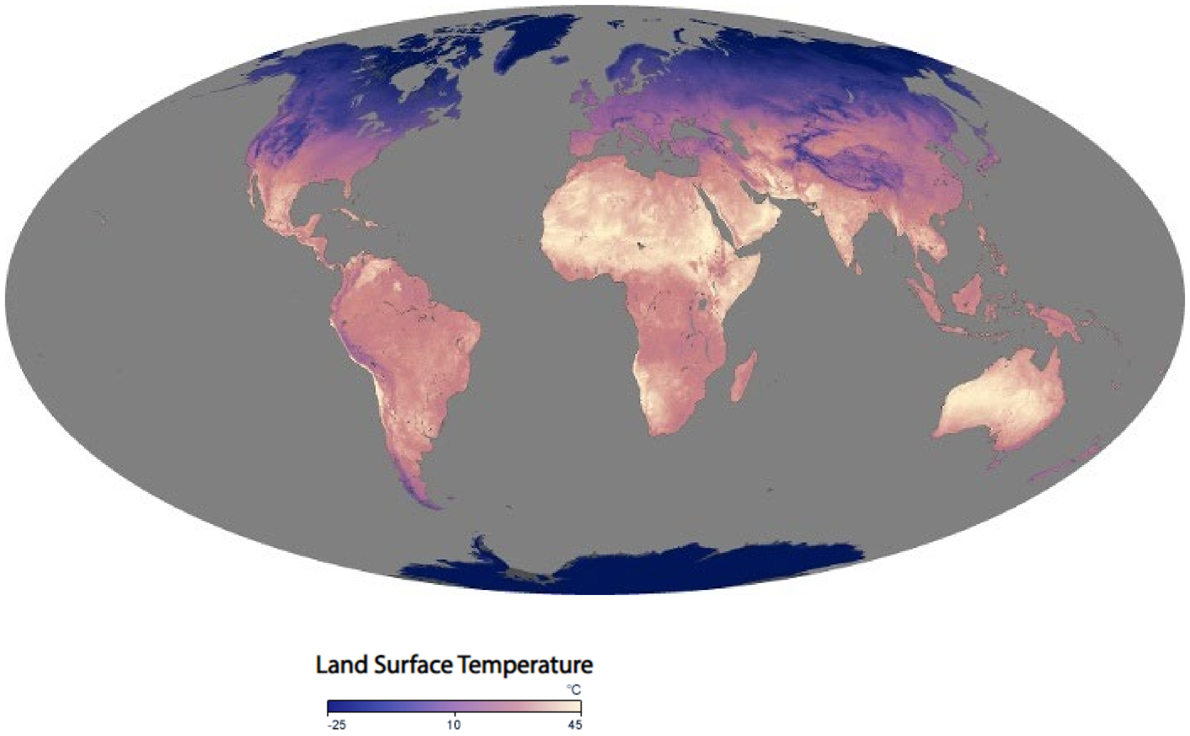






Motivation

- Looking at the most extreme climate zones, they have
  1. higher indoor building loads
  2. Increased pressure and temperature lifts in the VCC, thus more compressor power
  3. Degraded system COP during the peak
- Demand reduction depends on location



Source: NASA Earth Observatory [1]

Potential for the Two Extremes

Extremely Hot-Dry Climate Zone (0B)

- In Dubai
  1. Temperatures exceed 35^{0}C and 40^{0}C in the summer [2]
  2. Air-conditioning consumes 50% of annual electricity [3]
  3. Peak hours are from 12 – 6 pm[3]

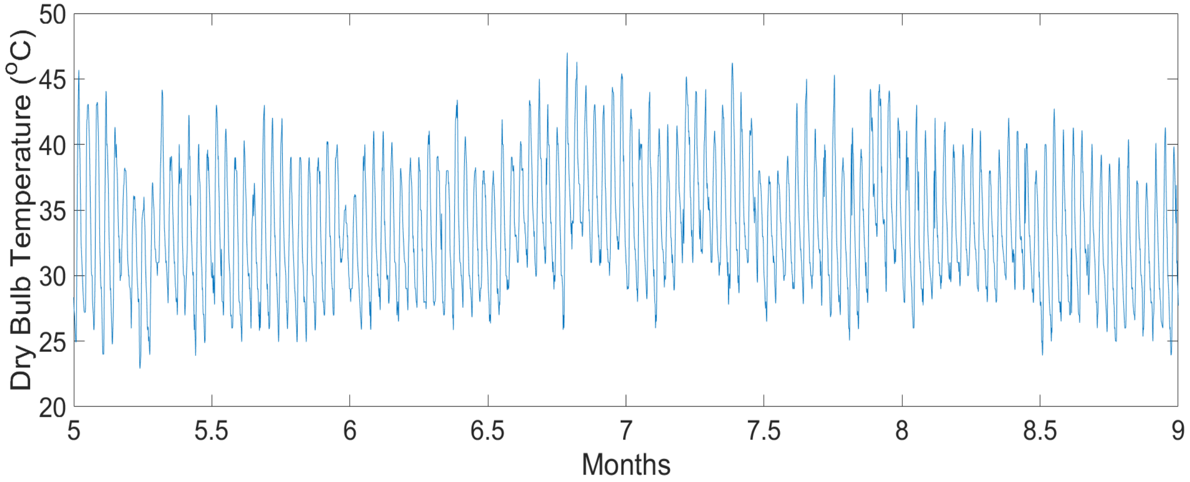
Very Cold Climate Zone (7)

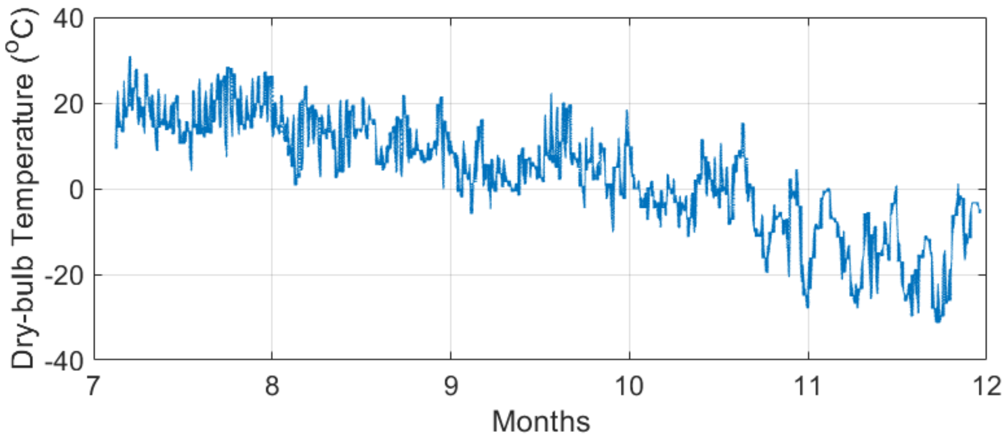
- In International Falls, MN (Climate Zone 7)
  1. Majority of homes rely on natural gas for heating
  2. COPs of HPs do degrade in these conditions
  3. Peak hours are from 9 am – 9 pm [4]

TES-HPs → ↓ Peak Power demand, ↑ COPs during peak

Objectives

- Analyze the system feasibility for demand reduction and economic savings in both extreme climates for using PCMs melting points of
  1. 22ºC
  2. 25ºC
  3. 28ºC
- System analysis conducted using 5-ton HP heating and cooling modes





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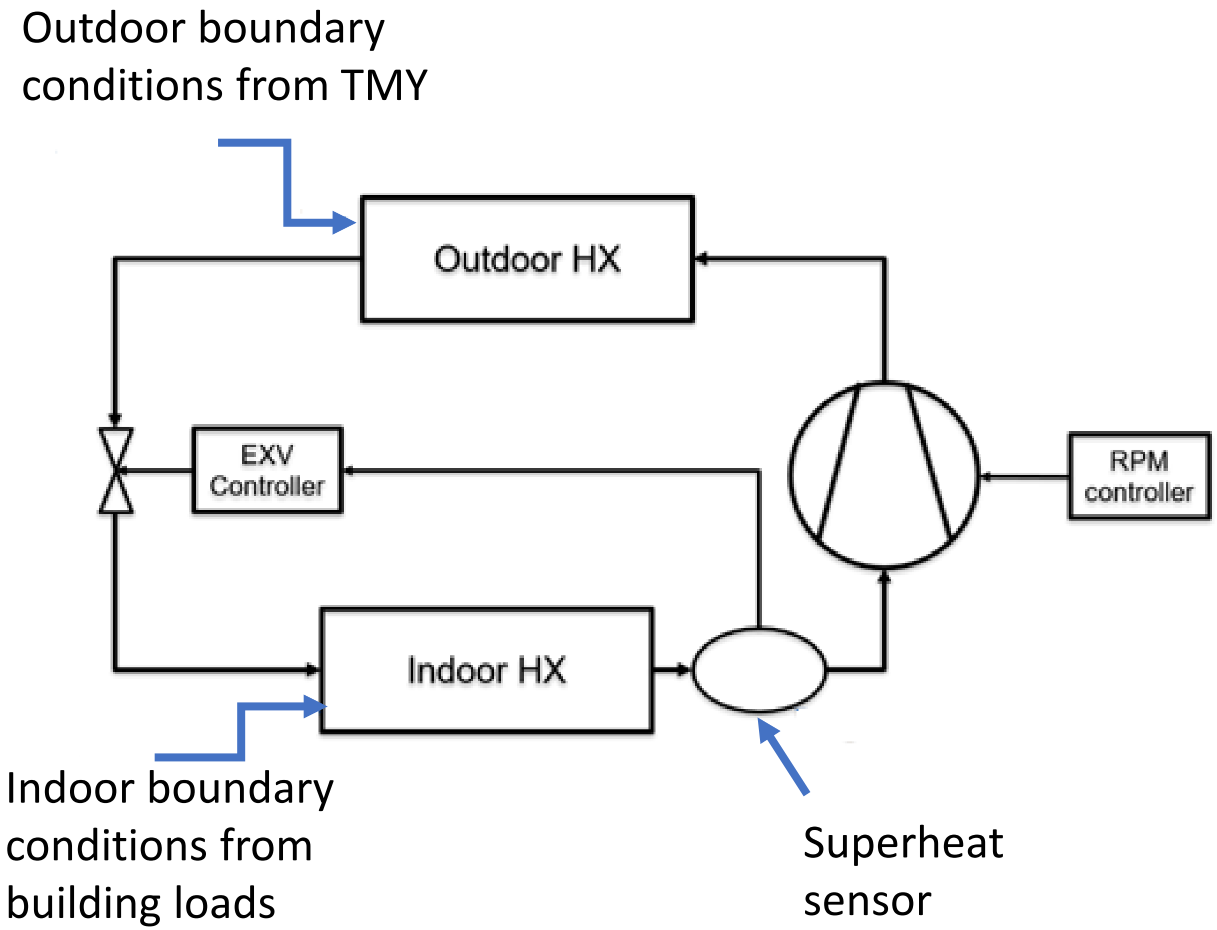
System Modeling

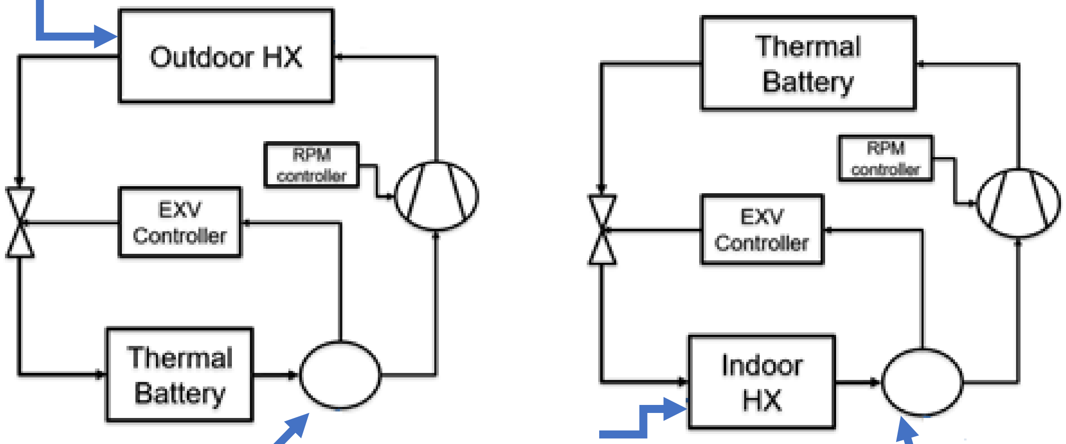
System Modeling: Baseline Cycle



- Cycle components were modeled using the CEEE Modelica Library [7-8]
- 20 Coefficient variable speed compressor maps
- The model can use any outdoor and indoor boundary conditions from any location

System Modeling: HPTES Models

Outdoor boundary conditions from TMY

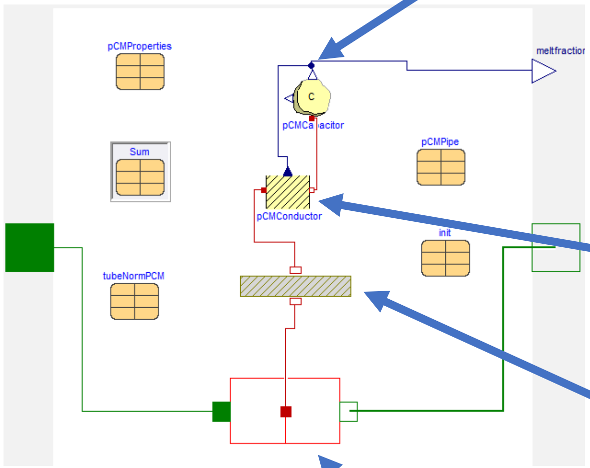


Superheat sensor

Indoor boundary conditions from building loads

Superheat sensor

TES Model [8]



$$T^* = T_{pcm} - T_m$$

$$h = c(T^* + s)$$

$$c = \begin{cases} C_s & \text{if} \quad T^* < \Delta T \\ \dfrac{C_s + C_l}{2} + \dfrac{H_{sl}}{2\Delta T} & \text{if} \quad -\Delta T < T^* < \Delta T \\ C_l & \text{if} \quad T^* > \Delta T \end{cases}$$

$$s = \begin{cases} \Delta T & \text{if} \quad T^* < \Delta T \\ \dfrac{C_s}{C_l}\Delta T + \dfrac{H_{sl}}{C_l} & \text{if} \quad T^* > \Delta T \end{cases}$$

$$Q = \frac{dh}{dt} M_{PCM}$$

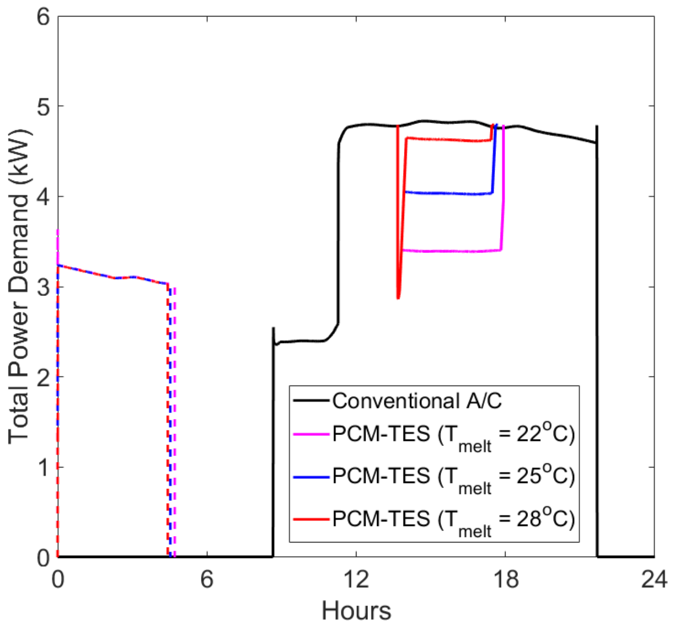
$$Q = h_{pcm} A_{pcm} \left(T_{surface} - T_{pcm} \right)$$

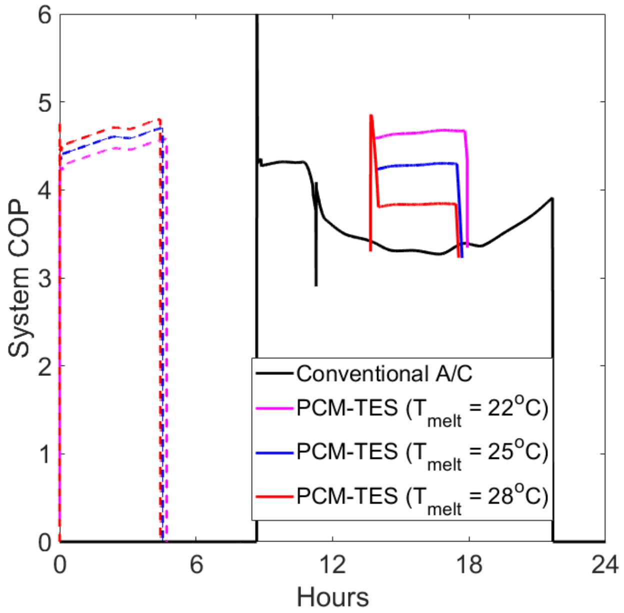
Conduction through the HX wall

$$Q = h_{ref} A_{\text{int}} \left(T_{surface} - T_{ref} \right)$$

System Assessment in Hot Climate Zone

Peak Demand Reduction on 35 – 40°C Days

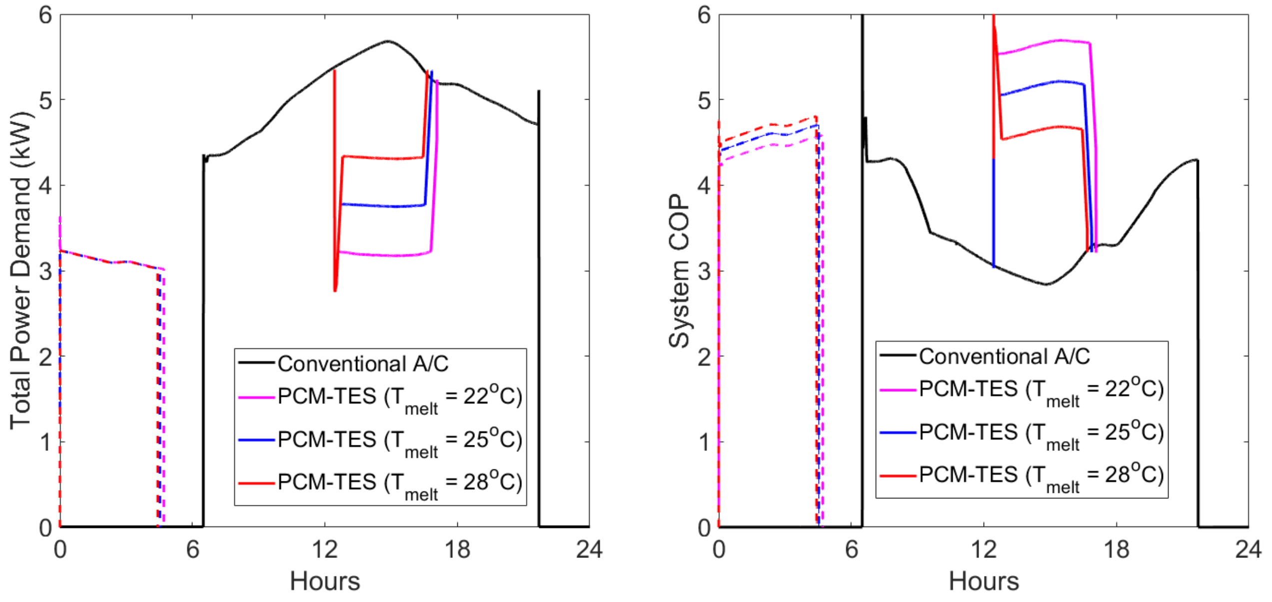




PCM melting temperature	22°C	25°C	28°C
% increase in COP during the Peak	42.5	31.2	17.4
% peak power savings	30.2	17.1	4.9
% increase in cooling capacity during the peak	10.1	9.8	8.7

- PCM at 22°C had:
  - Lowest recharge time
  - Highest peak demand reduction
  - More reasonable to use when load shifting
- All PCMs were able to achieve this demand reduction

Peak Demand Reduction on 40 – 45ºC Days



PCM melting temperature	22ºC	25ºC	28ºC
% increase in COP during the Peak	99.6	82.5	63.5
% peak power savings	51.2	33.1	24.4
% increase in cooling capacity during the peak	18.1	14.8	12.5

- PCM at 22ºC had similar observations as before
- Increase in COP and demand reduction were higher at the most extreme, given the significant temperature lift decrease

Economic Assessment

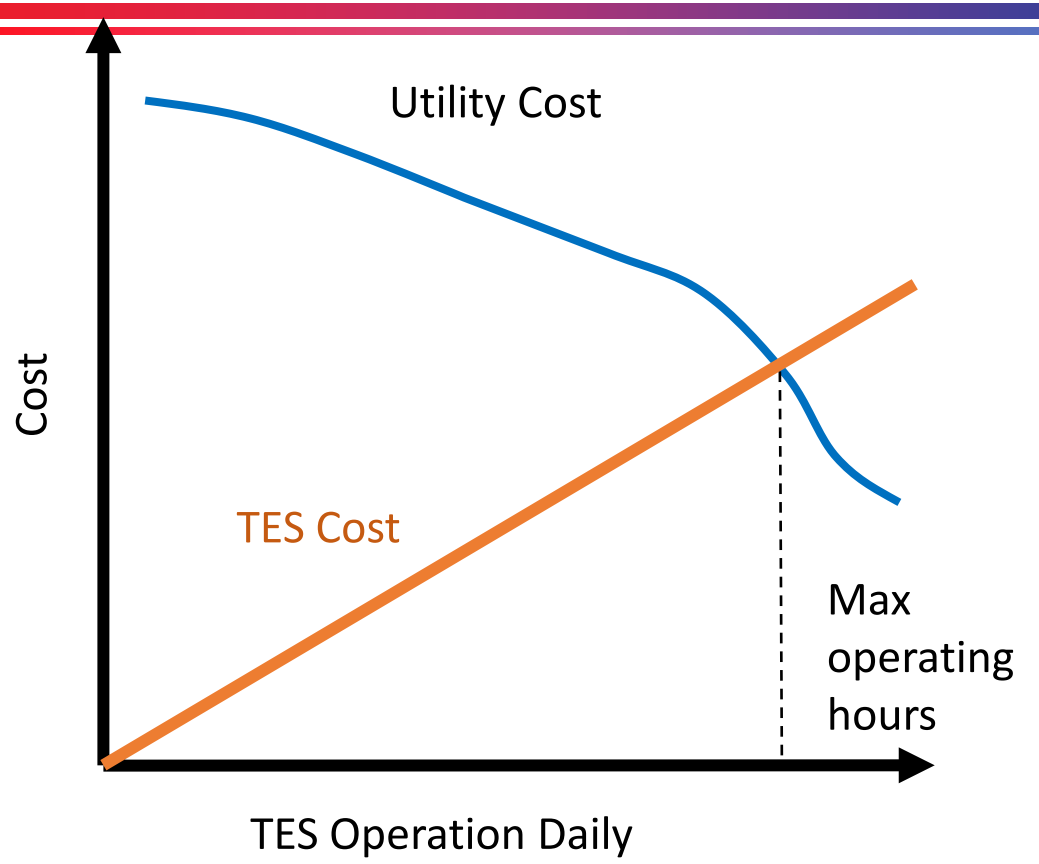
- Challenges with the economic assessment
  1. Dubai has a single utility rate (~$0.11/kWh) [3]
  2. Current utility rates are subsidized

Power Stations	Power Station Type	Current Energy Production Year 2021 (MW) [9-11]
Aweer Power Station "H" Phases I to III	Natural Gas and Diesel Turbines	1996
Hassyan Power Plant Phases I and II	Natural Gas Turbines (Converted from Coal)	1200
Jebel Ali Station "D"	Natural gas and oil combined cycle	1027
Jebel Ali Station "E"		616
Jebel Ali Station "G"		818
Jebel Ali Station "K"		948
Jebel Ali Station "L" Phases I to II		2401
Jebel Ali Station "M" with Extension		2885
Mohammed bin Rashid Al Maktoum "All Phases until 2022"	Currently Solar PV	1526

- Looking at the economic impact on the city level, the total utility rate were estimated to $0.48/kWh

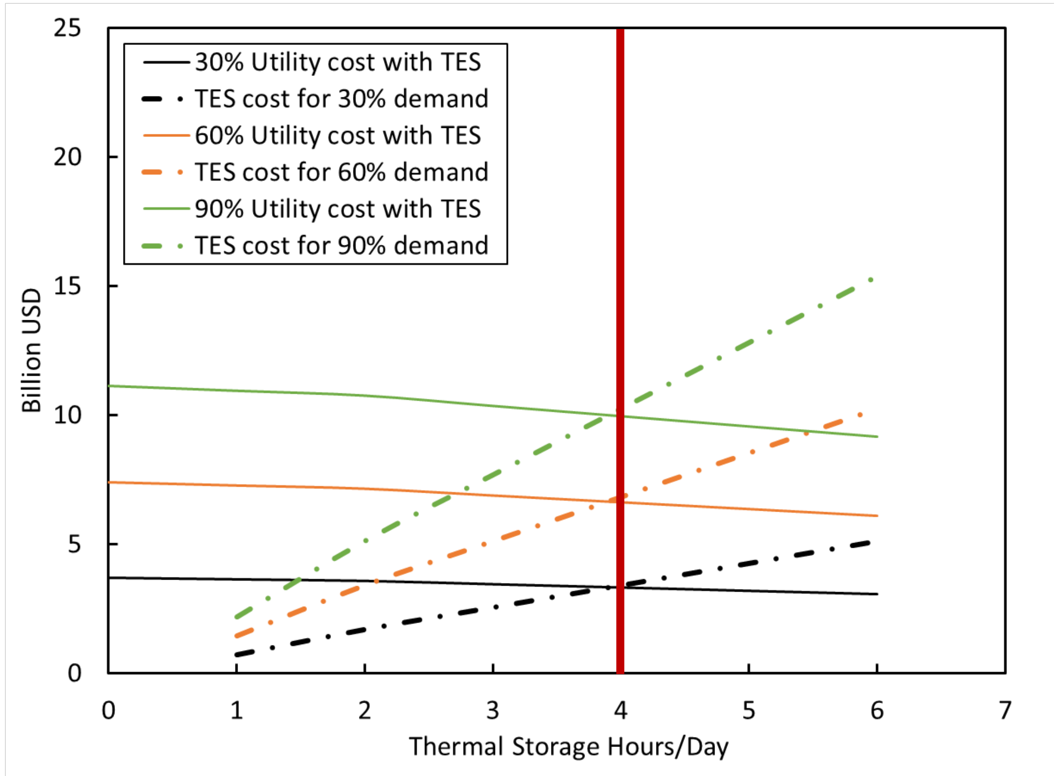
Economic Assessment

- Important variables
  1. PCM-TES cost
     - ➢ PCM cost is low \$3-30/kWh [12]
     - ➢ However, with current market TES \$200-500/kWh [13]
  2. Utility savings during the peak hours
     - ➢ Calculated using the demand reduction from Modelica,
     - ➢ Savings rate is weight by the number of peak hours with temperature <40^{o}C and between 35 – 40^{o}C

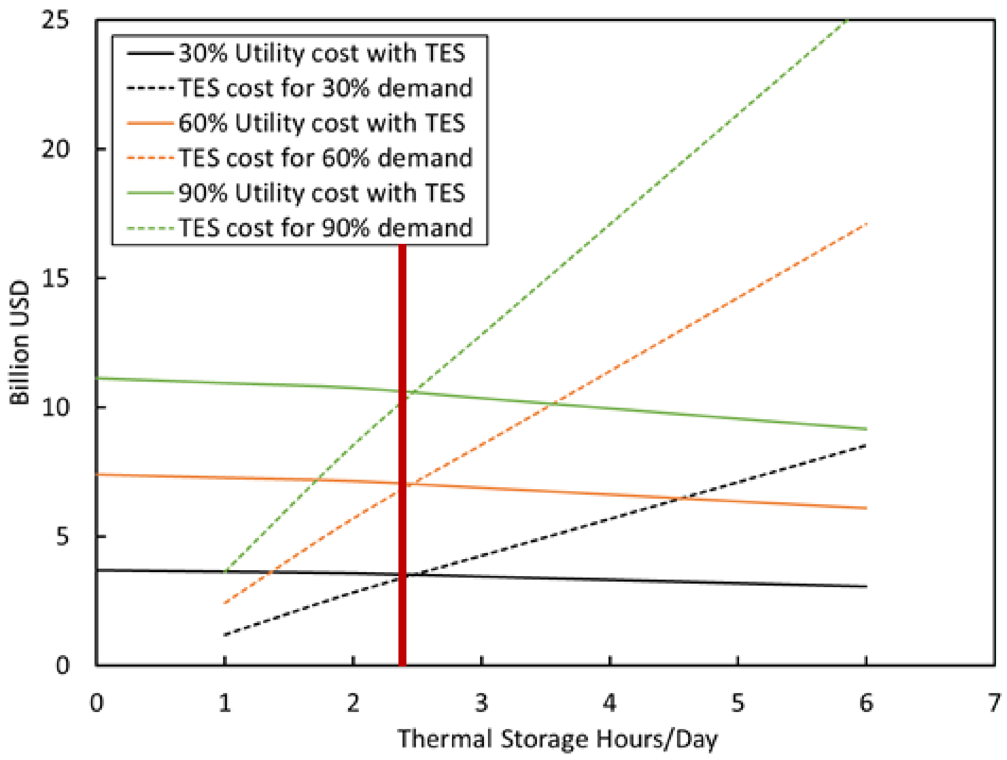


Economic Assessment

TES cost: $200/kWh



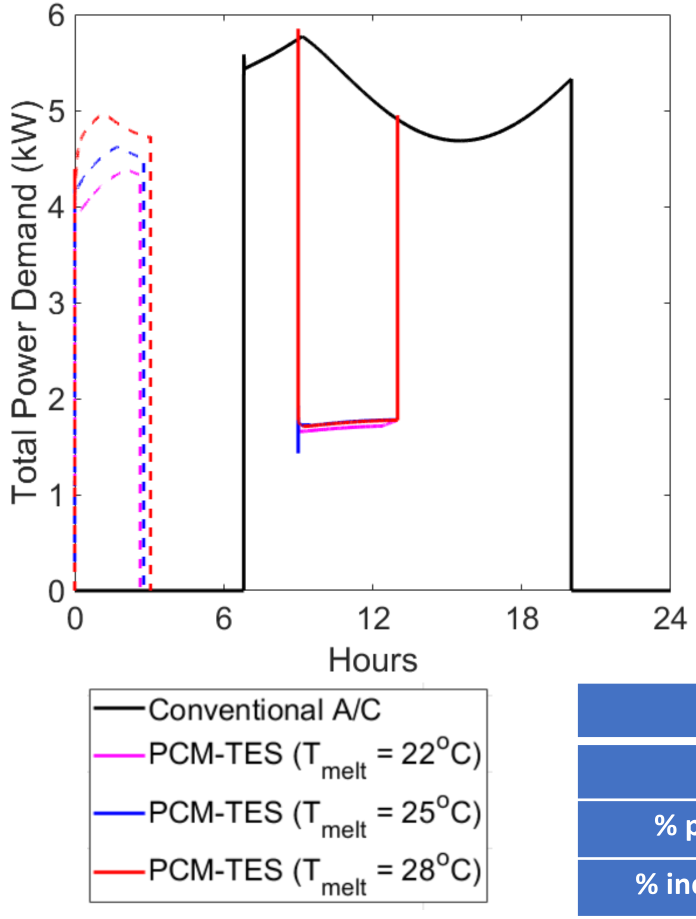
TES cost: $500/kWh

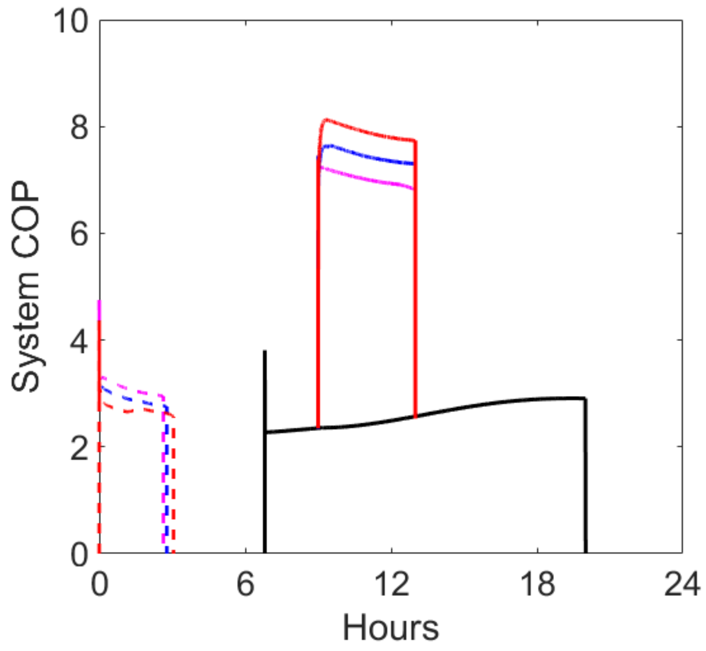


Potential Demand Reduction and Economic Assessment

Cold Climate Zone

Peak Demand Reduction and Potential Savings





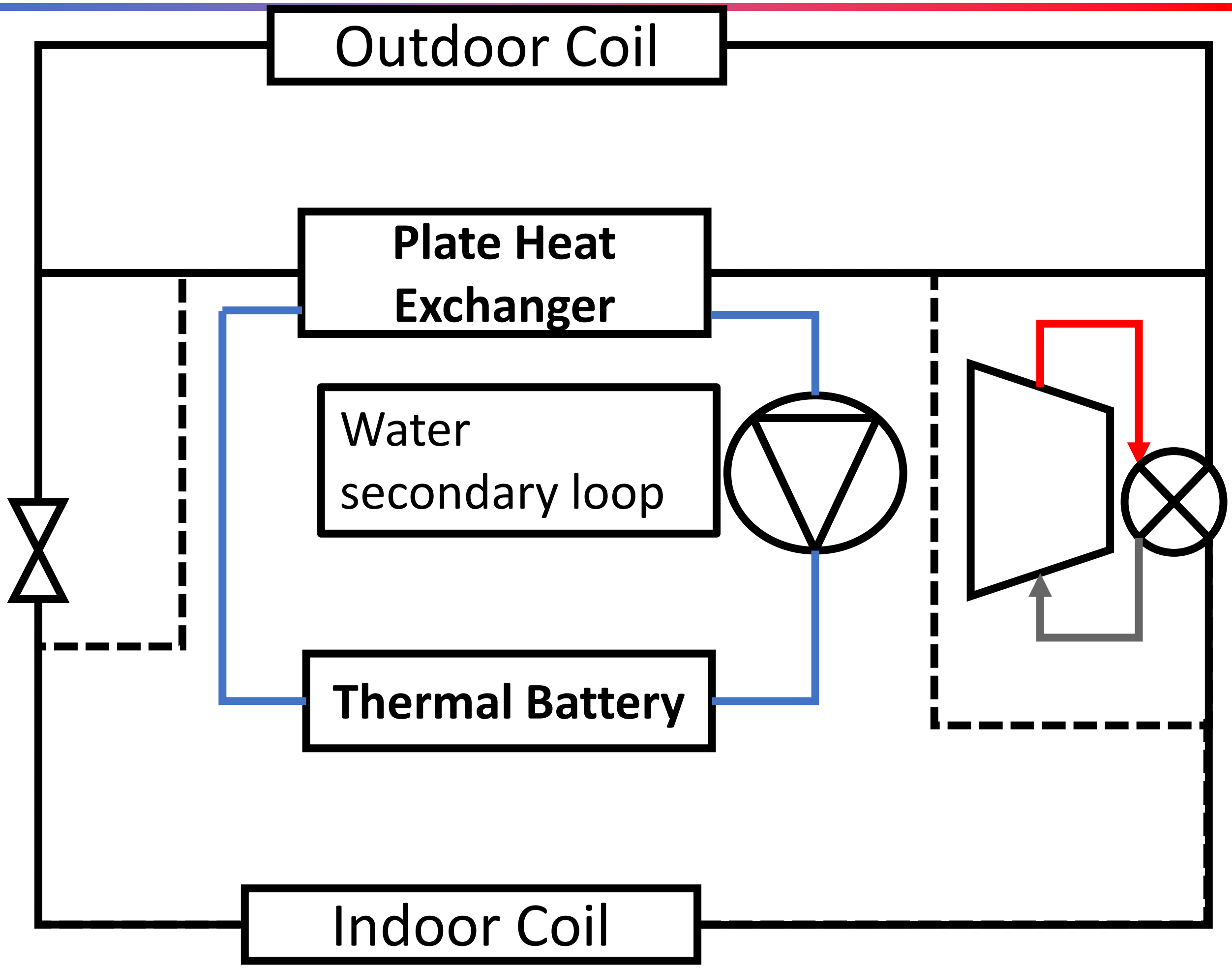
- PCM 22°C had the lowest power demand and recharge time
- Utility rates [4]:
  - On-peak $0.16/kWh
  - Off-peak $0.04/kWh
- Utility cost reduction 19%

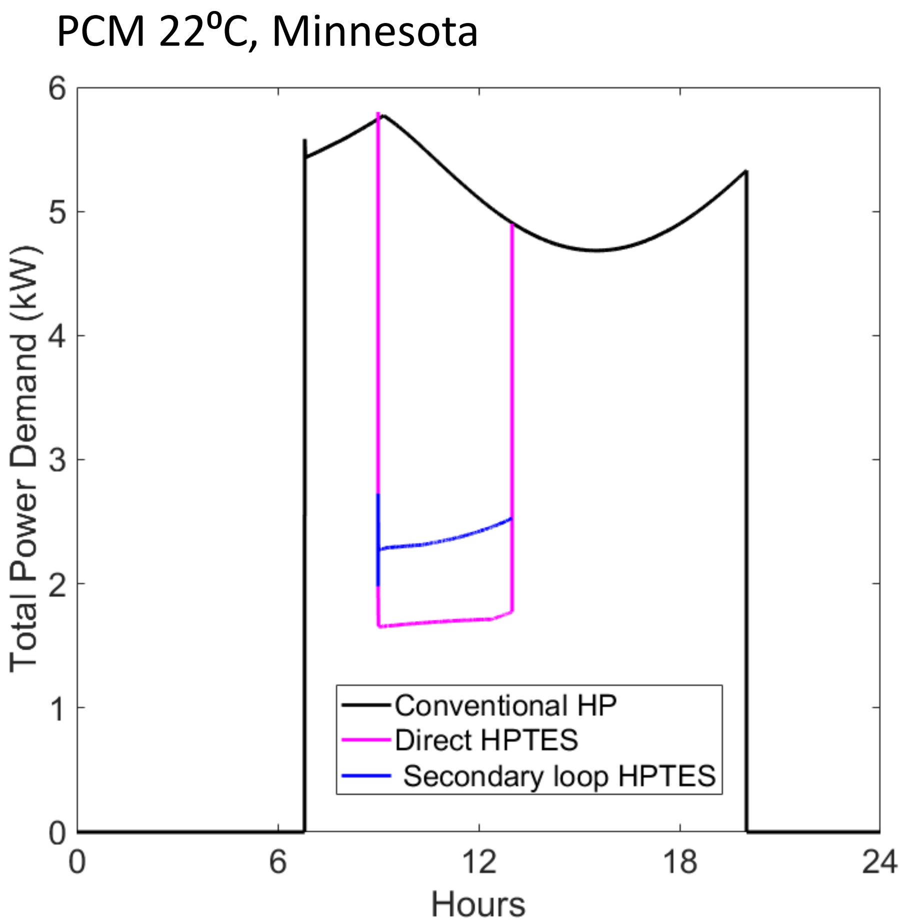
PCM melting temperature	22°C	25°C	28°C
% increase in COP during the Peak	130	143	164
% peak power savings (cost reduction/day)	64 ($1.70)	63 ($1.78)	67 ($1.83)
% increase in heating capacity during the peak	4	6	11

Challenges

- For a directly integrated system
  1. TES weight limits rooftop applications (6 x HP weight)
  2. 5 x Refrigerant charge increase
  3. TES aluminum HX are susceptible to corrosion from PCM salt hydrates
  4. Lower thermal conductivities are present for organic PCMs
  5. Demand reduction potential is dependent on location
  6. Compressor overall efficiency may degrade at lower temperature lifts given that the compressor design
- These all present challenges given the EPA proposed to phase-down HFCs by 40% in 2024 [15]

Potential Solution





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Conclusions

- A proposed PCM-TES air conditioning feasibility was assessed in extreme conditions
- In Dubai PCM at 22^{o}C
  - Presented the highest peak demand reduction
  - At higher outdoor temperatures, the demand reduction was up to 50% and doubled the COP
  - Increases of 8-18% in the system cooling capacity can be achieved
- In Dubai, economically TES can operate daily for
  - 2.5 hours for a $500/kWh system
  - 4 hours for a $200/kWh system
- In Minnesota
  - PCM at 28^{o}C had the highest COP during peak hours
  - PCM at 22^{o}C had the lowest recharge time and power demands (lower temperature lifts)
  - Utility cost reduction was just below $2/day

Thank you

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