Energy Systems

Peak load reduction using thermal energy storage in a HVAC system of a building

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Research Advisor: *Elena Gryazina*

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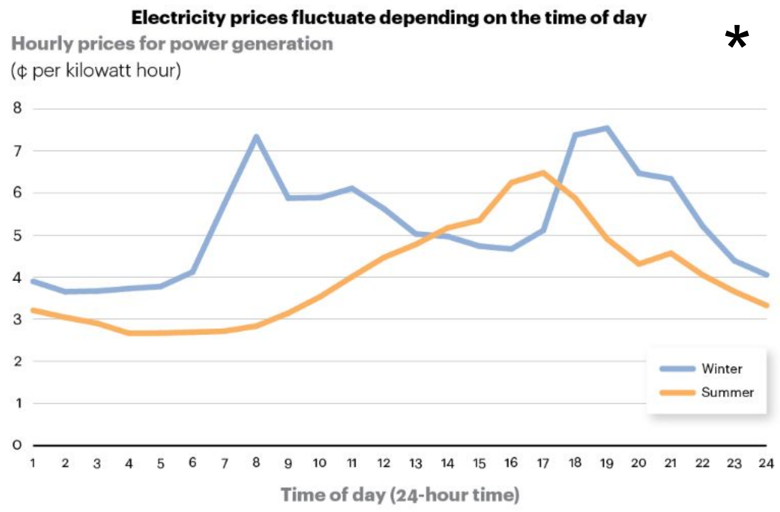
General problem

- ➢ The peak electricity demand leads to expensive energy generation;
- ➢ Increased price of energy in the market up to 4-5 times;
- ➢ High price -> high electricity bills.



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* A.T. Kearney analysis.
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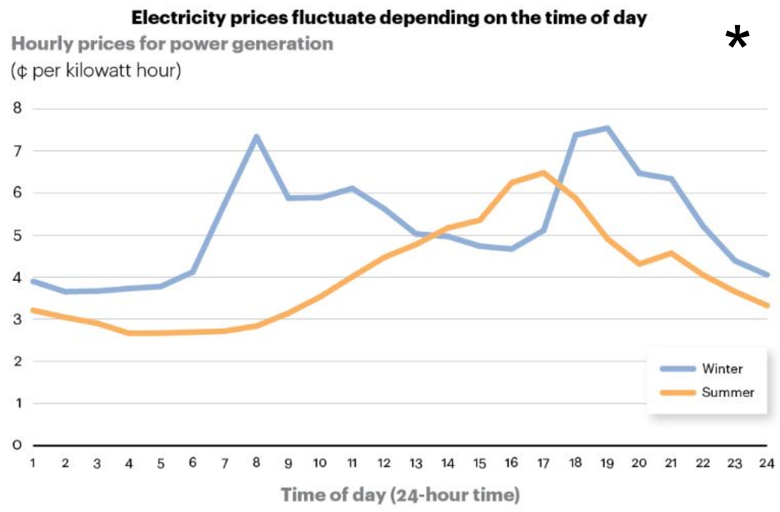
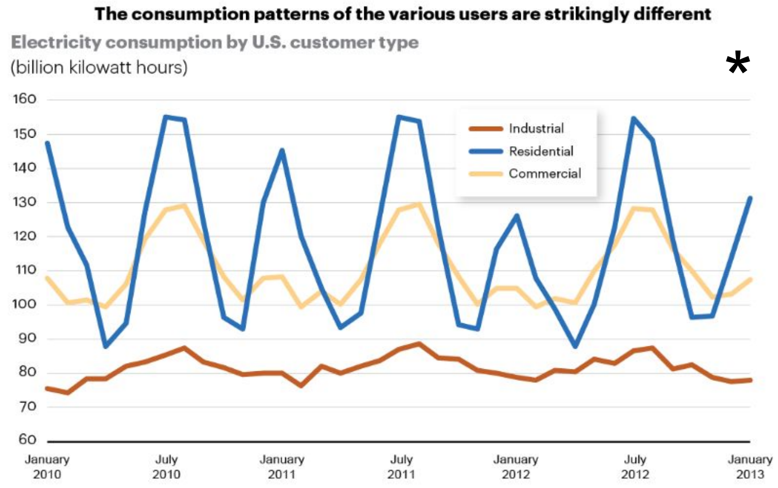
- ➢ Additional equipment is idle the rest of the time -> extra expenses.





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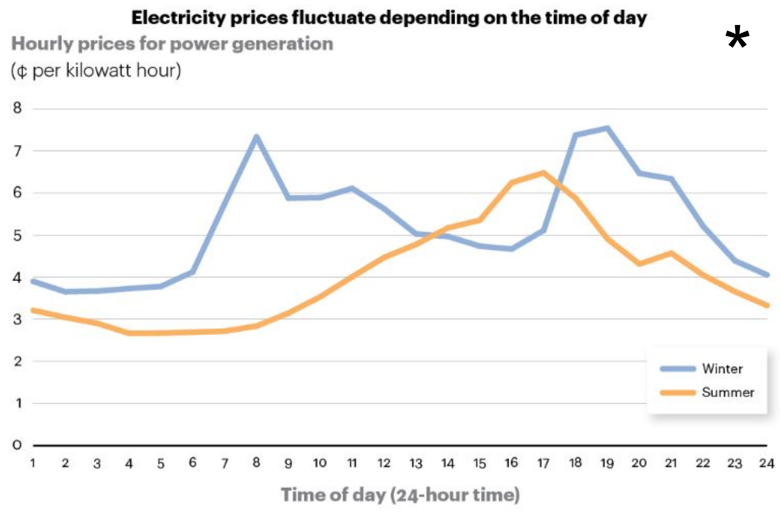
- ❑ **Participants pain**: Peak loads leads electricity consumers and generation companies spend a lot of money



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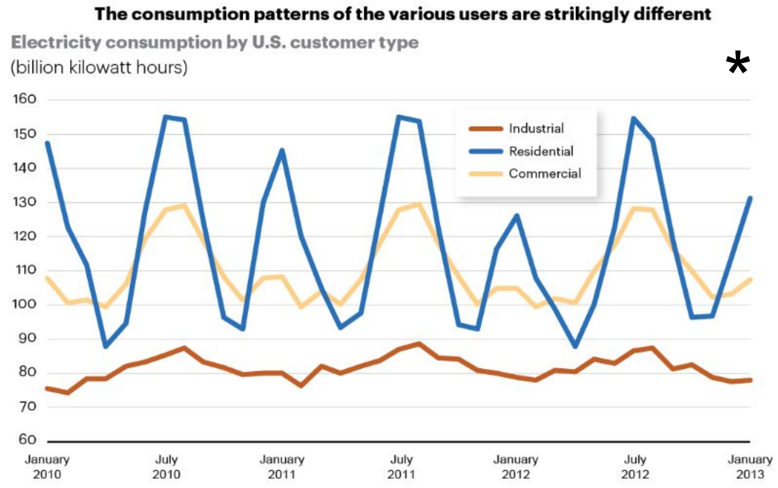

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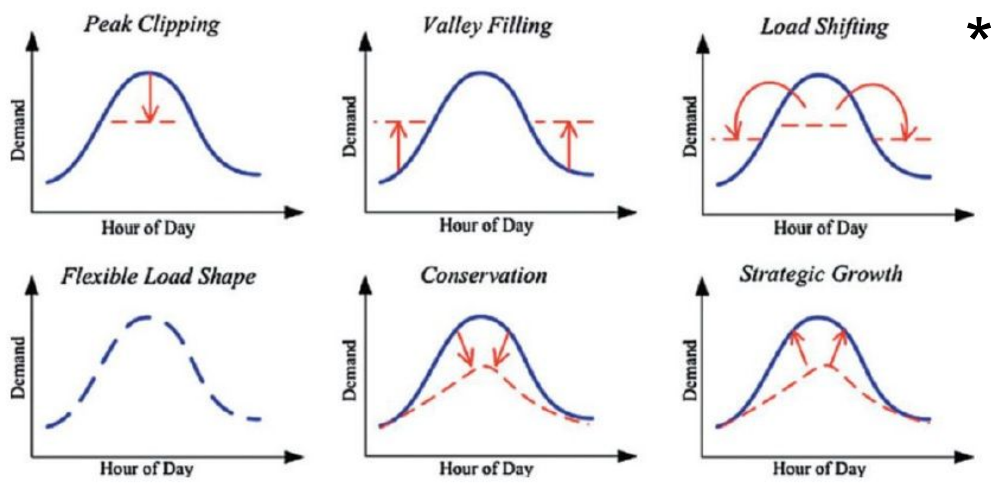
Task formulation

Among different approaches to peak load reduction we focus on peak shifting.

The thesis aims to numerically evaluate the possibility of reducing the peak for commercial buildings.

Since the major consumer is the air conditioning system, we are reducing the peak load modifying HVAC with low CAPEX.



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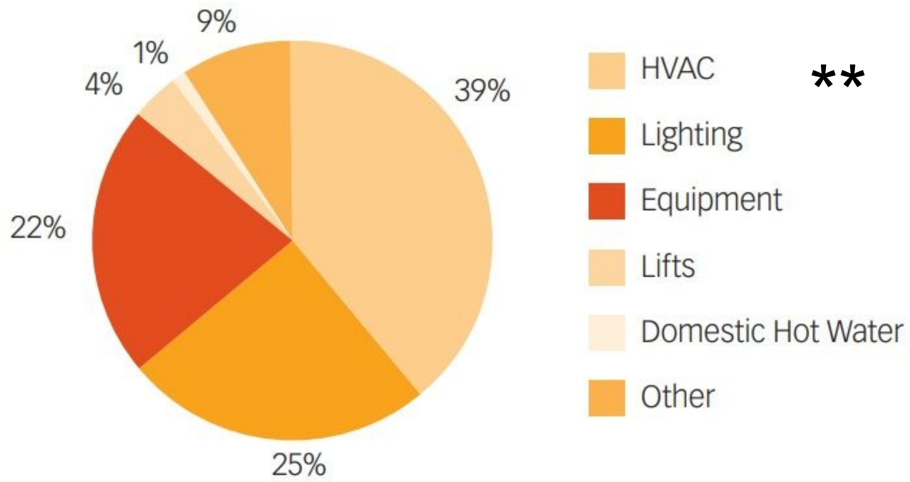

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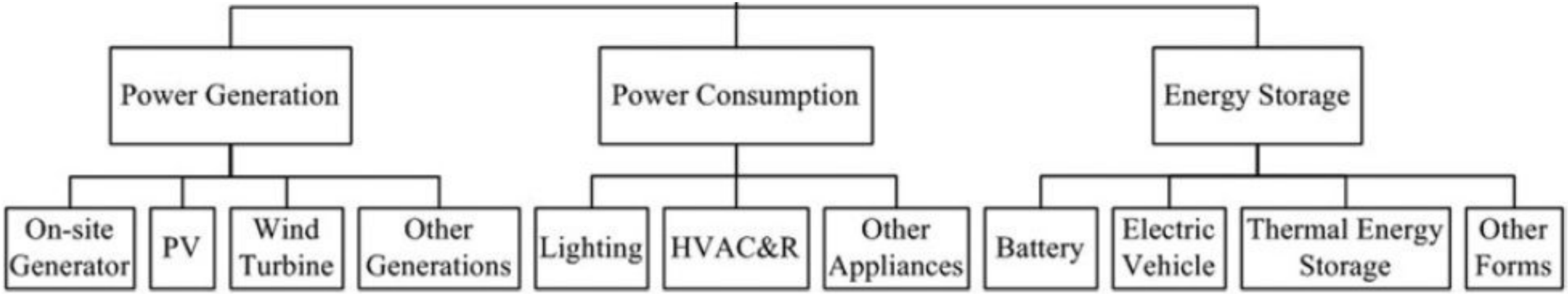
* Wang, Shengwei & Xue, Xue & Yan, Chengchu. (2014).
Building power demand response methods toward smart grid. HVAC&R Research
** Guide to Best Practice Maintenance and Operation of HVAC Systems for Energy Efficiency (January 2012), p. 36-37

Peak reduction from consumer side



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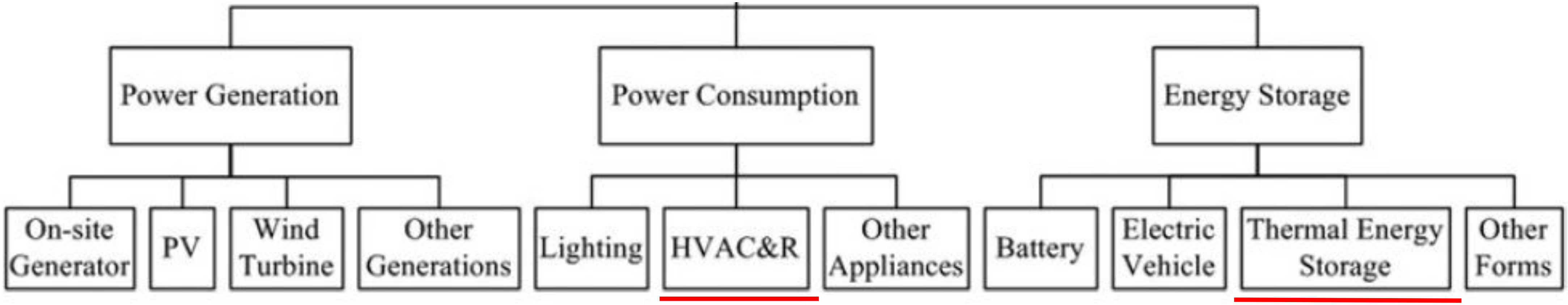

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Main focus on the task:

Numerically evaluate peak load reduction using different types of thermal energy storage in a HVAC system of a building

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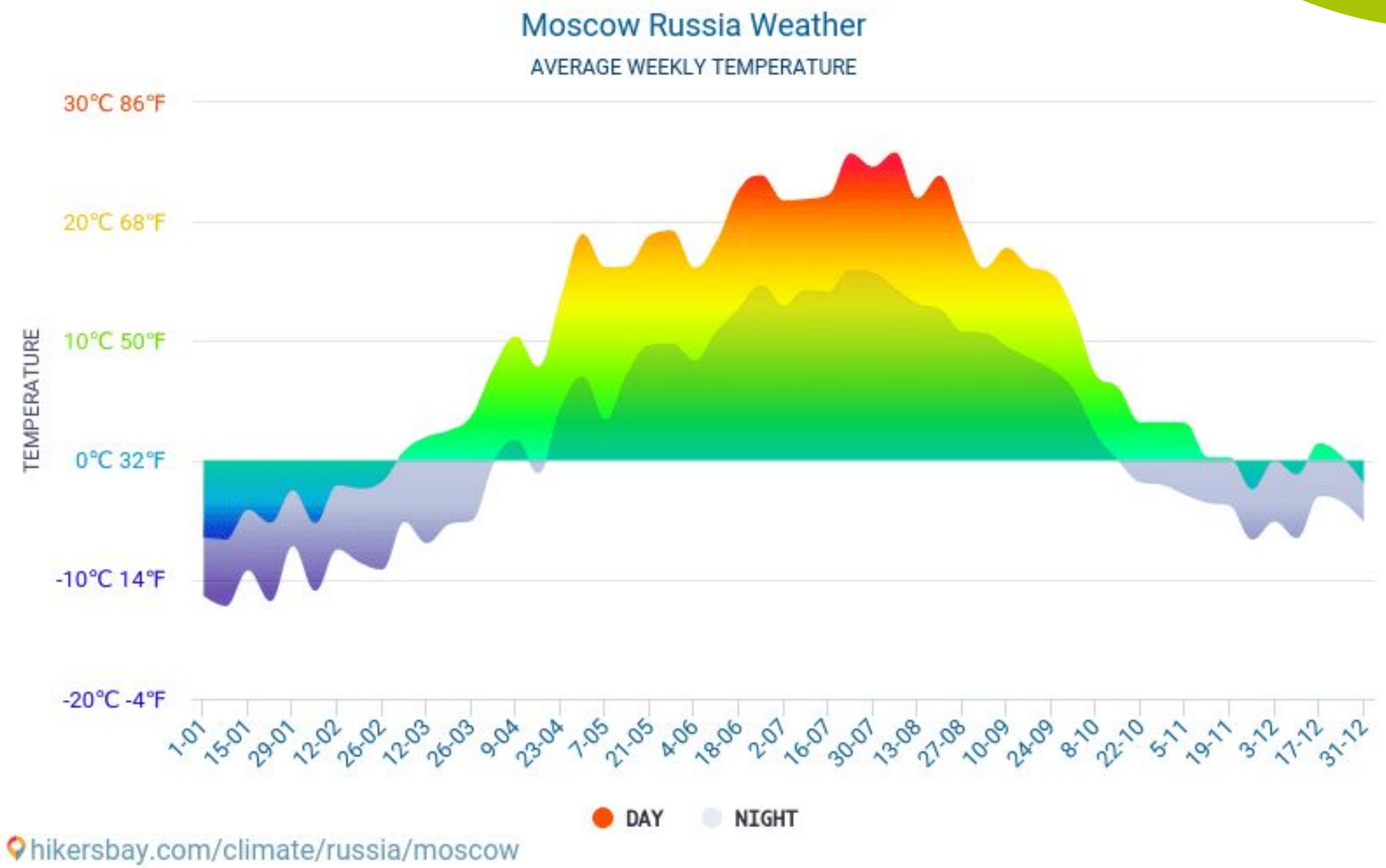
The hypothesis to test:

★ Check the ability to store the energy at the night time from ambient cold air



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Possible approaches for buildings

Control	Peak Load Reduction, %
Rule-based control [2]	up to 15%
Model predictive control [3]	up to 20%
AI based control [2]	up to 20%

Technology	Peak Load Reduction, %
Energy-efficient equipment [1]	up to 15%
Ground heat exchanger [4]	up to 20%
Electrochemical storage [5]	up to 60%
Thermal energy storage [2]	up to 60%

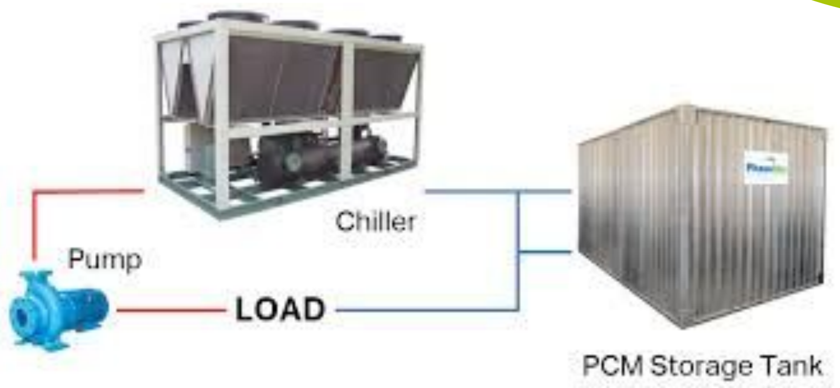
[1] Lee et al. (2018) Improvements to the customer baseline load (CBL) using standard energy consumption considering energy efficiency and demand response.
[2] Wang, Shengwei & Xue, Xue & Yan, Chengchu. (2014). Building power demand response methods toward smart grid. HVAC&R Research
[3] A. Ryzhov, H. Ouerdane, E. Gryazina, A. Bischi, K. Turitsyn. (2019). Model predictive control of indoor microclimate: Existing building stock comfort improvement.
[4] B. Akhmetov, A. G. Georgiev, A. Kaltayev, A. A. Dzhomartov, R. Popov M. S. Tungatarova. (2016). Thermal energy storage systems – review.
[5] He, G., Chen, Q., Kang, C., Pinson, P., & Xia, Q. (2016). Optimal bidding strategy of battery storage in power markets considering performance based regulation and battery cycle life.

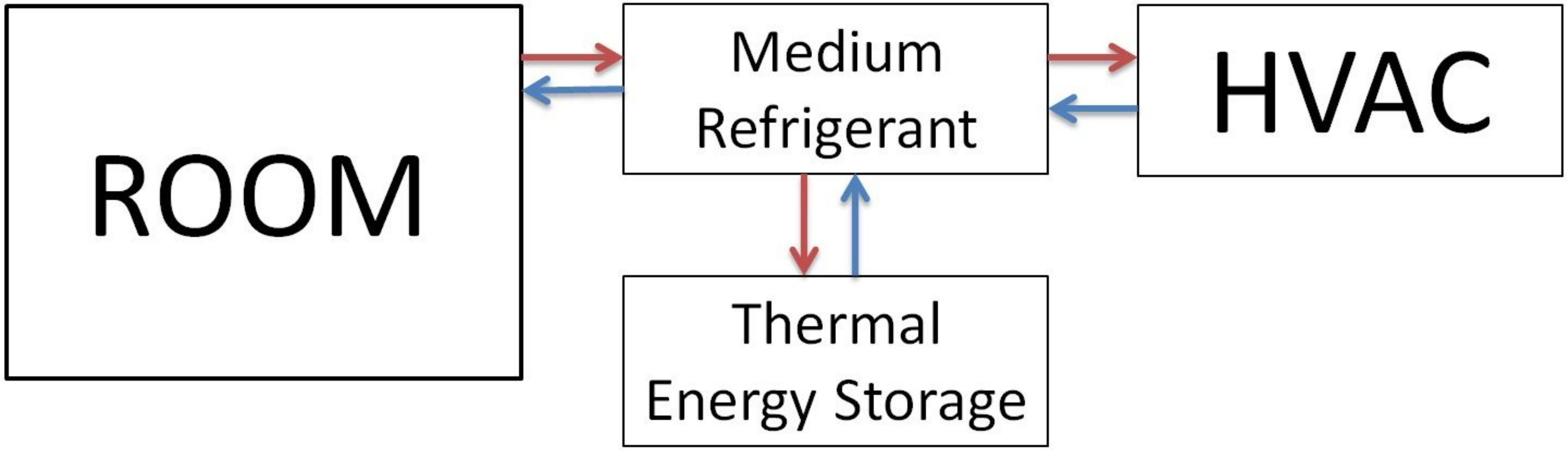
Thermal energy storages

Water storage

Ice storage

PCM storage





Microclimate model

Heat balance equation:

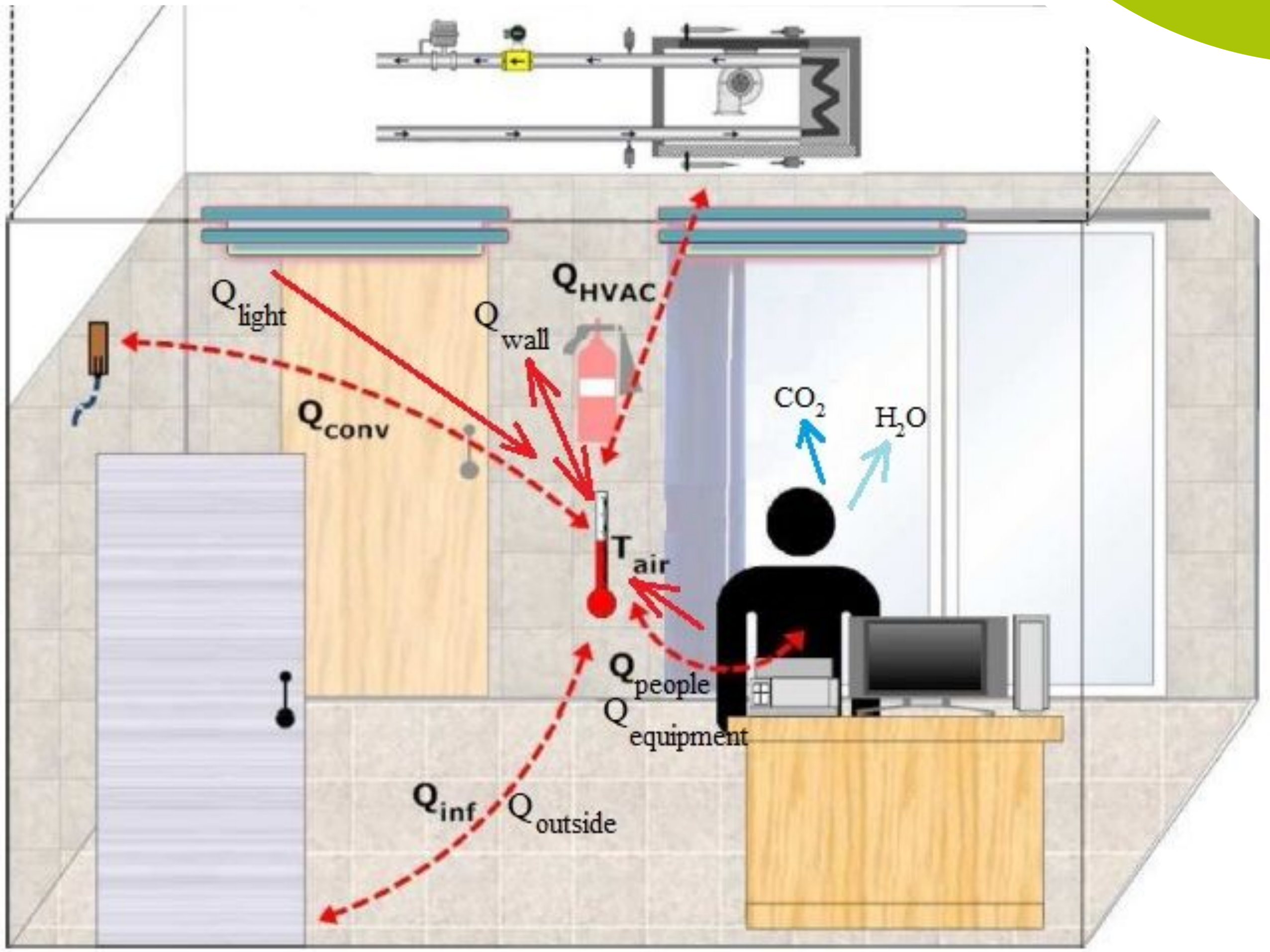
$-Q_{HVAC}\ -Q_{wall}\ -Q_{inf}\ +Q_{light}\ +Q_{people}$
$+Q_{equip} + Q_{vent} + \Delta Q_{air} = 0;$

Heat flux:

$Q_{flux} = k^*\Delta T = (1/R)(T_{in}-T_{out})$

Human activity:

$Q_{people} = M_{met}{}^*N_{oc}$



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* A. Ryzhov, H. Ouerdane, E. Gryazina, A. Bischi, K. Turitsyn. (2018). Model predictive control of indoor microclimate: Existing building stock comfort improvement.

Microclimate model modification

- Before(*):
    - comfort parameters: T, CO_2;
    - constant heat transfer coefficients;
    - wall temperature is constant;
    - people are heat and CO_2 sources;

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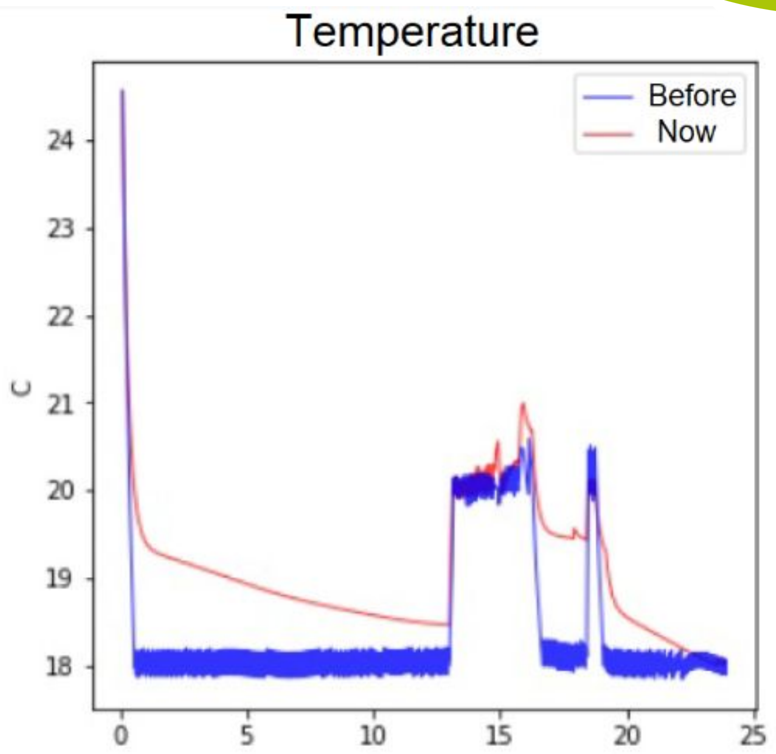
Microclimate model modification

- Before(*):
  - comfort parameters: T, CO_2;
  - constant heat transfer coefficients;
  - wall temperature is constant;
  - people are heat and CO_2 sources;

- Now:
  - comfort parameters: T, CO_2, humidity;
  - heat transfer coefficients vary;
  - wall temperature is introduced;
  - working equipment and lighting are assumed to emit heat
  - people are also moisture sources.
  - added thermal energy storage to HVAC



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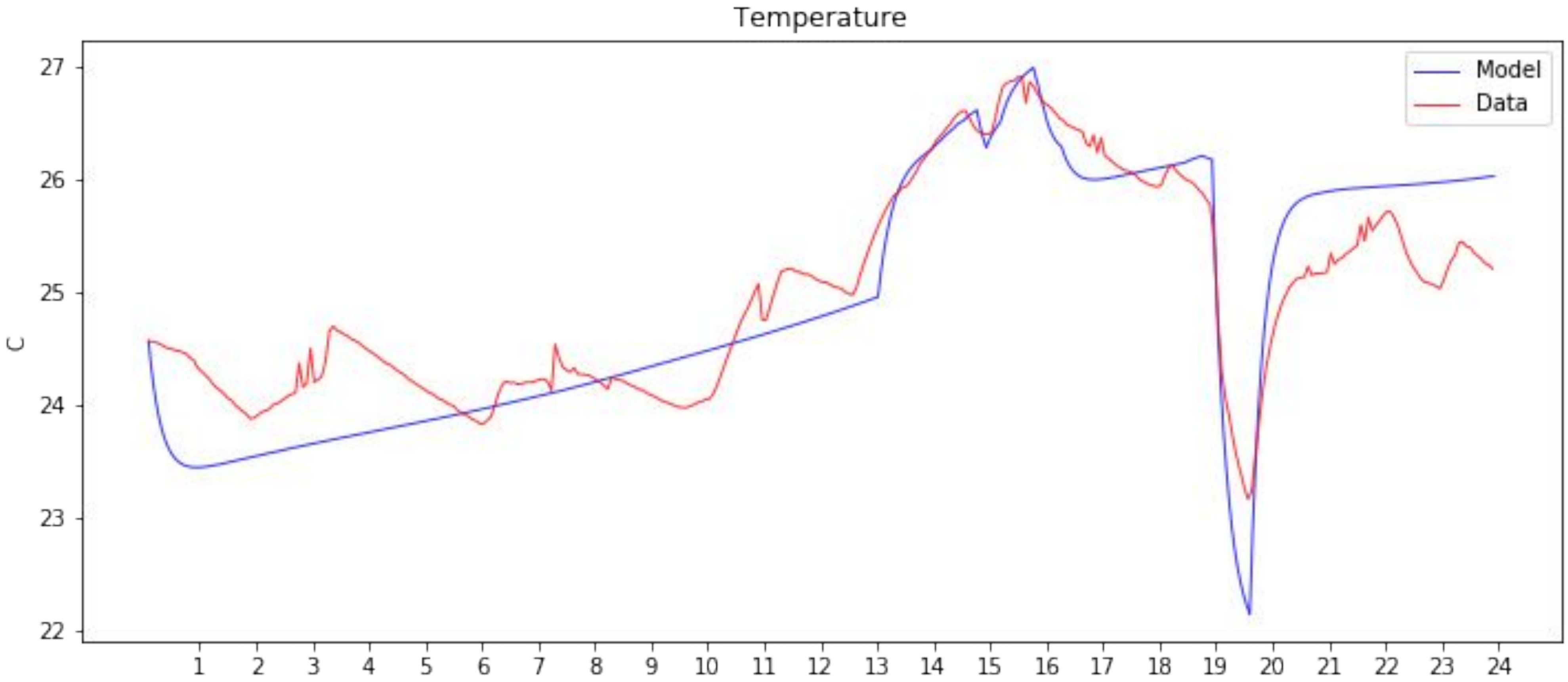
Microclimate model validation



Maximal average error in the worst case is equal to 4.23% (~1.15 ℃)

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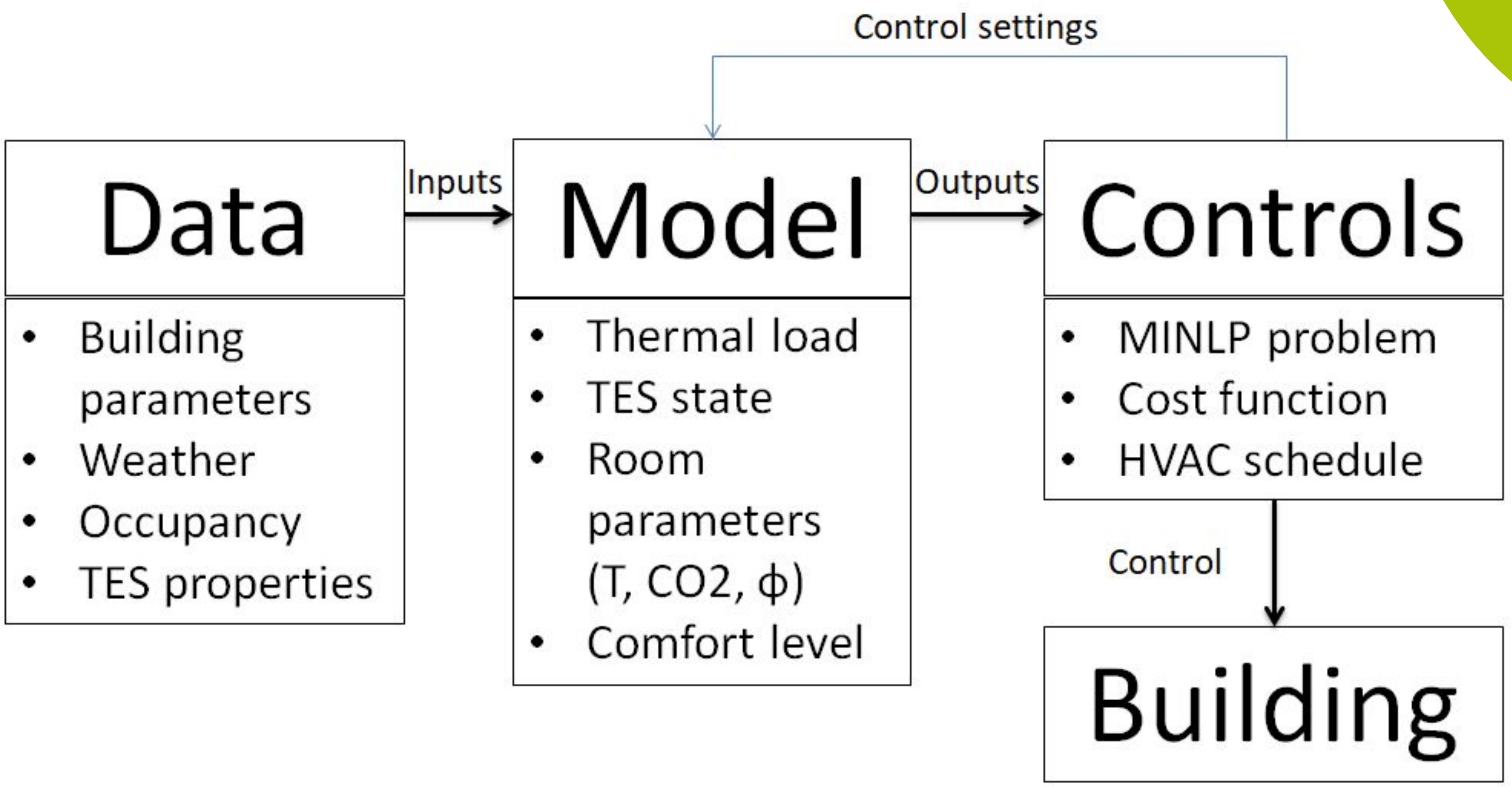
Control scheme



Optimization problem

$$\min \quad \sum_t c_t(P_t^c + P_t^f), \forall t \in \mathbb{T}$$

objective function - bills

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Optimization problem

$$\min \quad \sum_t c_t(P_t^c + P_t^f), \forall t \in \mathbb{T}$$

objective function - bills

$$\text{s.t.} \quad W_t^{HVAC} = COP \cdot P_t^c + W_t^{dis} - W_t^{ch}$$

$$Q_t = 0.55 \frac{P_t^f}{100}$$

HVAC system cooling function

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HVAC system cooling function

$$E_{t+1} = E_t - \tau(W_t^{dis} + W_t^{ch})$$

$$W_t^{ch} = W_t^{HVAC}, t \in [00.00 - 07.00]$$

$$W_t^{dis} = C_{out} Q_t (T_{input} - T_{output}), t \in [9.00 - 18.00]$$

TES functions

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Optimization problem

$$\min \quad \sum_t c_t(P_t^c + P_t^f), \forall t \in \mathbb{T}$$

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TES functions

$$T_{t+1}^r = T_t^r + p_{a1}((p_{a2} + p_{a4})(T_t^{out} - T_t^r) + p_{a3}(T_t^w - T_t^r) + p_{a5} N_t^{oc} -$$
$$- W_t^{HVAC} + C_{out} T_{vent} Q_t - C_{in} T_t^r Q_t + W_{light})$$

$$T_{t+1}^w = T_t^w + p_{w1} p_{w2}(T_t^r - T_t^w))$$

$$n_{t+1}^{CO_2} = n_t^{CO_2} + p_{n1}((Q_t + p_{n2})(300 - n_t^{CO_2}) + k_{CO_2} N_t^{oc})$$

Room parameters functions

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Optimization problem

$$\min \quad \sum_t c_t(P_t^c + P_t^f), \forall t \in \mathbb{T}$$

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Room parameters functions

$$W_t^{HVAC} \geq 0$$

$$0 \leq E_t \leq E_{max}$$

HVAC and TES constraints

$$P_t^c = \{0, 500, 1000, 1500\}$$

$$P_t^f = \{0, 10, 20, 30, 40\}$$

Discrete regulation constraint

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Optimization problem

$$\min \sum_t c_t(P_t^c + P_t^f), \forall t \in \mathbb{T}$$

objective function - bills

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HVAC and TES constraints

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$$P_t^f = \{0, 10, 20, 30, 40\}$$

Discrete regulation constraint

$$18^o C \leq T_t^r \leq 24^o C$$

$$0 \leq n_t^{CO_2} \leq 800$$

Comfort conditions constraint

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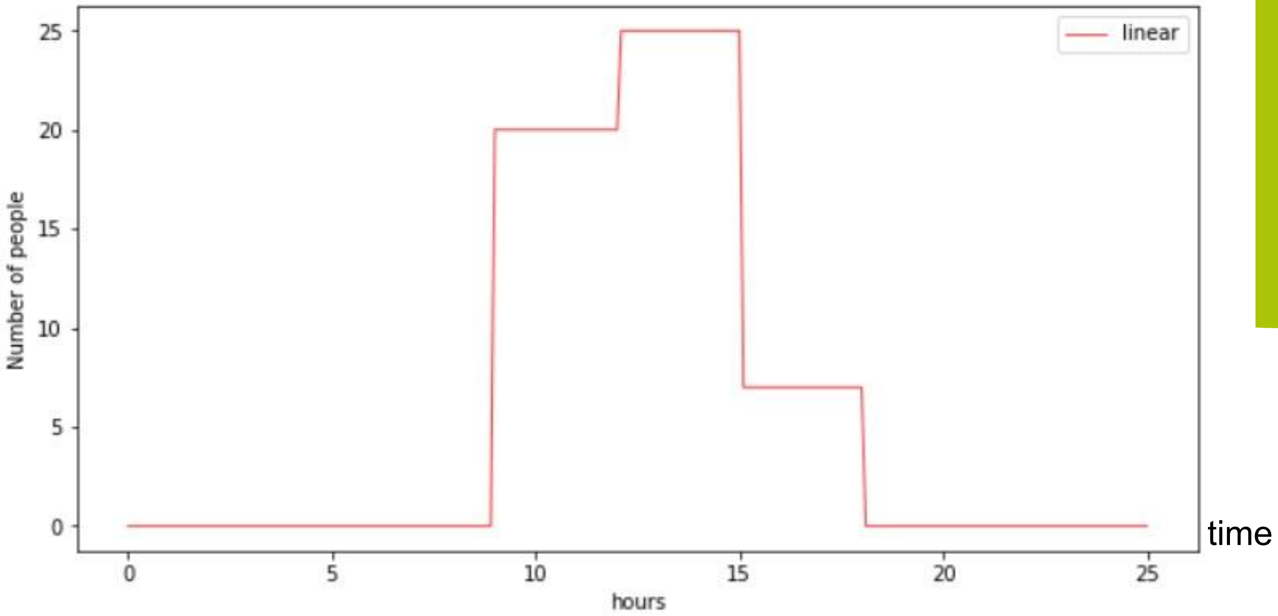
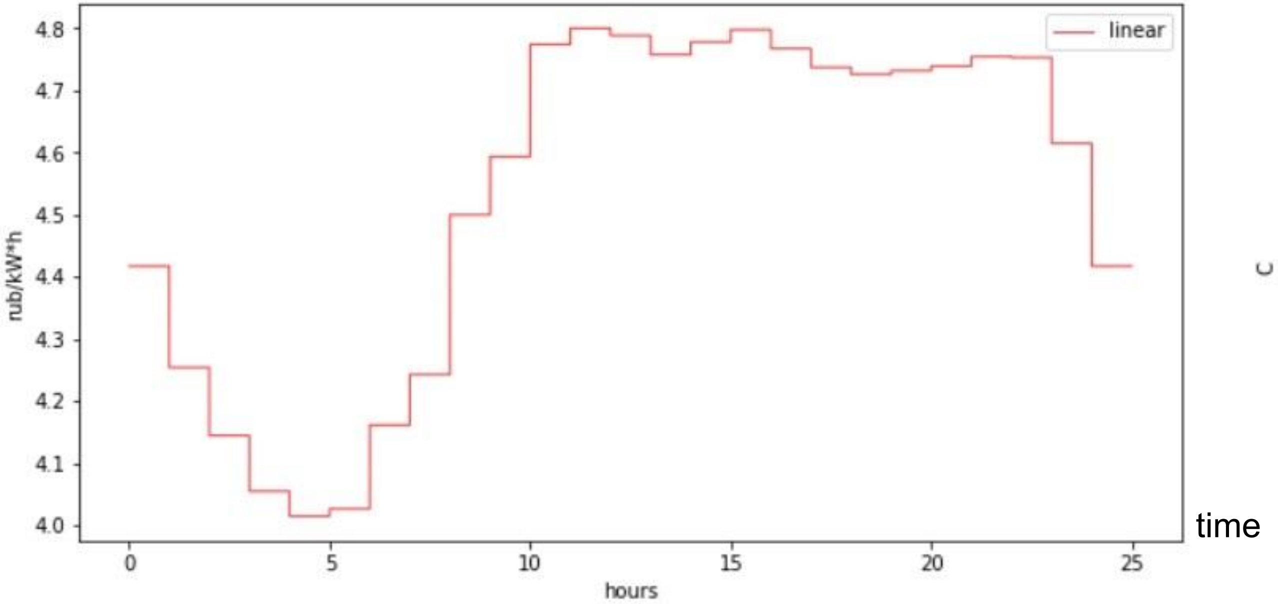
Results - Input Data

- ➢ Occupancy
- ➢ Price
- ➢ Ambient temperature

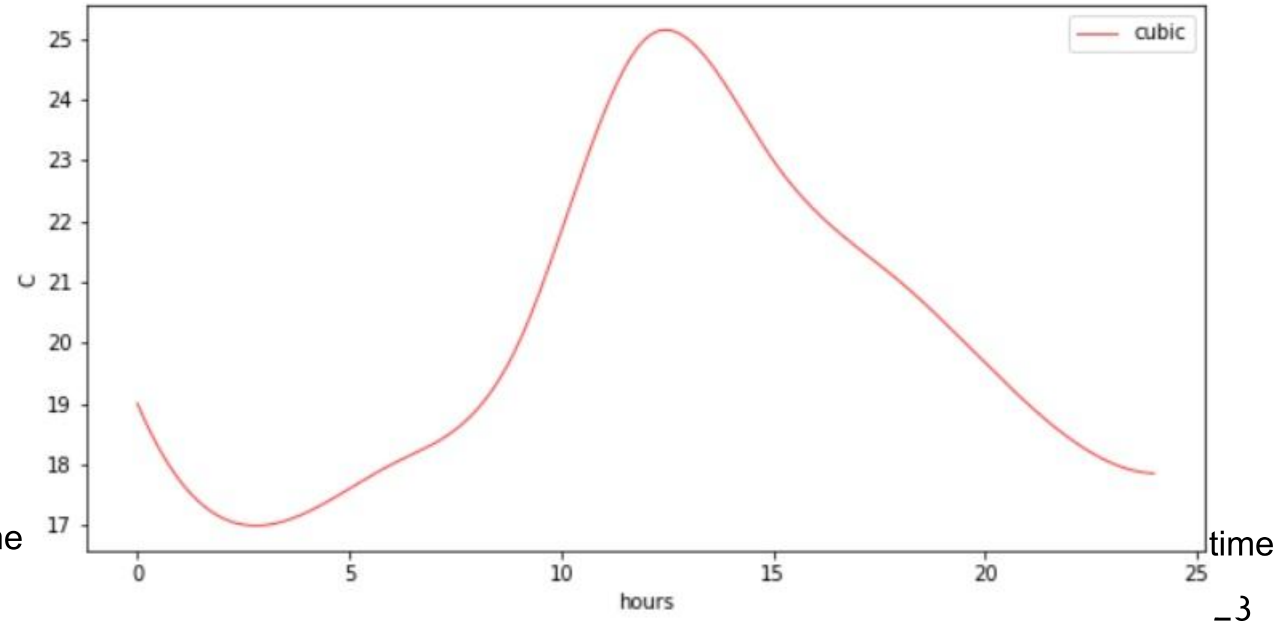
Occupancy



Price



Ambient temperature



Results - comparison of Base case and TES case

- ➢ Base case - Opt. problem for usual HVAC system
- ➢ TES case - Opt. problem for modified HVAC system (TES included)
- In the TES case, 100% of the compressor’s power consumption has been transferred from the peak time to the night time.
- In comparison with Base case, there is a reduction in electricity costs in the amount of 6.6%

Type of run	Bills, rub	Consumption, kW*h	Time, sec
Base MPC	9.3	1.9	76
MPC using TES	8.7	2.0	638

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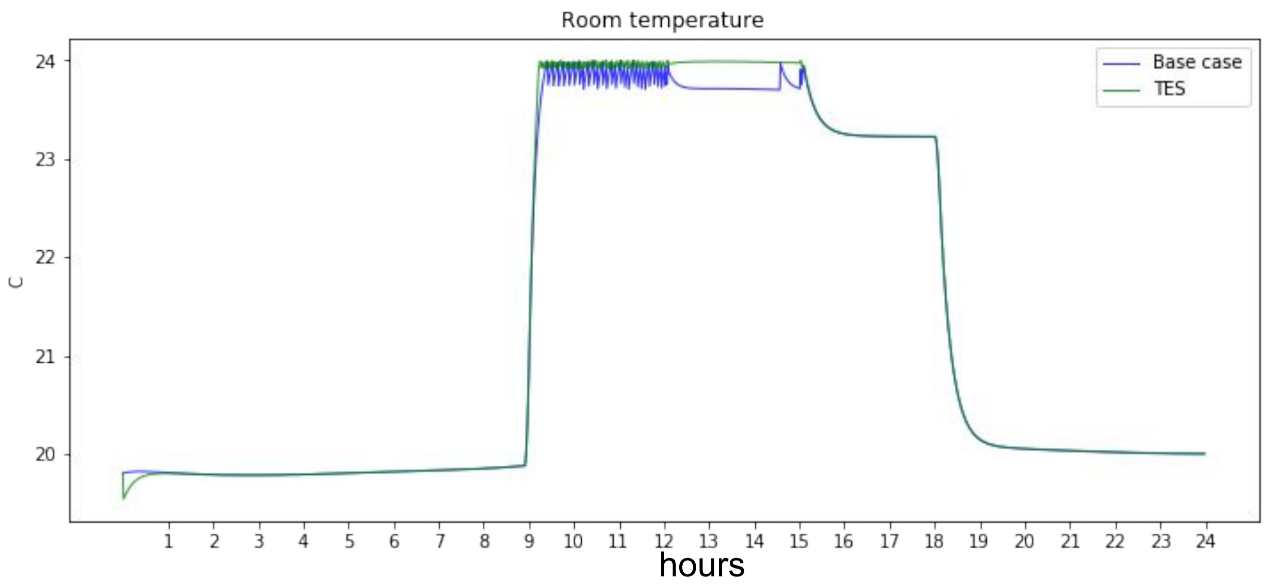
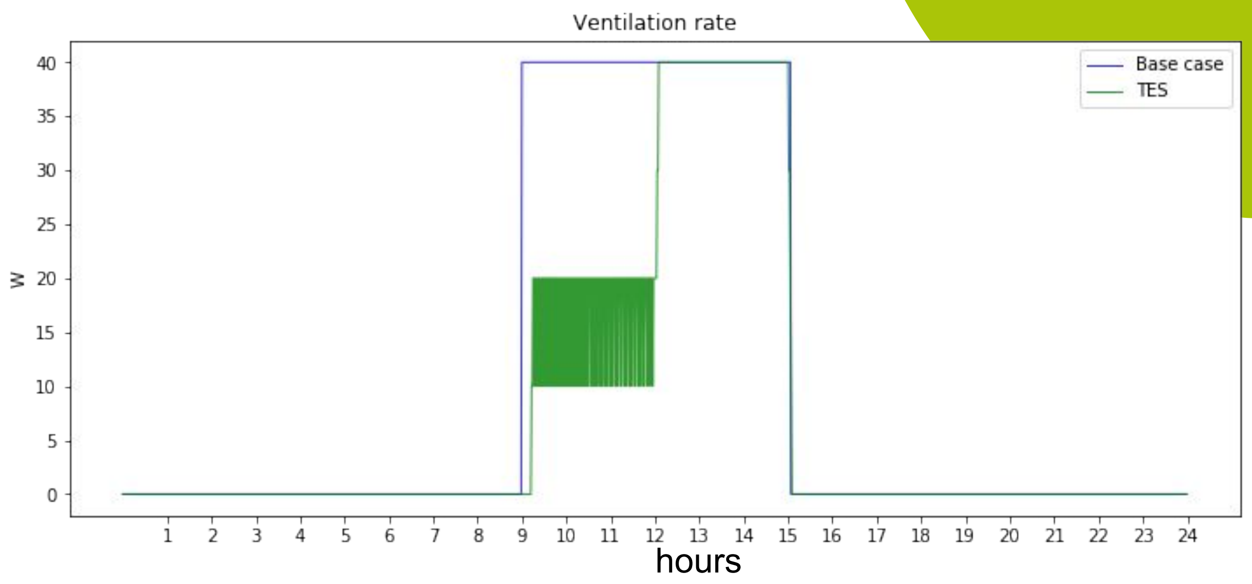
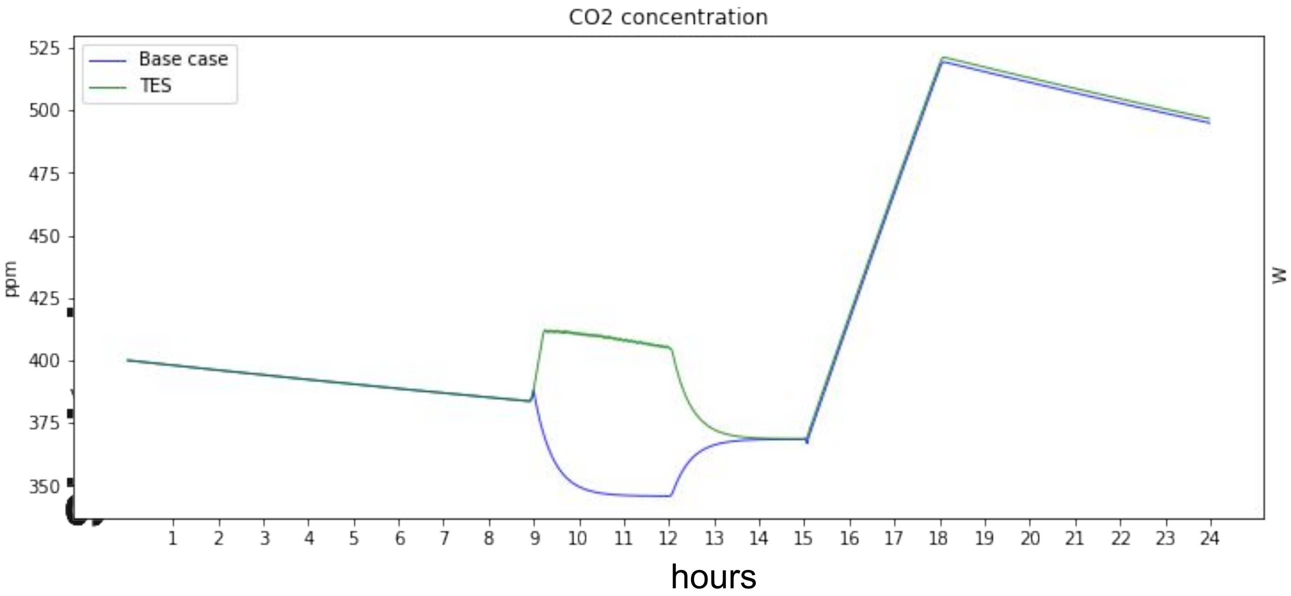
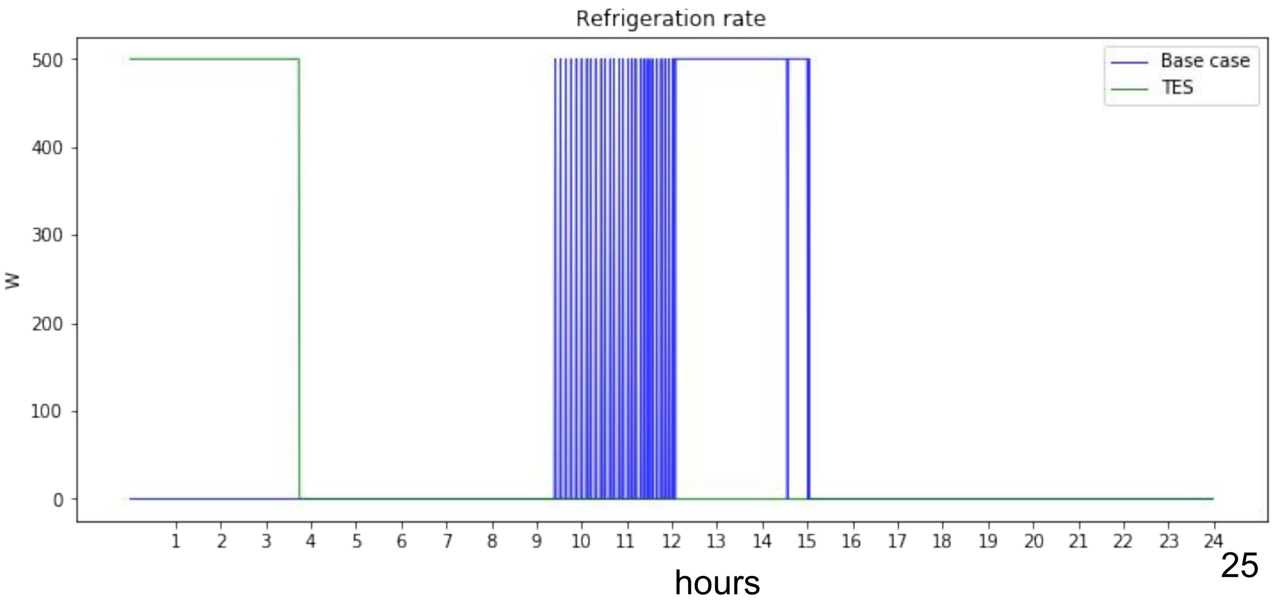
Results - comparison of Base case and TES case









Results - comparison of different fluid types

Opt. problem is formulated for usual HVAC system including TES

- ➢ Water - Distilled water, T_m = 0 °C;
- ➢ PCM1 - Dipotassium phosphate hexahydrate, T_m = 14 °C;
- ➢ PCM2 - Salt hydrate S13 ("PCM Products"), T_m = 13 °C.

- There is low difference in costs
- Visible differences in the graphs are only in the temperature of the working substances

Type of run	Bills, rub	Consumption, kW*h	Solve time, sec
TES water/ice	9.0	2.2	687
TES PCM 1	8.9	2.1	726
TES PCM 2	8.9	2.1	689

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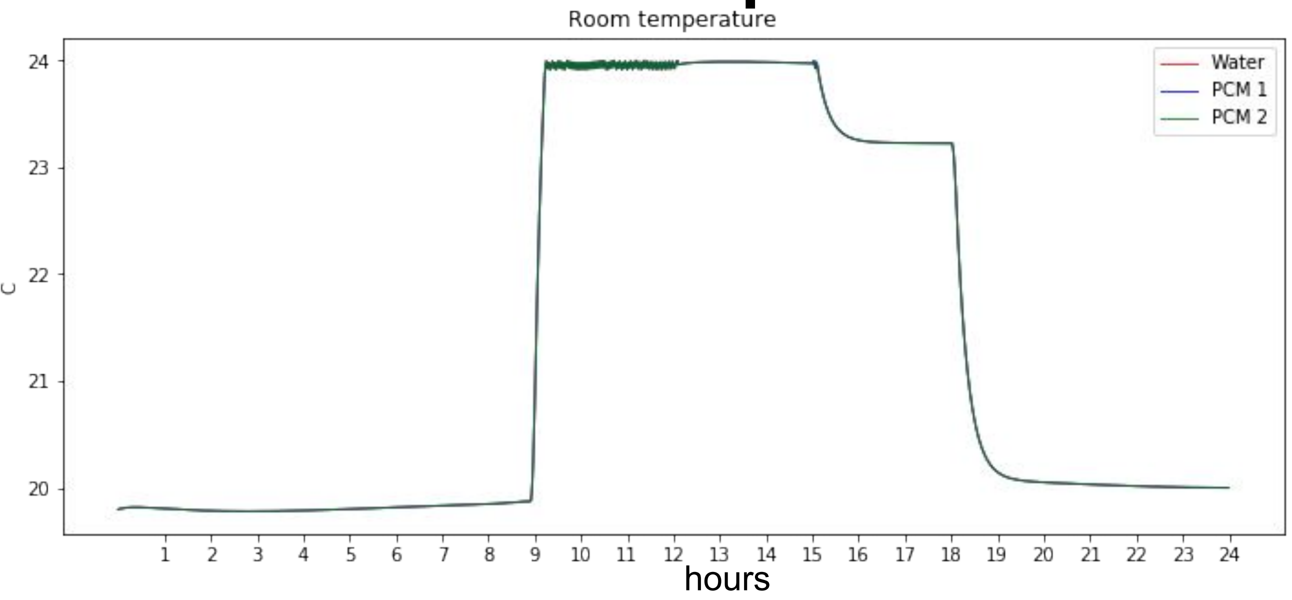
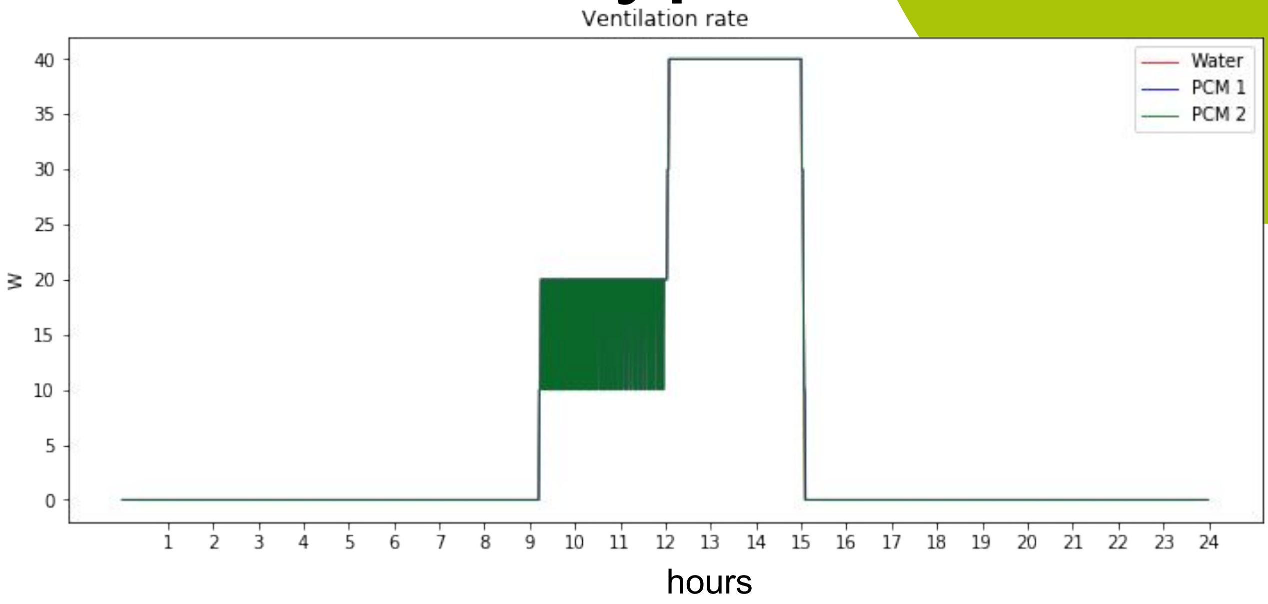
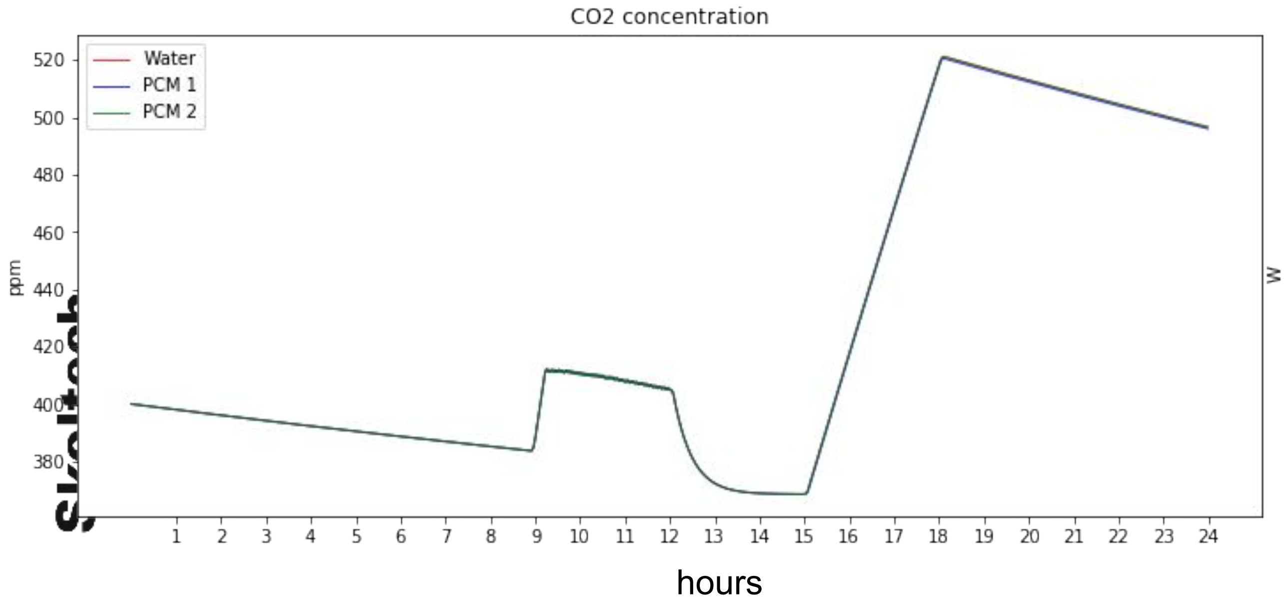
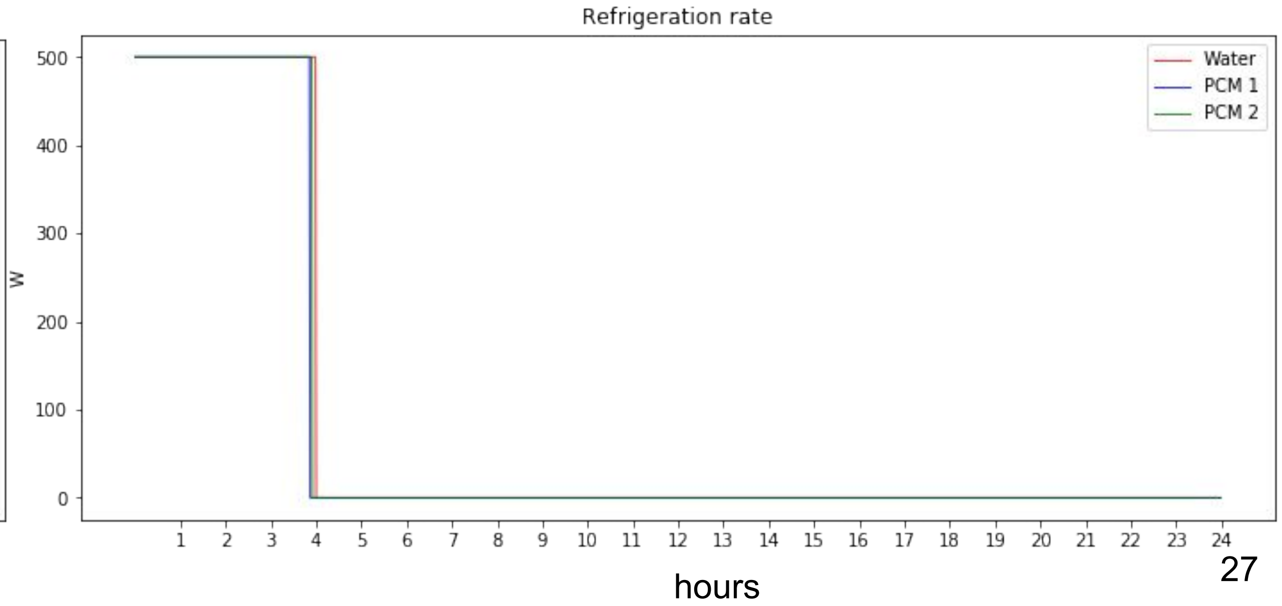
Results - comparison of different fluid types









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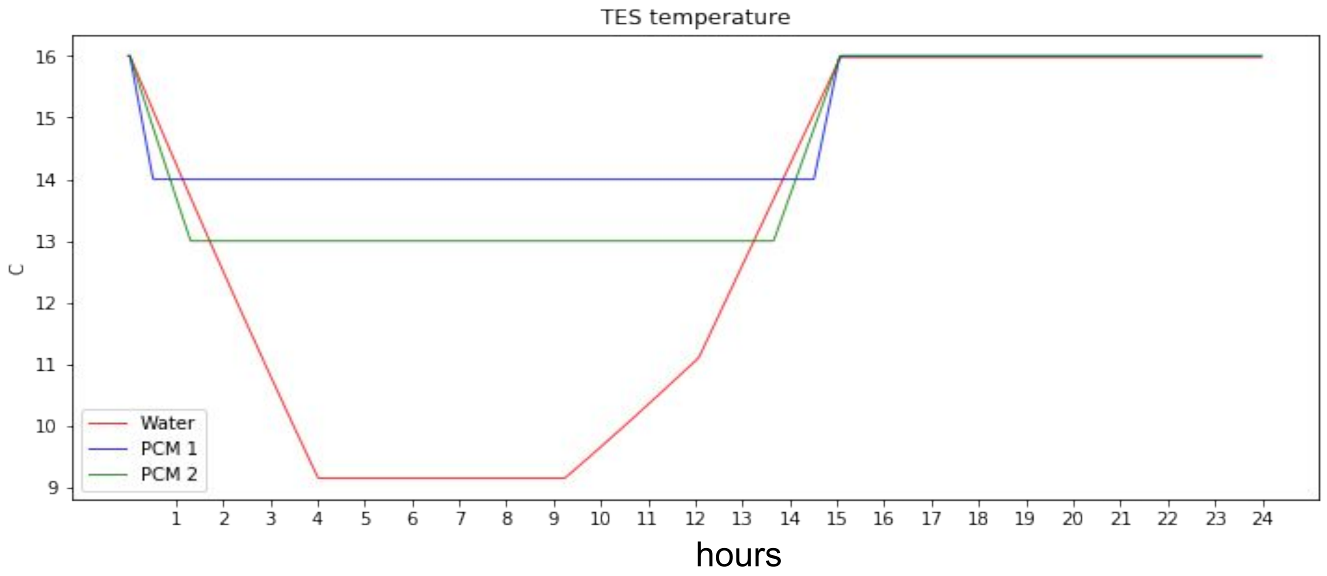

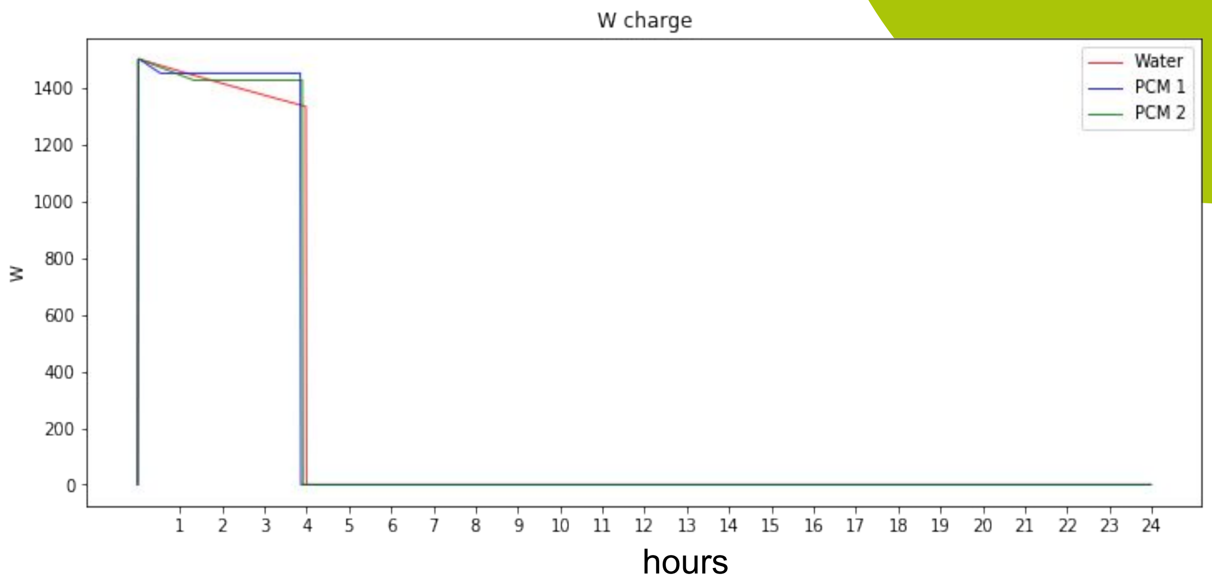

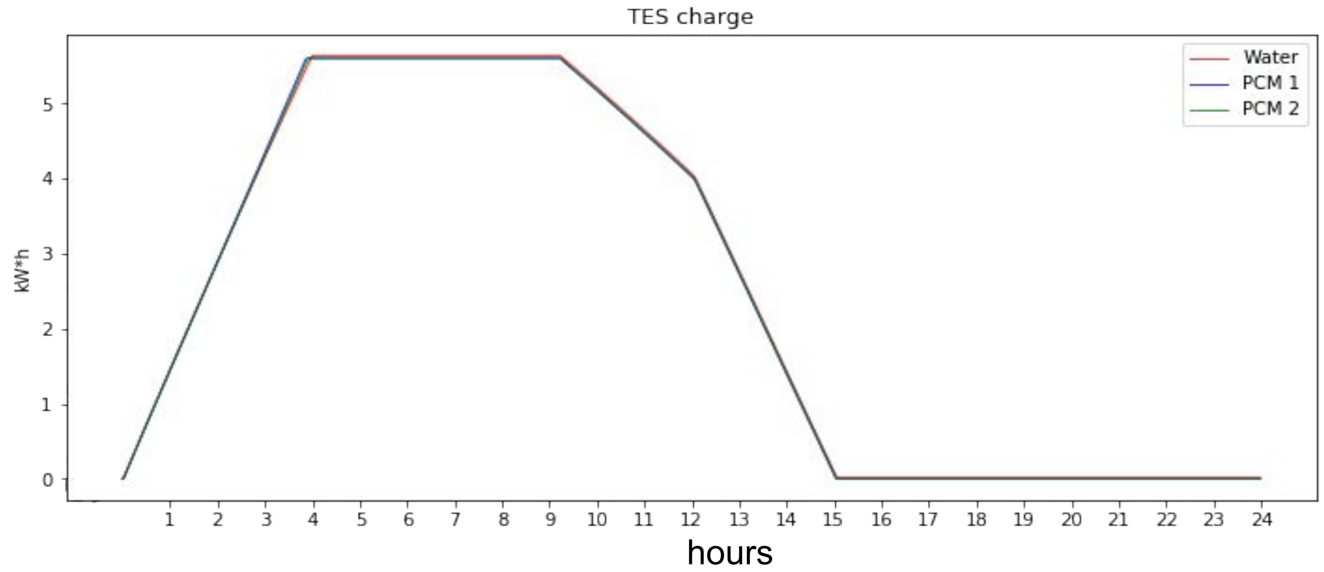

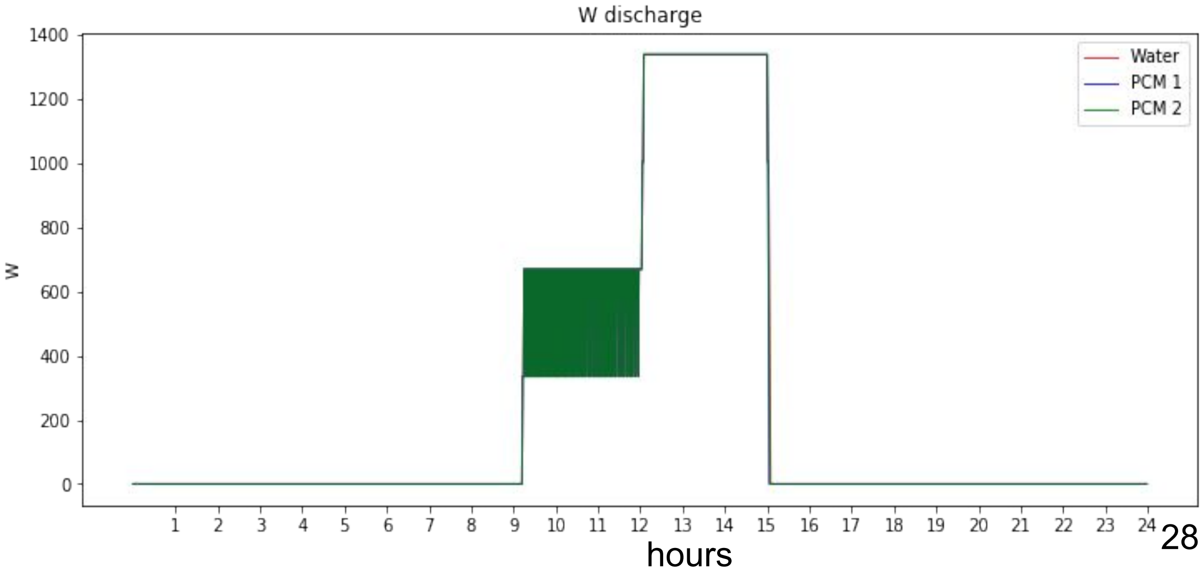

Results - comparison of different fluid types in the long-term during 153 days

- ➢ Period - May 1, 2019, to September 30, 2019
- ➢ Place - Moscow

- There is significant difference in total costs
- The hypothesis of charging TES from night cold air works
- Melting temperature affects seasonal reductions in air conditioning costs

Type of run	Bills, rub	Consumption, kW*h
Base MPC	1293	271.6
TES water/ice	1108	260.7
TES PCM 1	1072	251.2
TES PCM 2	1085	258.8

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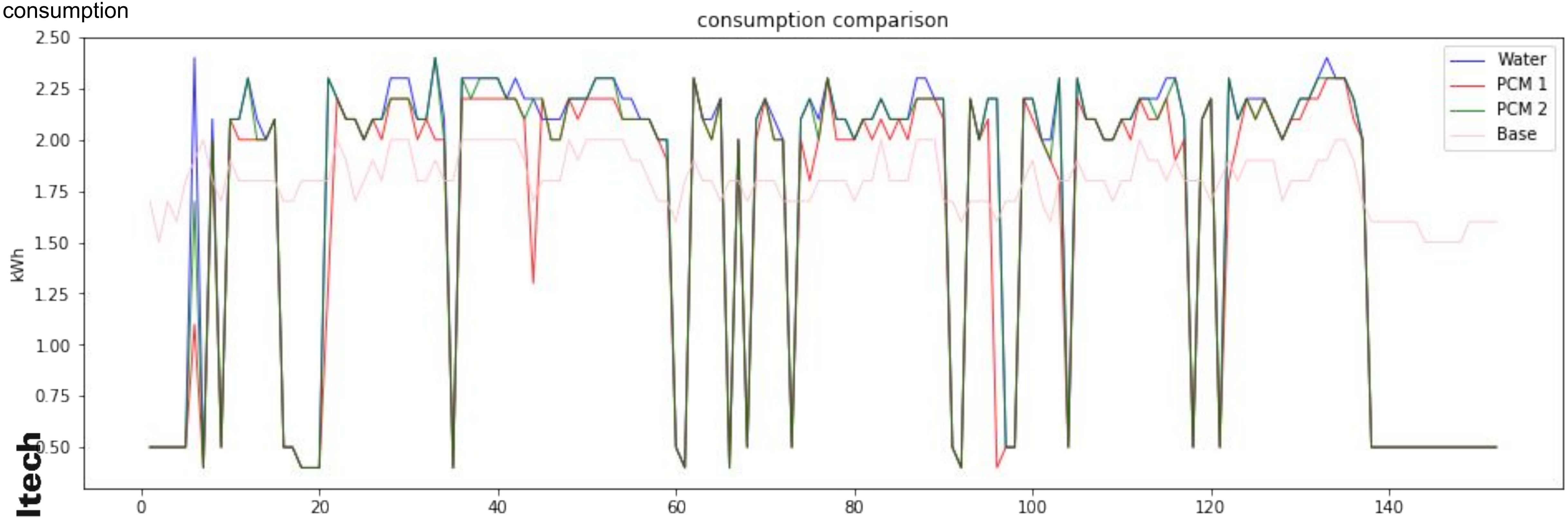
Results - comparison of different fluid types in the long-term during 153 days

consumption



days

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Conclusions

- Technology review demonstrates that PCMs is the most widely spread fluid for TES used in HVAC systems;
- Complex thermodynamic room model was created;
- TES implemented to the MPC optimization problem formulation;
- Hypothesis with charging thermal energy storage at night from ambient is working and useful;
- TES usage allow us to reduce bills up to 6 % at constant COP;
- PCM1 ($K_2HPO_4(H_2O)_6$) with the melting temperature T_m = 14 ^oC shown the best efficiency in the long-term period during 153 days;

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Research plans

- ✓ Analyse the international experience in peak load reduction;
- ✓ Estimate the potential of existing technologies;
- ✓ Explore real TES implementations;
- ✓ Modificate the room model and validate it;
- ✓ Integrate thermal energy storage (TES) to the model;
- ✓ Formulate the Optimization Problem for current task;
- ✓ Make simulations and analysis of results.

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Acknowledgements

★ Prof. Elena Gryazina, Skoltech

★ Aleksandr Baluev, TION

THANK YOU FOR
YOUR ATTENTION!

TES applications in building scale

- Thermal comfort maintaining with lower fluctuations;
- Emergency water supply in case with water TES;
- Possibility in Demand Response programs participation;
- Increase of building demand flexibility;
- Reduction of peak load consumption -> decreased bills;
- Possibility to charge TES in mid-season by ambient temperature.

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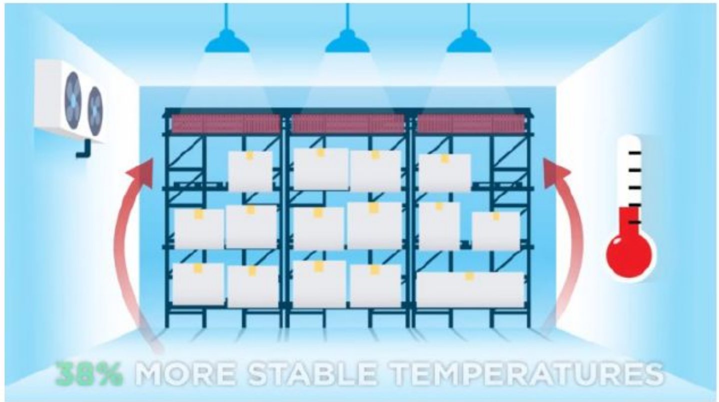
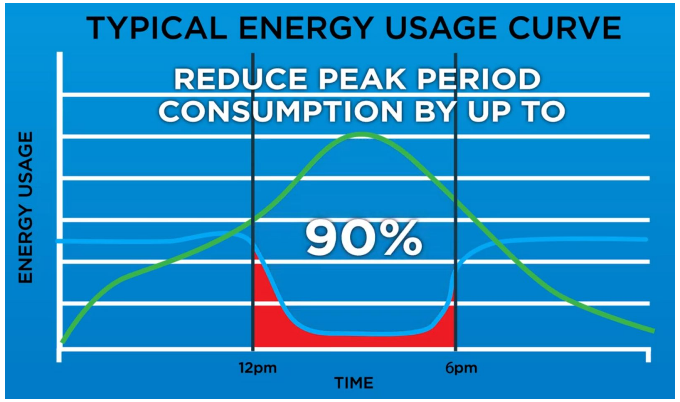
PCM usage in industry

VIKING COLD Solutions



This company mainly operates in the market for food storage. Using of PCM materials allows to customers to reduce peak loads up to 90%.



PCM Products Limited

The company is a leader in the application of PCM in HVAC systems. Examples include University of Bergen, Norway; Australian parliament house, Canberra, Australia and other.

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Sensitivity analysis

Input data	Input data change, %	Bills shift, %	Consumption shift, %
Occupancy	+ 5	+ 7	+ 9.5
Occupancy	- 5	- 17	- 16
Out temperature	+ 5	+ 1	+ 5
Out temperature	- 5	+ 1	0
Price	+ 5	0	0
Price	- 5	0	0
M_{met}	+ 5	+ 8	+ 9.5
M_{met}	- 5	- 18	- 15.5

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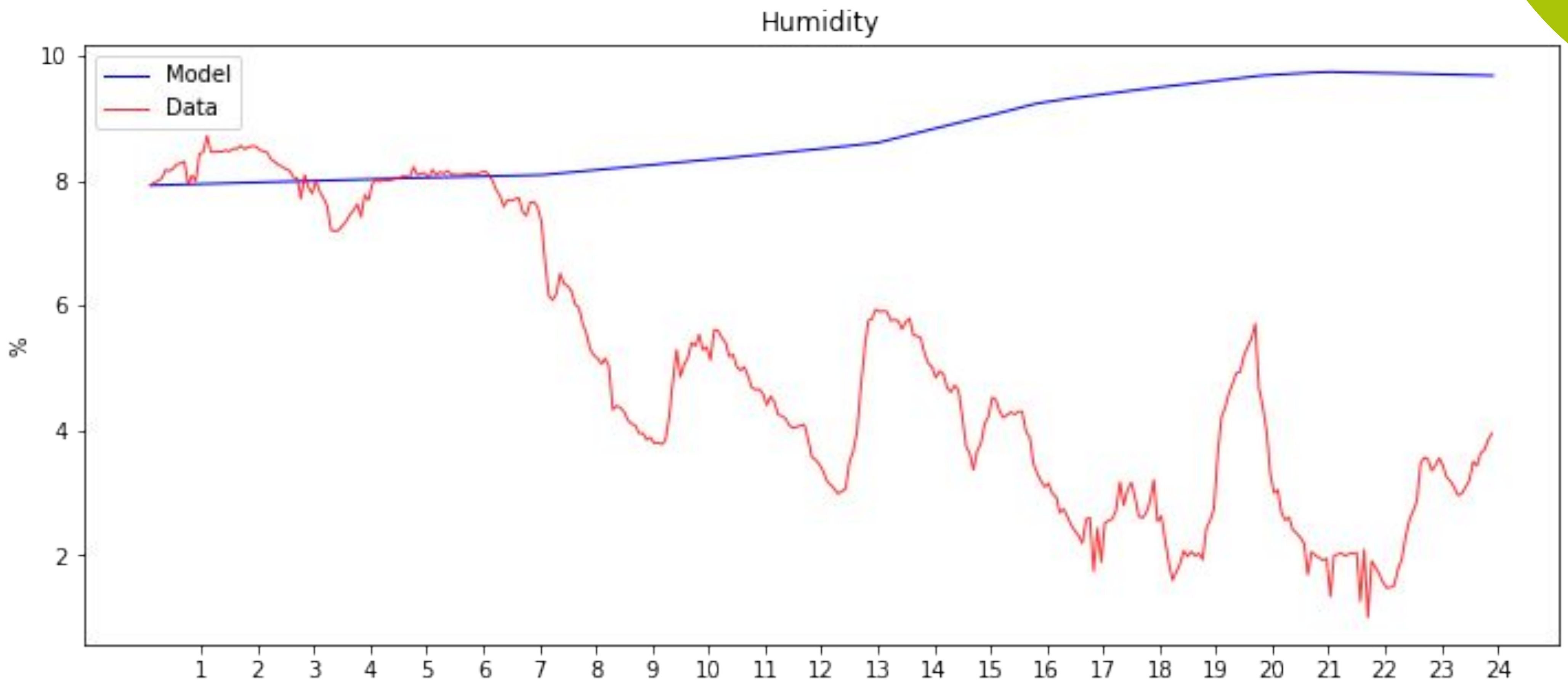
Microclimate model validation



Unusual sensor readings forced us not to use humidity as a parameter

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Solving algorithm

- MINLP problem solver (Juniper) did not converge for 24 hours;
- P^f variable specification as input gives us NLP problem simplification to simple LP, but there was permissible error equal to 0.3%;
- MILP problem solvers (Cbc, GLPK) did not converge for 6 hours;
- This forced us to write our own algorithm with assumptions for solving this particular problem.

Solver	Problem	Bills, rub	Consumption	Error, %
JuMP	NLP	8.14	1.7	base
CVXPY (P^f specified)	LP	8.16	1.71	0.3
A-solver (P^f specified)	MILP	8.18	1.7	0.5

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What if all the customers will use TES?

- The total consumption will remain the same, since using TES we primarily reduce the load of the air conditioning system;
- The peak load will shift to the evening hours, which will reduce the daily load on generators and avoid short-term use of expensive generators - baseline takes the form of a plateau (ideal);
- Consumers will get reduced payments and lower peak prices, and generation companies will rid from the need to maintain expensive equipment;

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TES functions

$$W_t^{ch} = \begin{cases} W, \text{ if } T_t^{out} \geq T_{melt} - 5^oC \\ C_{out}Q(T_t^{out} - T_{melt}), \text{ if } T_t^{out} < T_{melt} - 5^oC \end{cases}$$

$$W_t^{dis} = C_{out}Q(T_{input} - T_{output})$$

$$T_t^{TES} = \begin{cases} T_{TES_0} - E_t/(m_{TES}C_{TES_l}), \text{ if } E_t < m_{TES}C_{TES_l}(T_{TES_0} - T_{melt})^{(*)} \\ T_{melt}, \text{ if } (*) \leq E_t \leq (*) + m_{TES}L_{TES} \\ T_{melt} - (E_t - (*) - m_{TES}L_{TES})/(m_{TES}C_{TES_s}), \text{ if } E_t \geq (*) + m_{TES}L_{TES} \end{cases}$$

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Room functions

$$T_{t+1}^{r} = T_t^r + \frac{\tau}{m_{air}C_{in}} \cdot (h \cdot b \cdot k(T_t^{out} - T_t^r) +$$
$$+0.5\alpha_{int}h(S/b+b) \cdot (T_t^w - T_t^r) + M_{met}N_t^{oc} - (COPP_t^c + W_t^{dis}) +$$
$$+C_{out}Q_tT_{vent} - C_{in}Q_tT_t^r + a_{inf}m_{air}C_{out} \cdot (T_t^{out} - T_t^r) +$$
$$+N_{light}M_{light} - L_{evap}M_{moisture}N_t^{oc}), t \in \mathbb{T}$$

$$T_{t+1}^{w} = T_t^w + 0.5\frac{\tau}{m_{wall}C_{wall}}\alpha_{int}h(S/b+b) \cdot (T_t^r - T_t^w)), t \in \mathbb{T}$$

$$n_{t+1}^{CO2} = n_t^{CO2} + \frac{\tau}{m_{air}}(Q_t(300 - n_t^{CO2}) + a_{inf}m_{air}(300 - n_t^{CO2}) + k_{CO_2}N_t^{oc}), t \in \mathbb{T} \quad (3.19)$$

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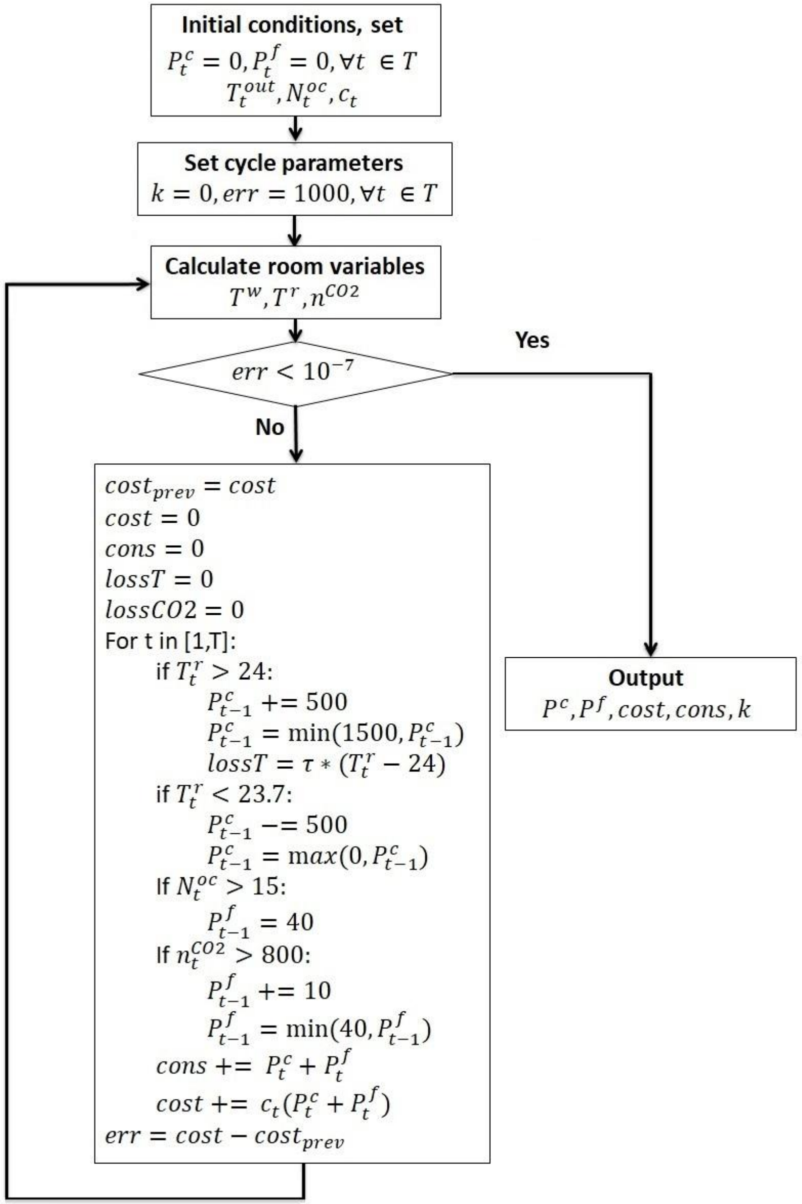
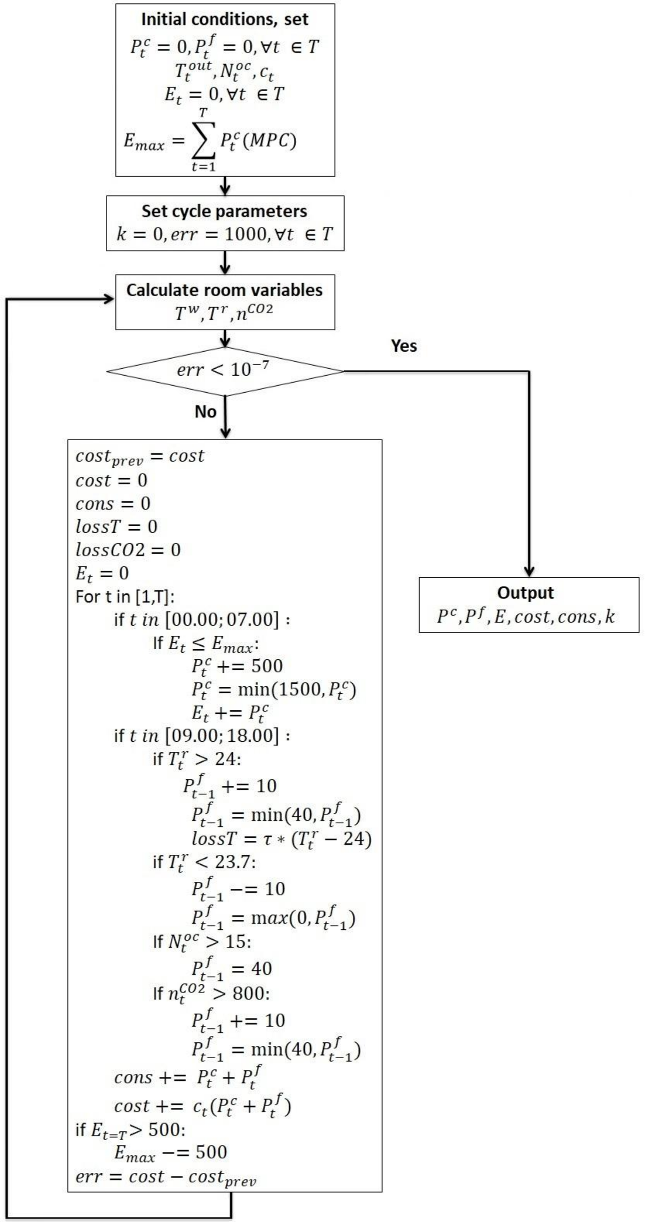
Proposed algorithms





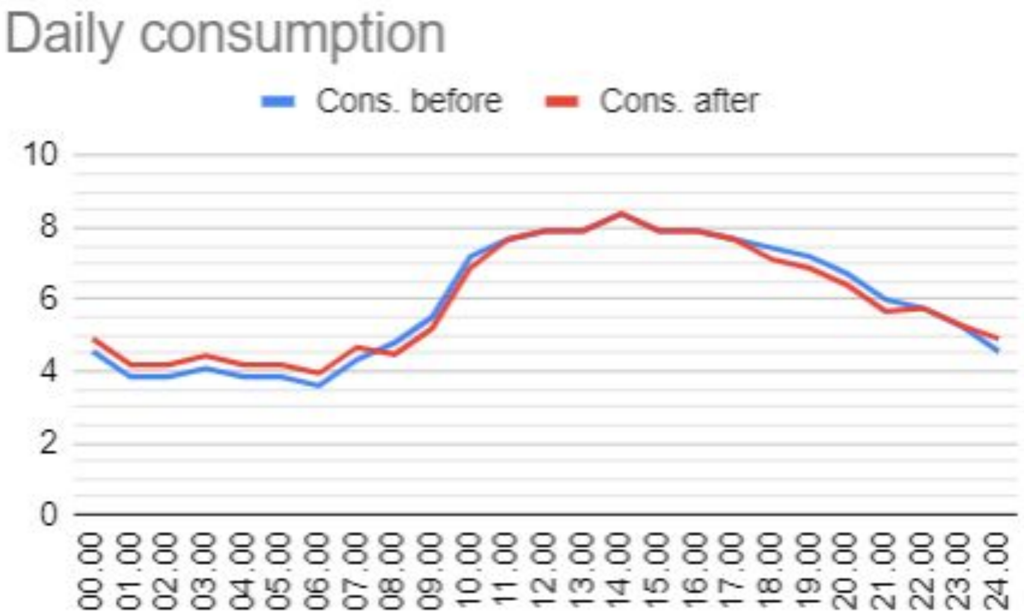
Methods used in Thesis

- Power Markets theory in demand-supply
- Mathematical modeling
- Application of heat-transfer theory
- Formulation of Optimization Problem
- Numerical calculations in Python

Benefits of using electrochemical energy storage devices

Commercial usage

Capacity = 0,7 MWh
Price = 25 mln. rub
Month save = - 8k rub (-0,04%)
ROI = No pay off



Aggregation usage

Capacity = 0,7 MWh
Price = 25 mln. rub
Month save = 417k rub (2,1%)
ROI = 5 years (stated payout = 600k rub/MW)

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