MODEL PREDICTIVE CONTROL FOR OPTIMUM INTEGRATION OF ACTIVE AND PASSIVE ENERGY SOURCES

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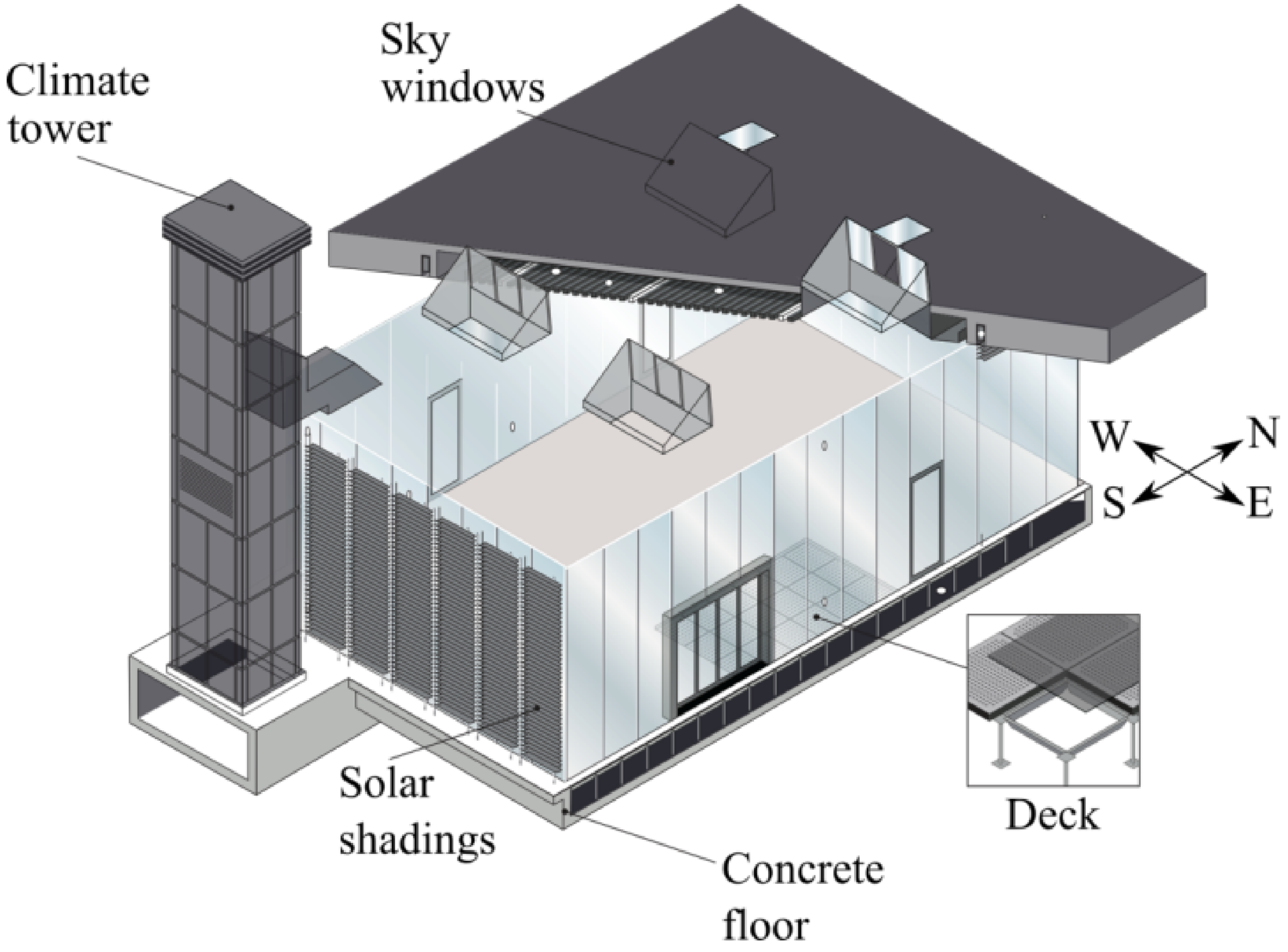
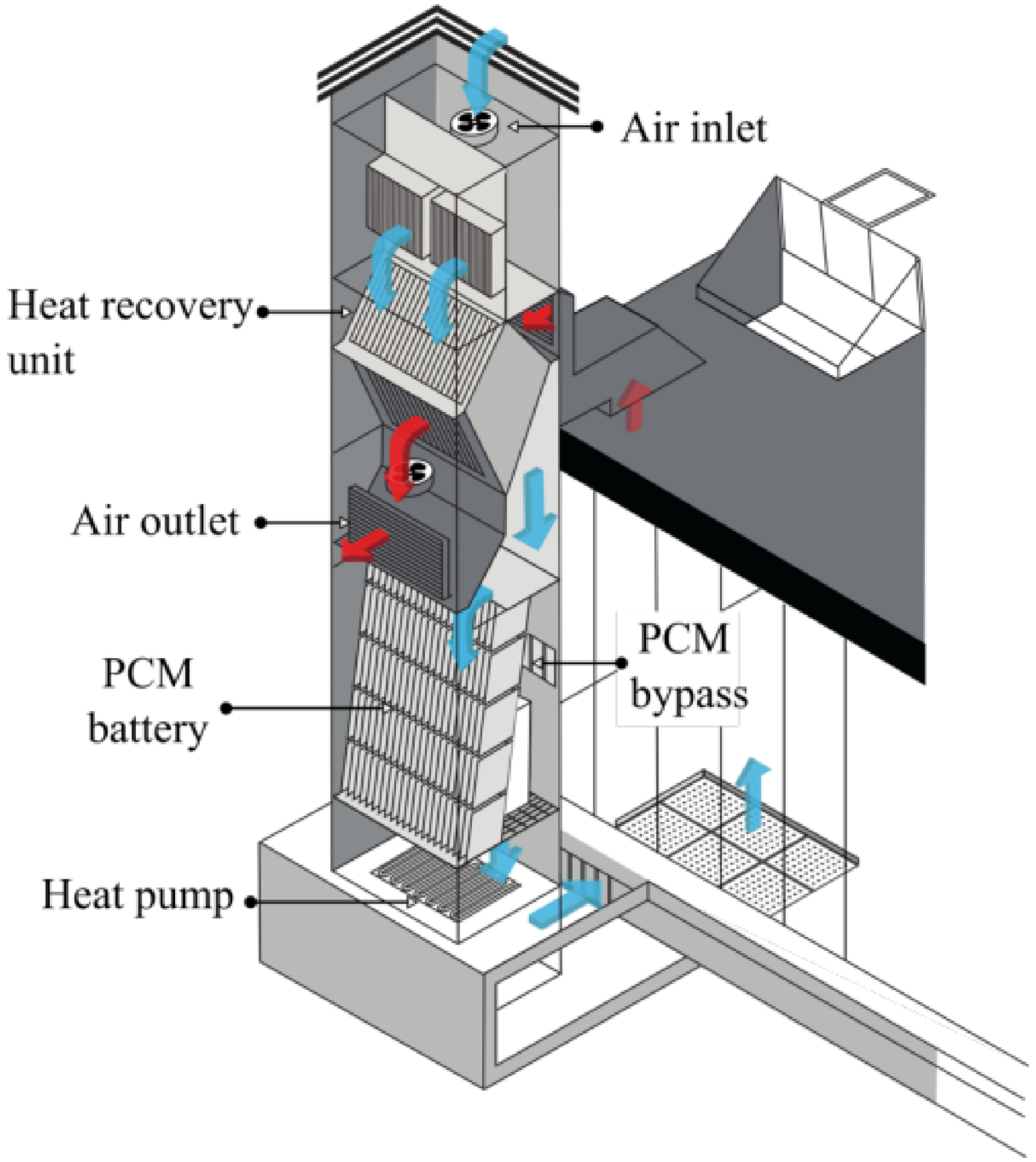
A closer look...





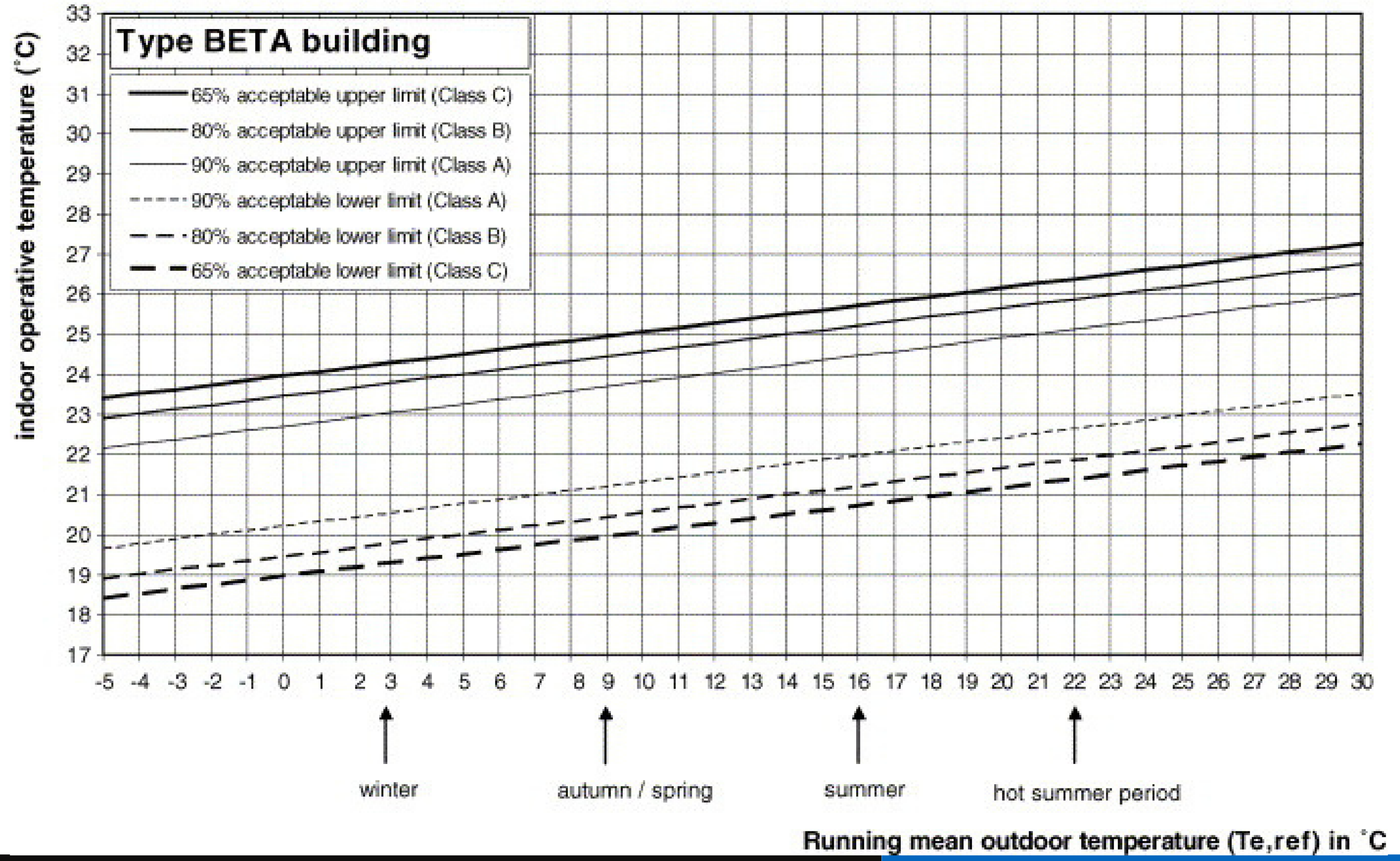
Research Goal

To save energy demand of Co-Creation Center as compared to Rule-based controller

Indoor comfort

- Thermal comfort
- Visual comfort
- Acoustic comfort
- Air quality

Adaptive thermal comfort model [12]



$$T_{e,ref} = \frac{T_{today} + 0.8T_{yesterday} + 0.4T_{day\ before\ yesterday} + 0.2T_{before\ two\ days}}{2.4}$$

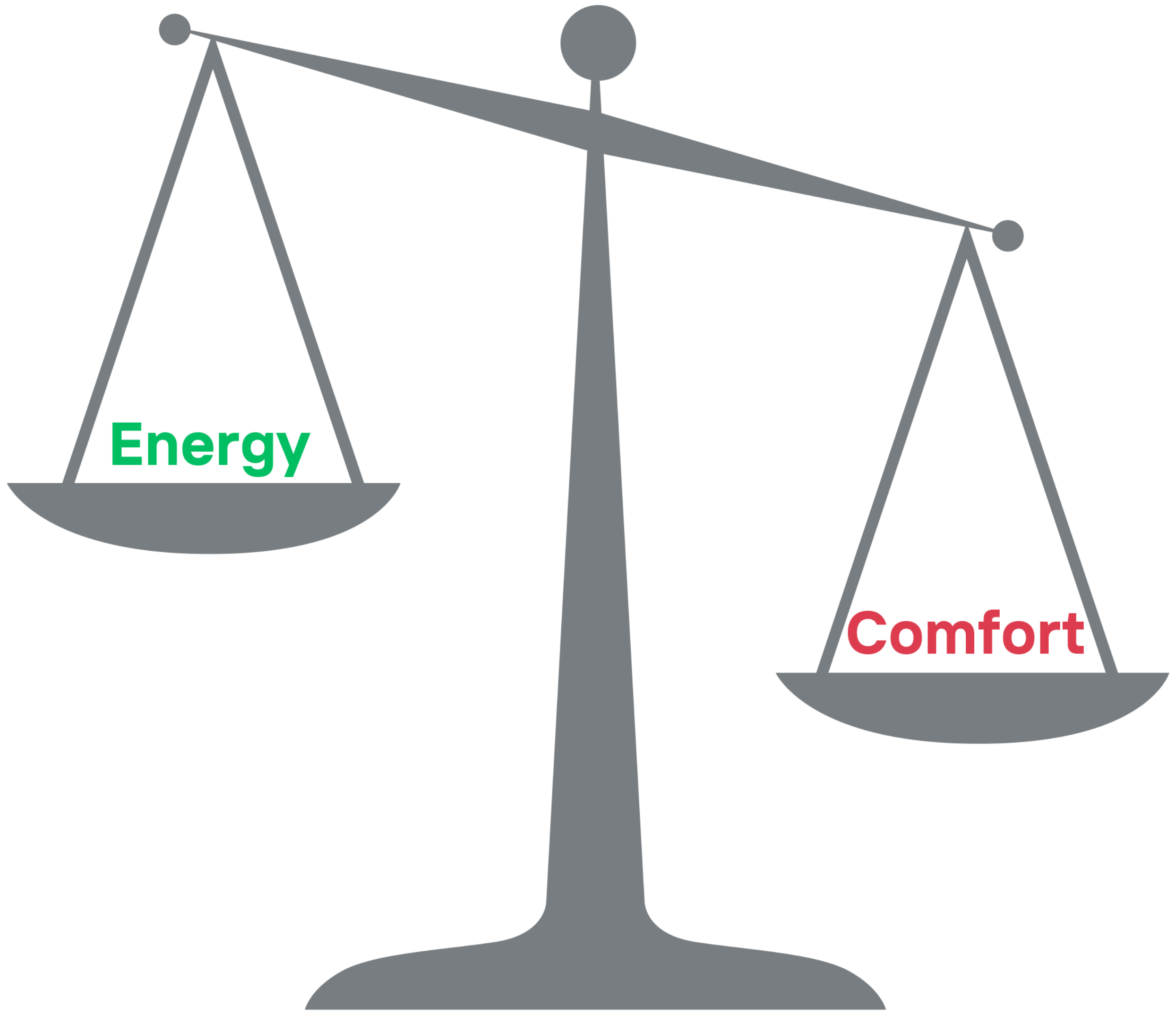
$$T_{operative} = 21.45 + 0.11 * T_{e,ref}$$

and the desired temperature bounds are:

$$\begin{cases} T_{operative,hour} \pm 2^oC & \text{for hour} < 8 \text{ or hour} > 16 \\ 24 \pm 6^oC & \text{otherwise} \end{cases}$$

Research Question

How to design an efficient MPC strategy to ***reduce heat pump energy*** *while maintaining* ***indoor thermal comfort*** *?*



Overview

1. Model Development and Validation → 2. MPC Setup → 3. Performance Assesment → 4. Improvements

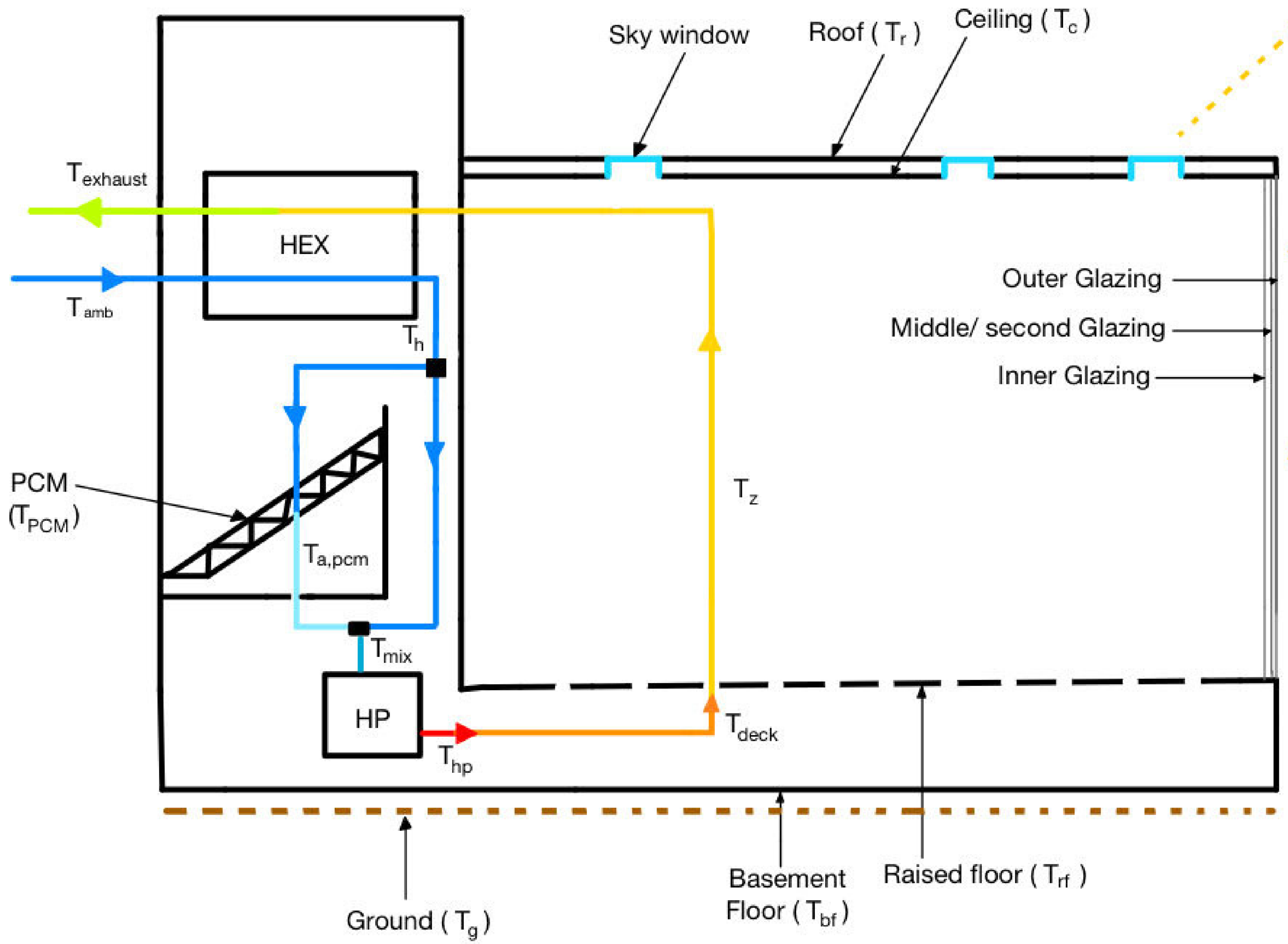
PHASE 1: MODELLING & VALIDATION

Modelling Approaches

Methods	Explanation
White-box modelling:	• Complex • Long time to converge • Software like EnergyPlus and TRNSYS too slow for control
Black-box modeling	• Based on statistical data • The inner processes remain unknown
Grey-box modeling	• Simplified through state-space dimensionality reduction • Lumped mass RC network analogy • Suitable for control

Existing model of the building

24 states/nodes , **6 controlled inputs**, and one distrurbance(occupancy)

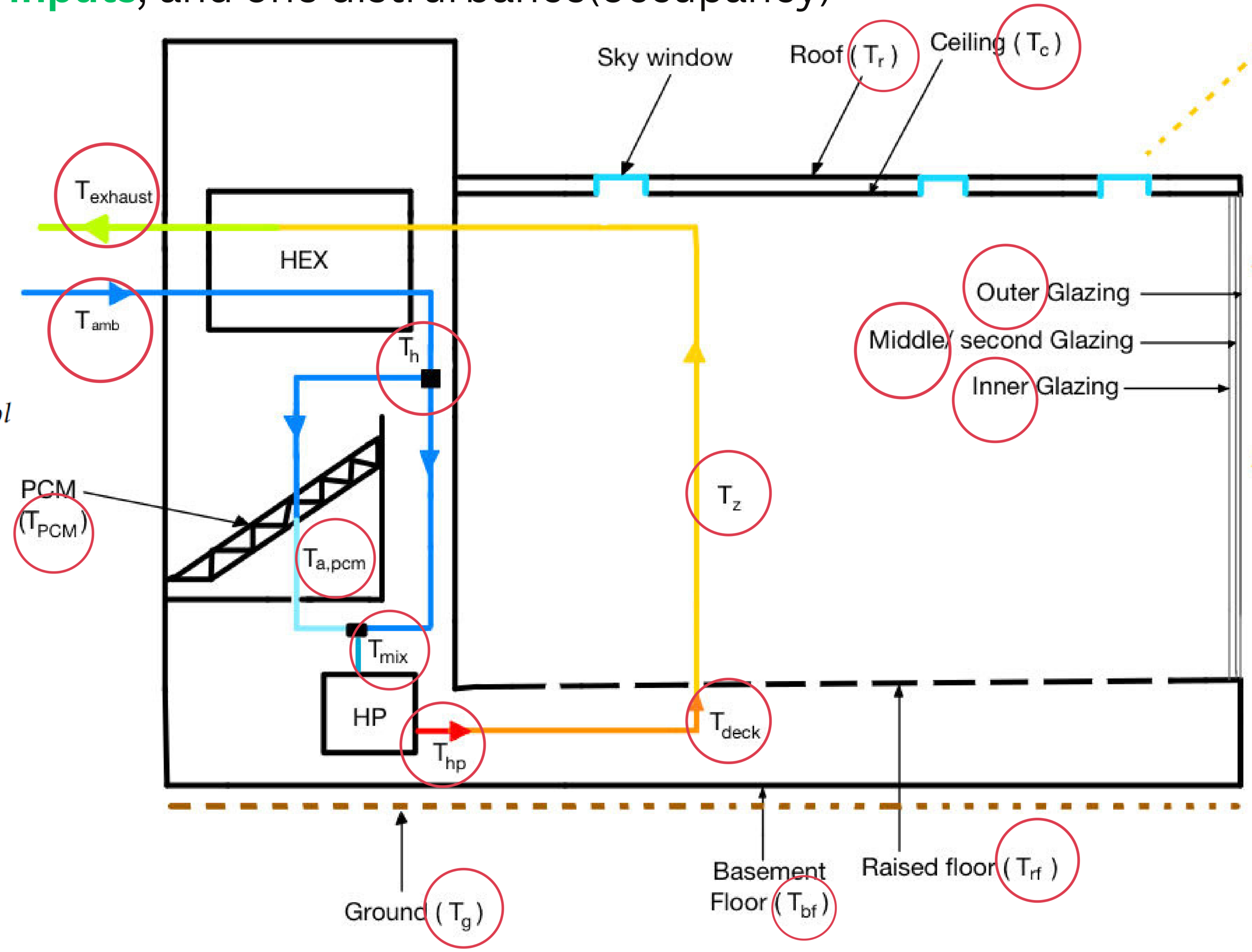


Existing model of the building

24 states/nodes , **6 controlled inputs**, and one distrurbance(occupancy)

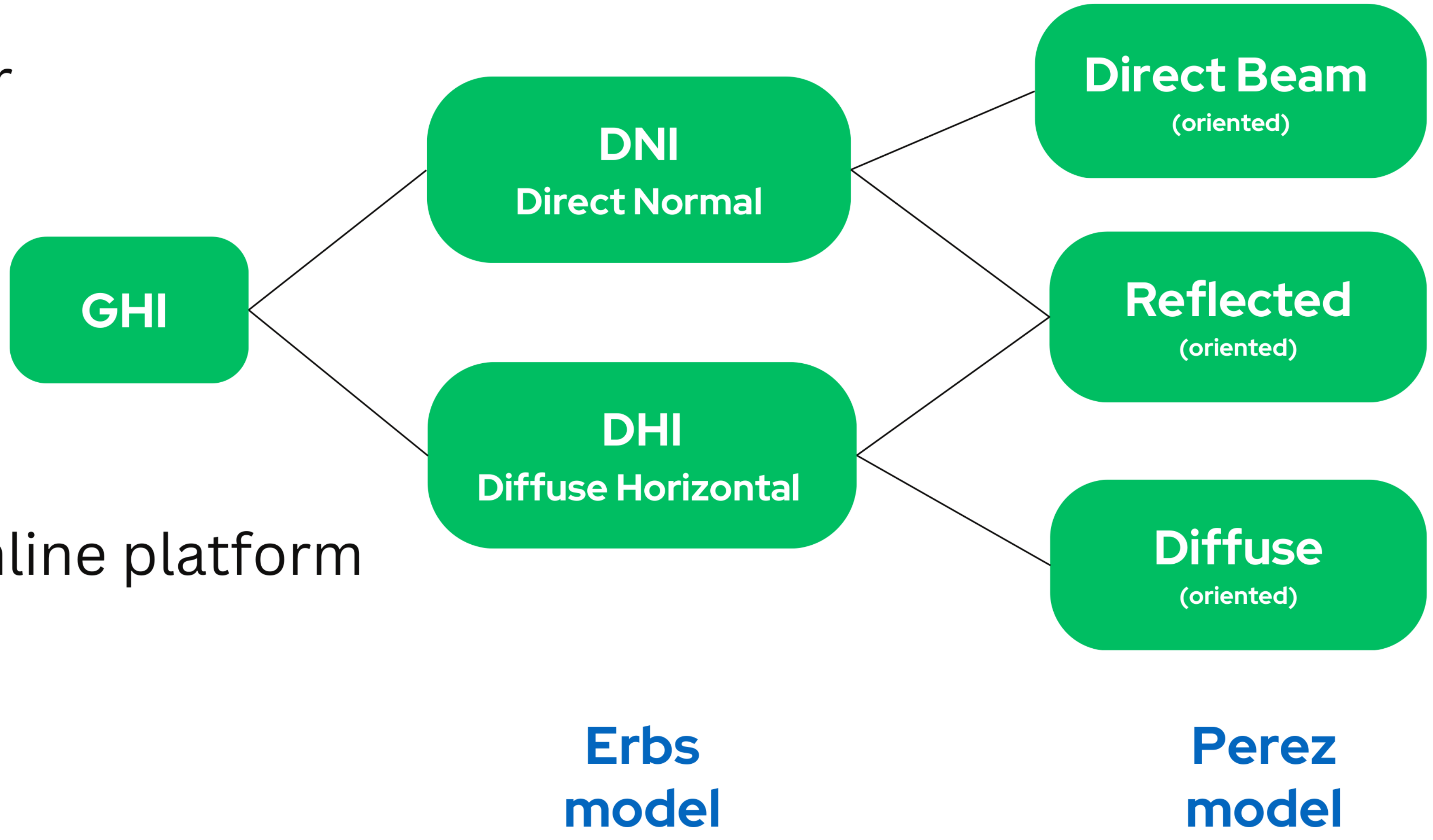
Each node has an equation like:

$$\rho V c_p \frac{dT}{dt} = \dot{Q}_{trans} + \dot{Q}_{vent} + \dot{Q}_{inf} + \dot{Q}_{int} + \dot{Q}_{sol}$$



Data fed to the model

- Wind data from Windfinder
- Solar Data from Solcast
- Occupancy from Priva's online platform



Model Validation

Validation setup :

- April 2 2021 to April 9 2021
- All systems turned OFF
- Temperatures of all components recorded

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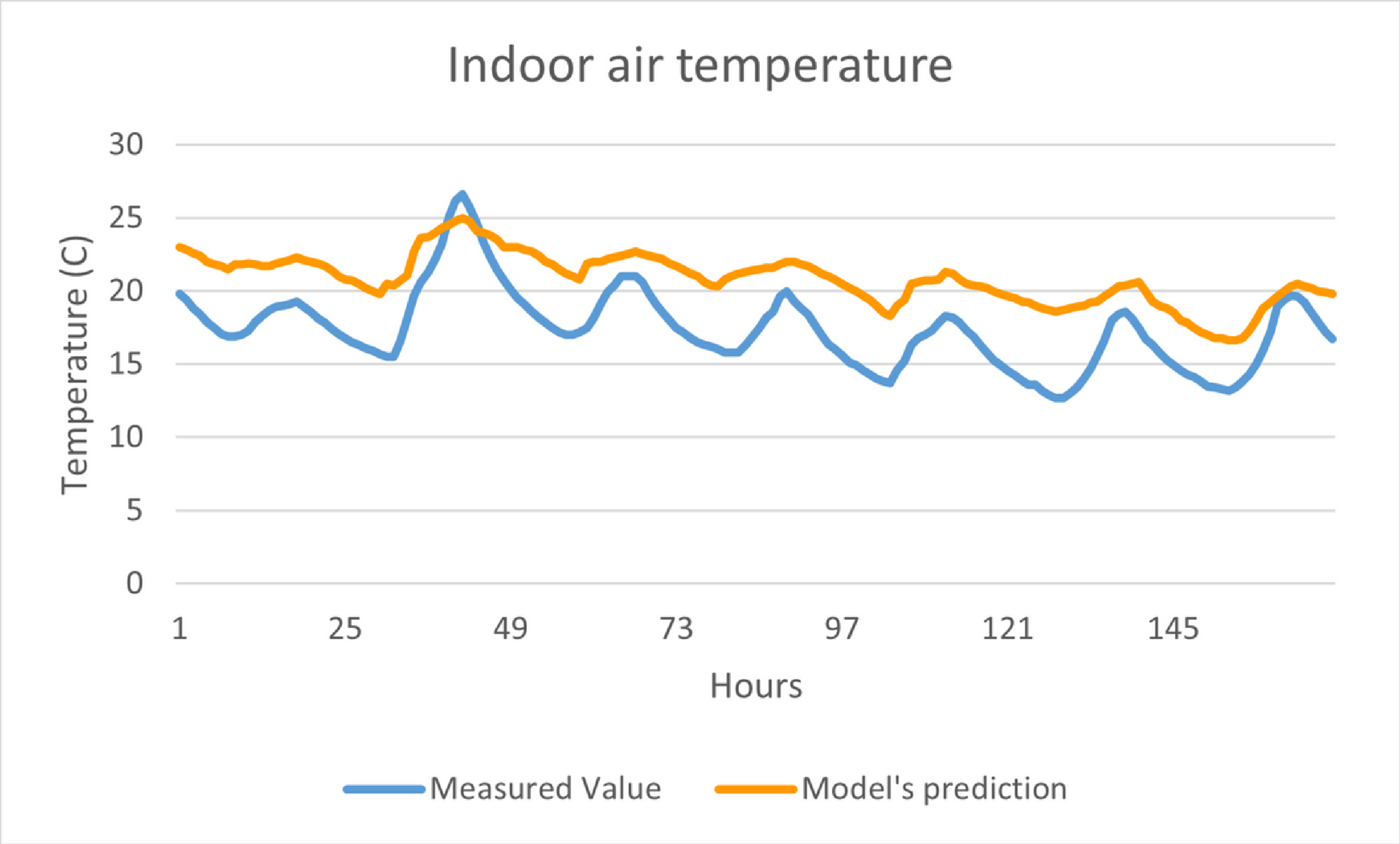


Results of Validation:

State	RMSE [K]	NRMSE	VAF
T_z	1.92	0.17	63.4
T_c	4.23	0.28	45.8
$T_{ext.walls}$	2.14	0.26	62.5
$T_{int.walls}$	5.53	0.32	18.2
T_{rf}	1.35	0.16	63.4
T_r	2.56	0.12	80.8

Parameter Optimization

Constrain to:

State	Parameter	Units	Initial value	Lower bound	Upper bound
T_c	κ	W/(m.K)	0.3	0.1	0.5
$T_{i,j}$	α	-	0.16	0.1	0.2
$T_{i,j}$	ϵ	-	0.8	0.6	1
$T_{i,j}$	ϵ_{low}	-	0.2	0.1	0.2
$T_{i,j}$	ξ	-	0.8	0.6	0.9
$T_{i,j}$	c_p	J/(KgK)	800	600	900

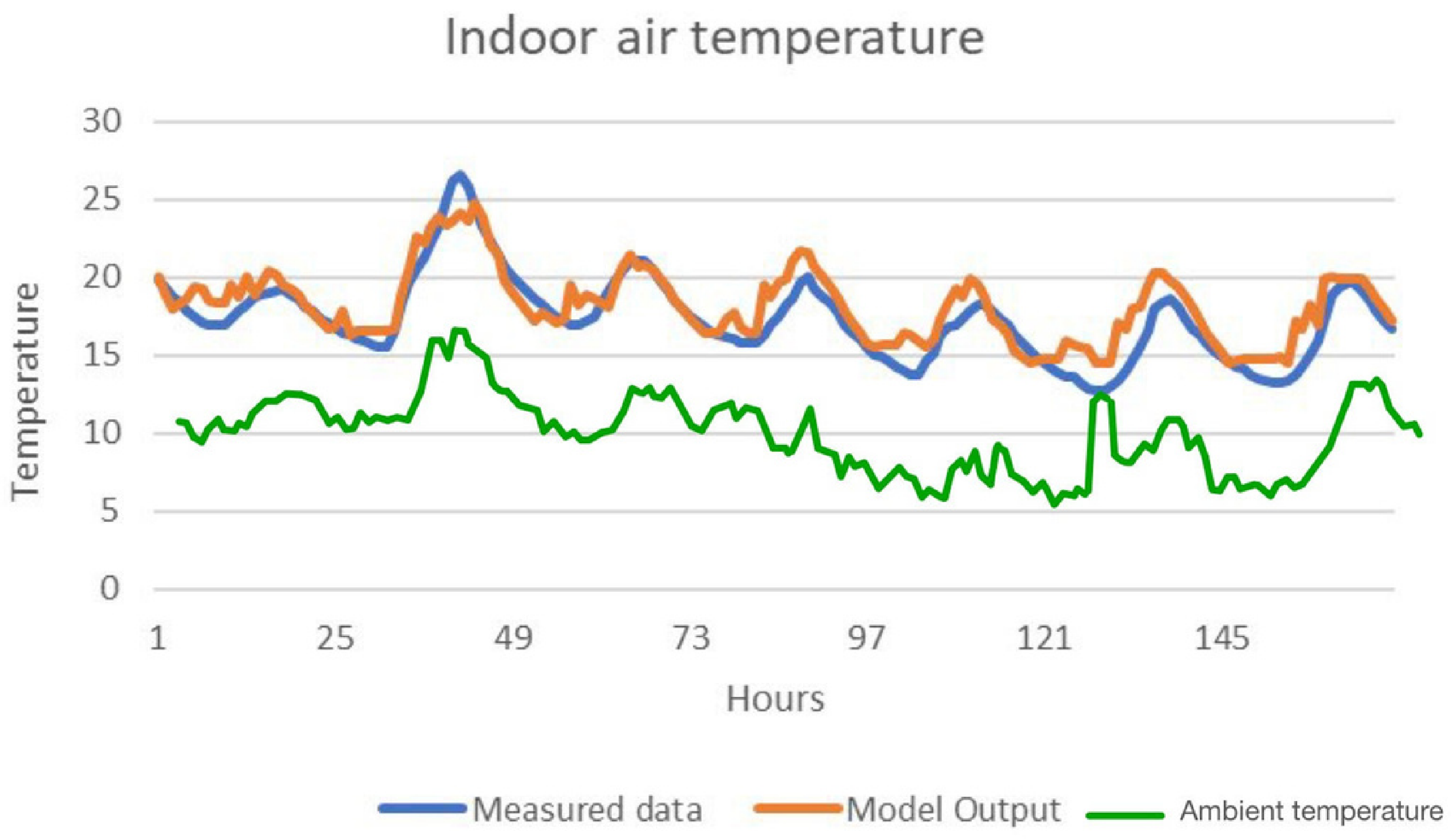
Objective function (to be minimized):

$$|T_{z\ measured} - T_{z\ predicted}| + |T_{rf\ measured} - T_{rf\ predicted}| + |T_{i,3\ measured} - T_{i,3\ predicted}| + |T_{c\ measured} - T_{c\ predicted}|$$

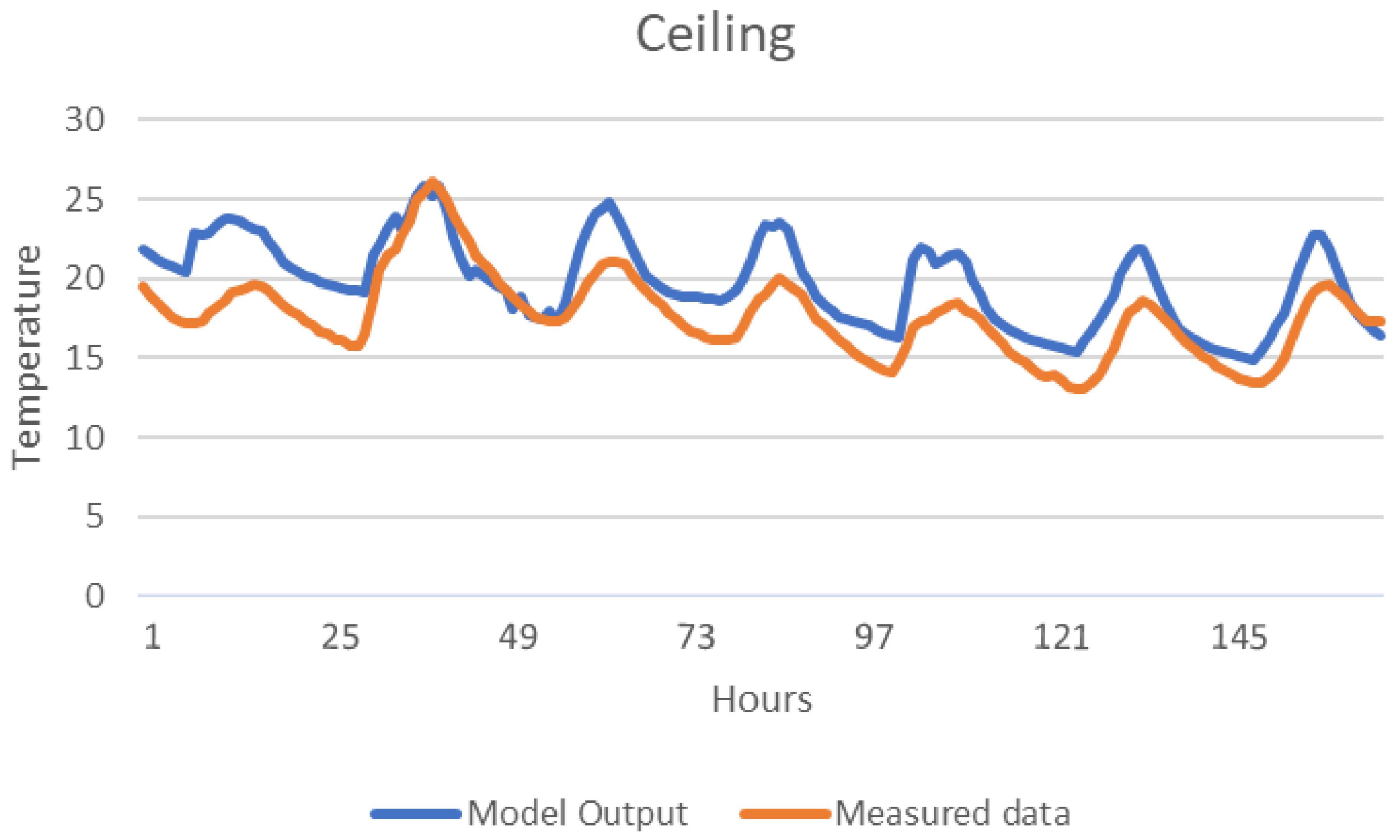
Results of Calibration:

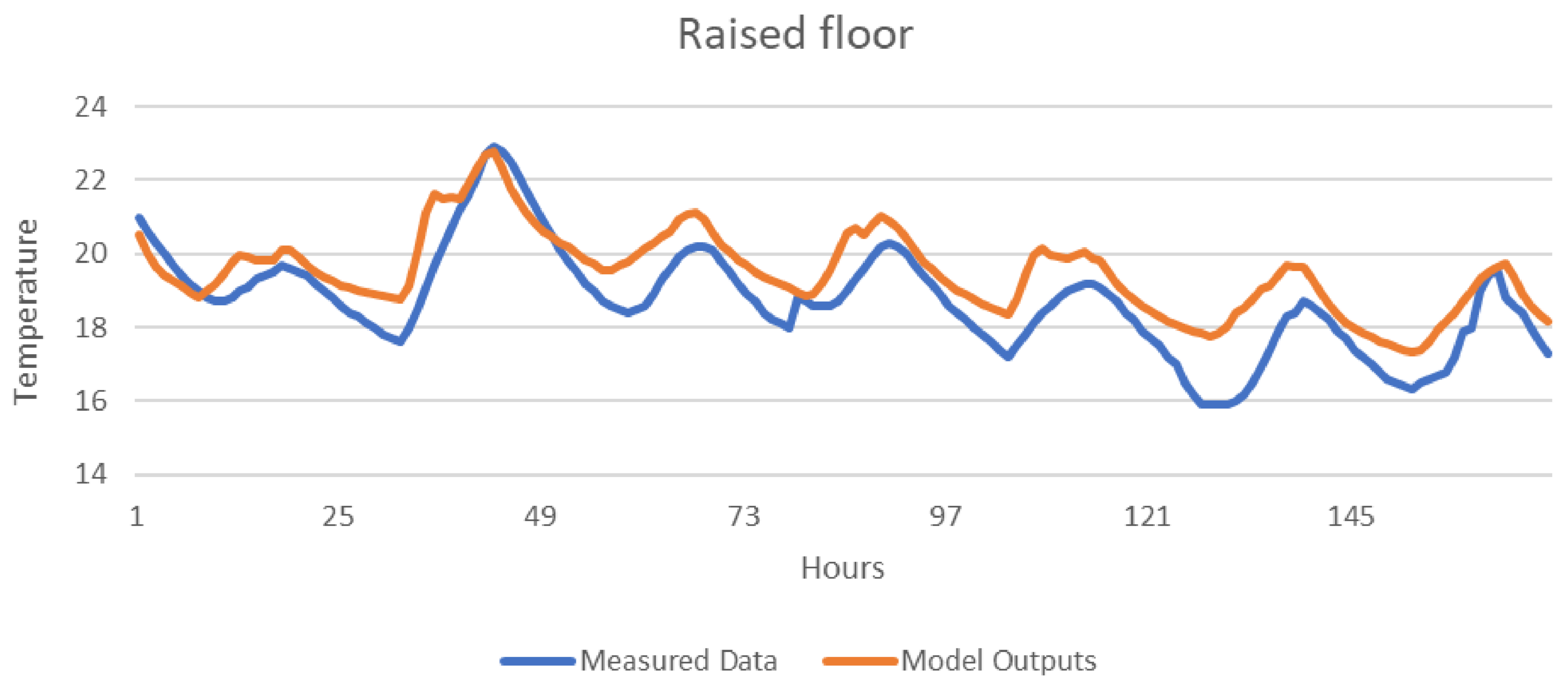
Parameter	Units	Initial value	Optimized value
κ	W/(m.K)	0.3	0.344
α	-	0.16	0.155
ϵ	-	0.8	0.77
ϵ_{low}	-	0.2	0.13
ξ	-	0.8	0.78
c_p	J/(KgK)	800	792

Model Validation



State	RMSE [K]	NRMSE	VAF
T_z	1.382	0.0995	82.15
T_c	2.574	0.1967	59.5
$T_{ext.walls}$	1.809	0.1587	75.6
$T_{int.walls}$	3.305	0.2322	28.1
T_{rf}	0.975	0.1393	80.92
T_r	2.421	0.0898	87.8





PHASE 2: MPC SETUP

Fundamentals of Model Predictive Control

How does MPC work?

1. Modeling the system

- Describes the system behavior
- How the system will respond to different actions

2. Predicting the future

- Considers current state, inputs and disturbances
- Anticipate what will happen

3. Optimizing the control actions

- Based on predicted behavior, MPC searches for best control actions to achieve objectives
- Considers constraints

4. Iterative process

- Repeats prediction and optimization at regular intervals
- Adapt to changes in environment

MPC Problem setup

Objective function

$$Q = \dot{m} c_p |(T_{hp} - T_{mix})|$$

Constraints

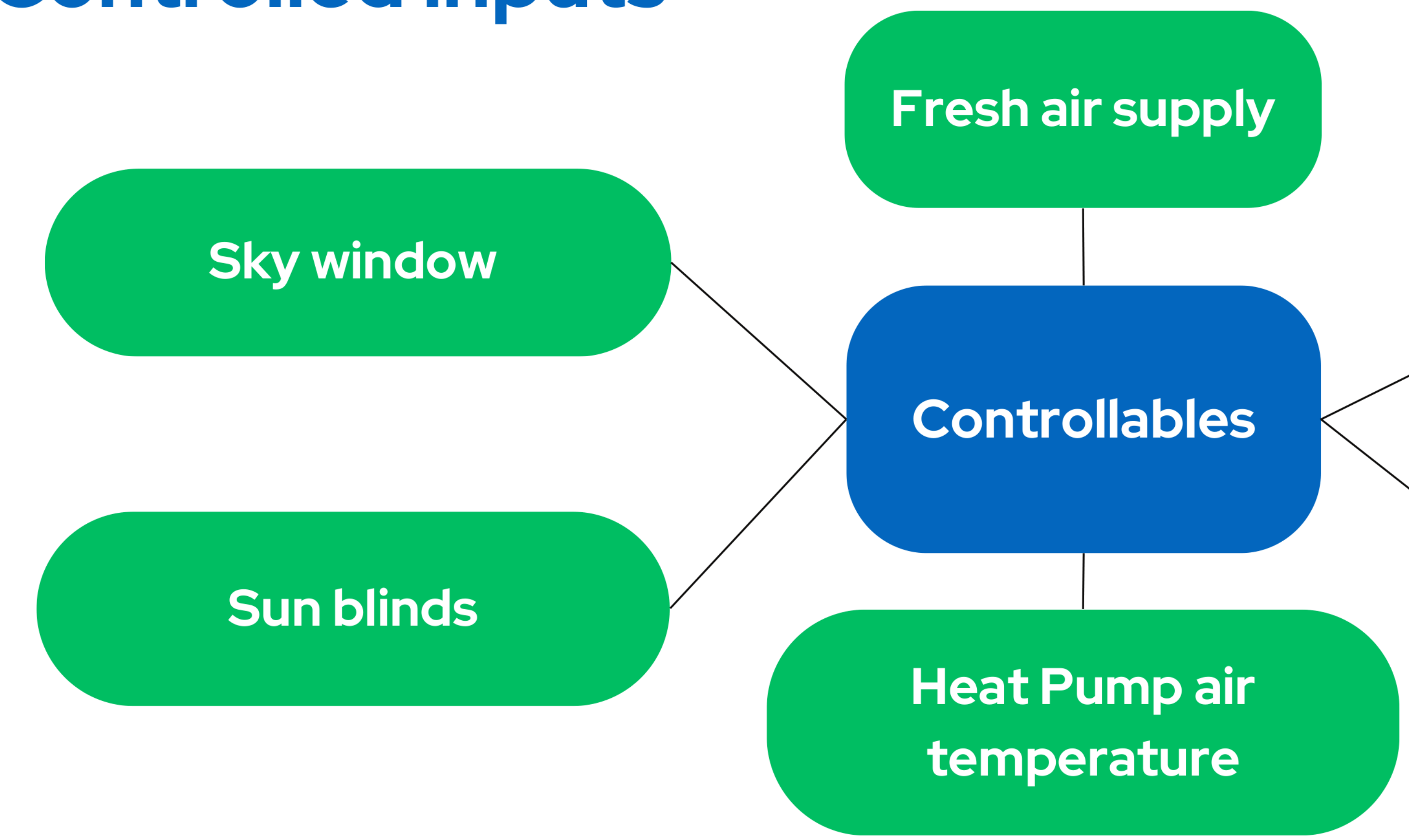
$$e_i = |T_{operative,i} - T_{zone,i}| \qquad \text{for i} \in n_p$$

$$T_{operative} = 21.45 + 0.11 * T_{e,ref}$$

and the desired temperature bounds are:

$$\begin{cases} T_{operative,hour} \pm 2^o C & \text{for hour} < 8 \text{ or hour} > 16 \\ 24 \pm 6^o C & \text{otherwise} \end{cases}$$

Controlled inputs

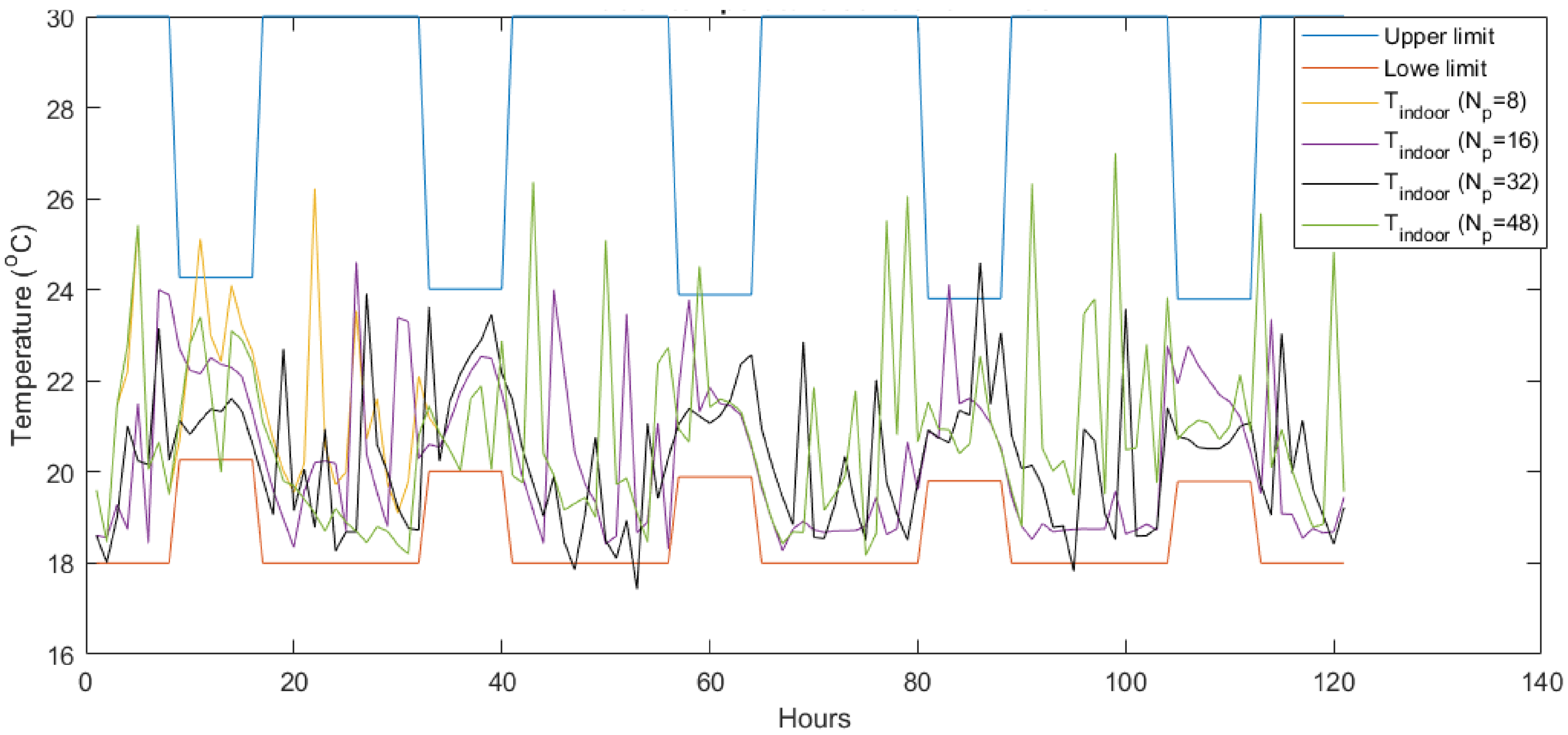


Parameter	Lower limit	Upper limit
T_{hp}	10	35
$\dot{m}$	0.1	1
x_h	0	1
x_{sw}	0	1
x_{pcm}	0	1
x_{rec}	0	1

How far should we predict into the future ?

Determination of Prediction Horizon

Winter



Prediction horizon (hours)	Computational time (s)	$\sum error$ [°C]	Energy supplied by HP [kWh]
4	40	1.82	148
8	261	0.16	144
16	492	0.68	138
24	1206	0.36	137

PHASE 3: PERFORMANCE ASSESMENT

Experimental Validation

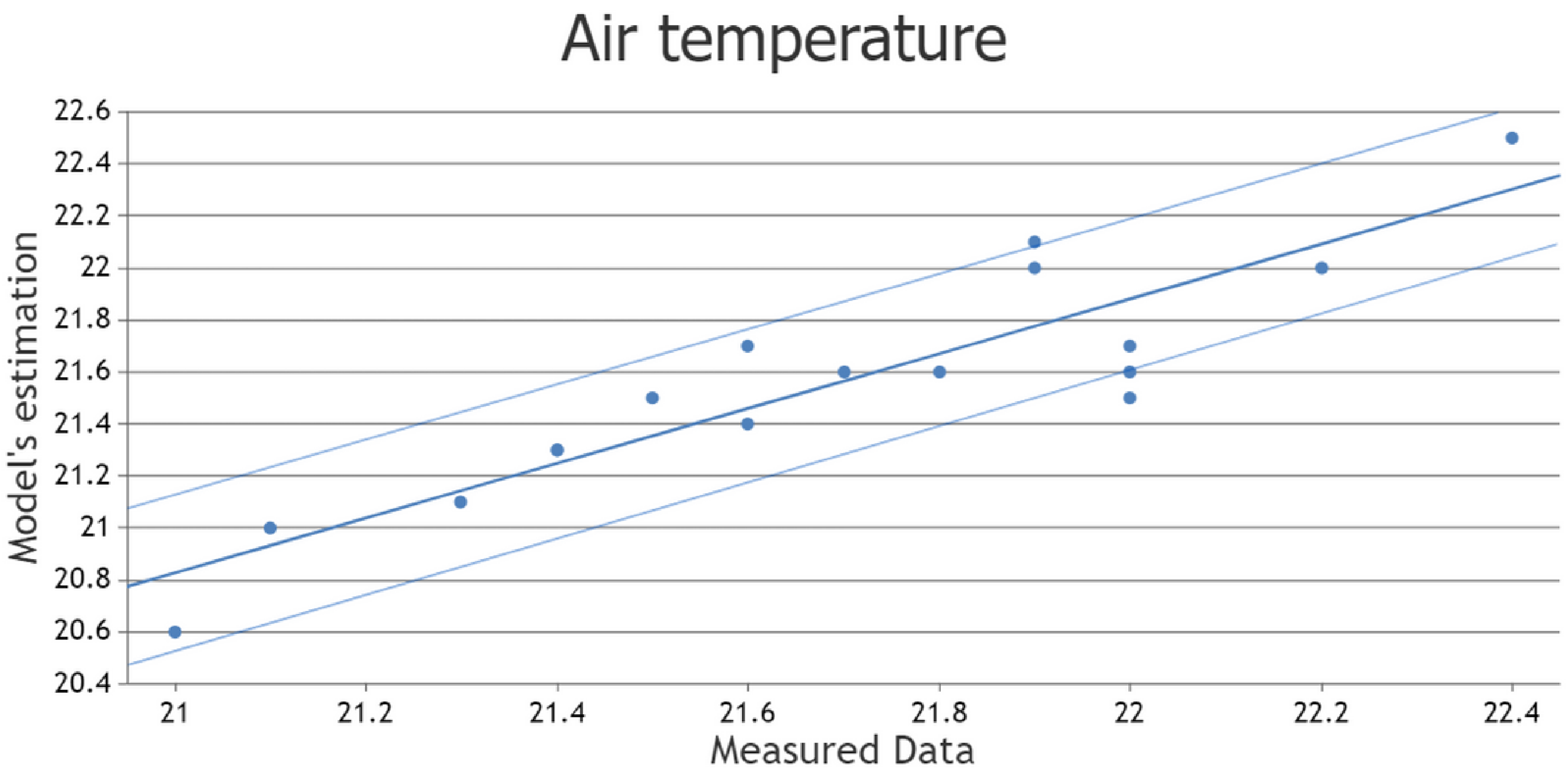
Why? To test the accuracy of the developed MPC.

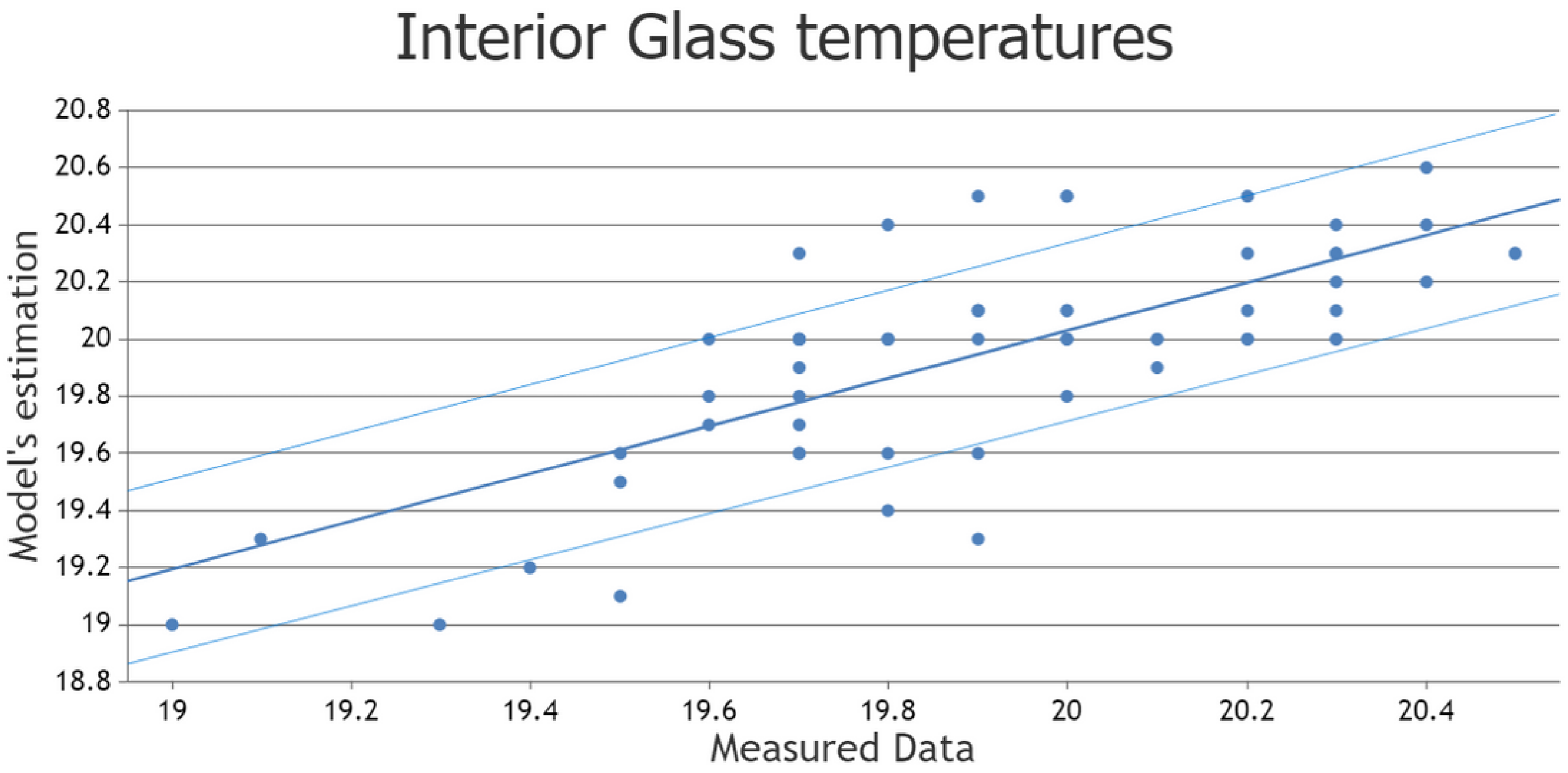
How?

- Experiments were conducted on 08-04-2023 and 09-04-2023.
- The model was fed with **weather predictions** and **zero occupancy**
- The fraction of solar blinds was **manually fed** to the model
- Control inputs were fed **from Model to the BEMS**

How to measure accuracy of MPC ? **Temperature predictions** vs **Measured temperature**

Experimental Validation of MPC





State	T_z	T_c	$T_{interiorglass}$	$T_{outsideglass}$	T_{floor}
RMSE [K]	0.23	0.12	0.26	0.23	0.29

Comparitive Study : Energy Savings Potential

Why? MPC vs RBC : How much energy can they save ?

How?

- Experiments were conducted on 10 April '23 to 14 April '23.
- RBC: **Actual** | MPC: **Simulated**
- identical **Weather, occupancy** and **temperature limits**

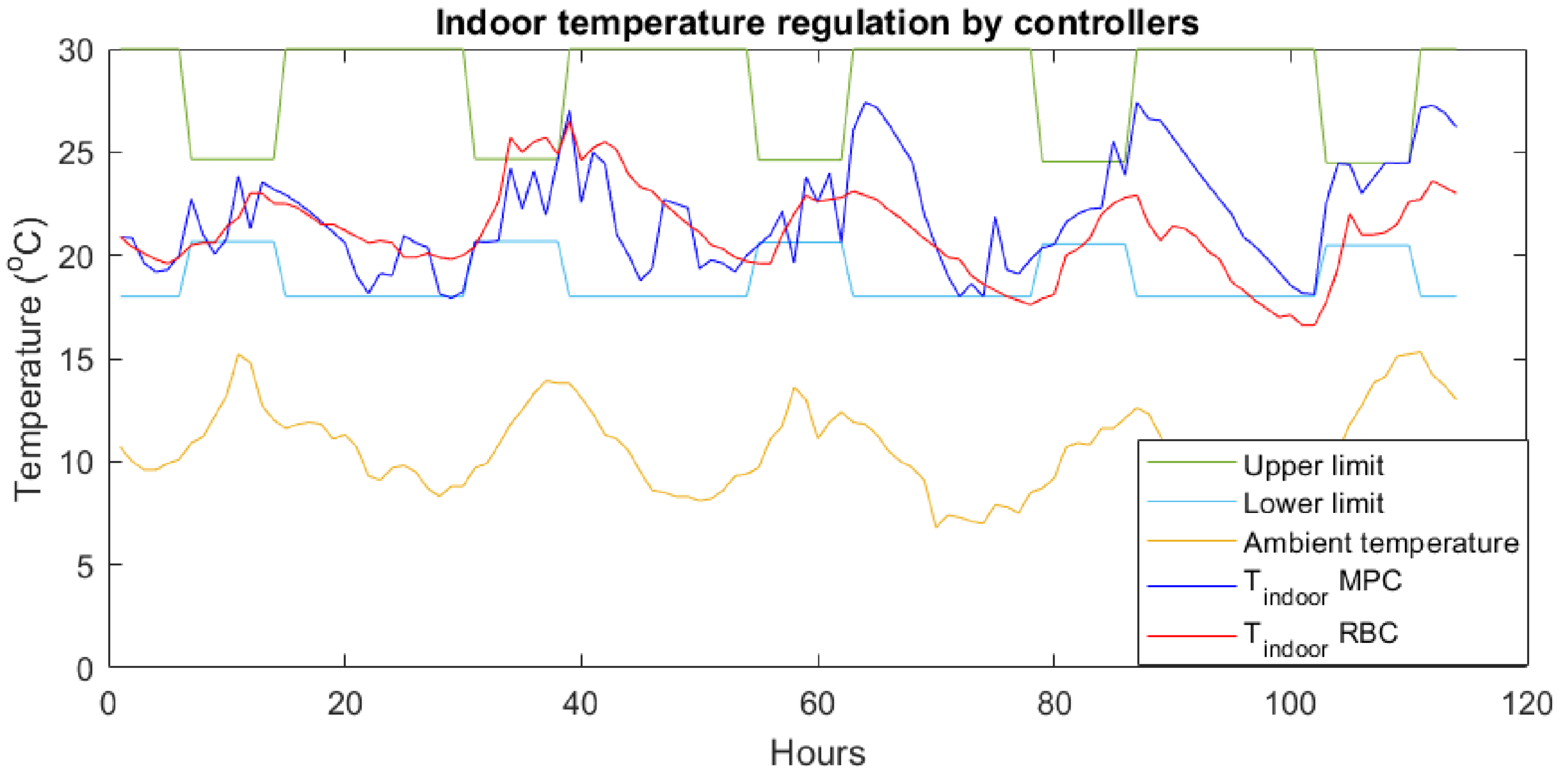
How to measure Performance ?

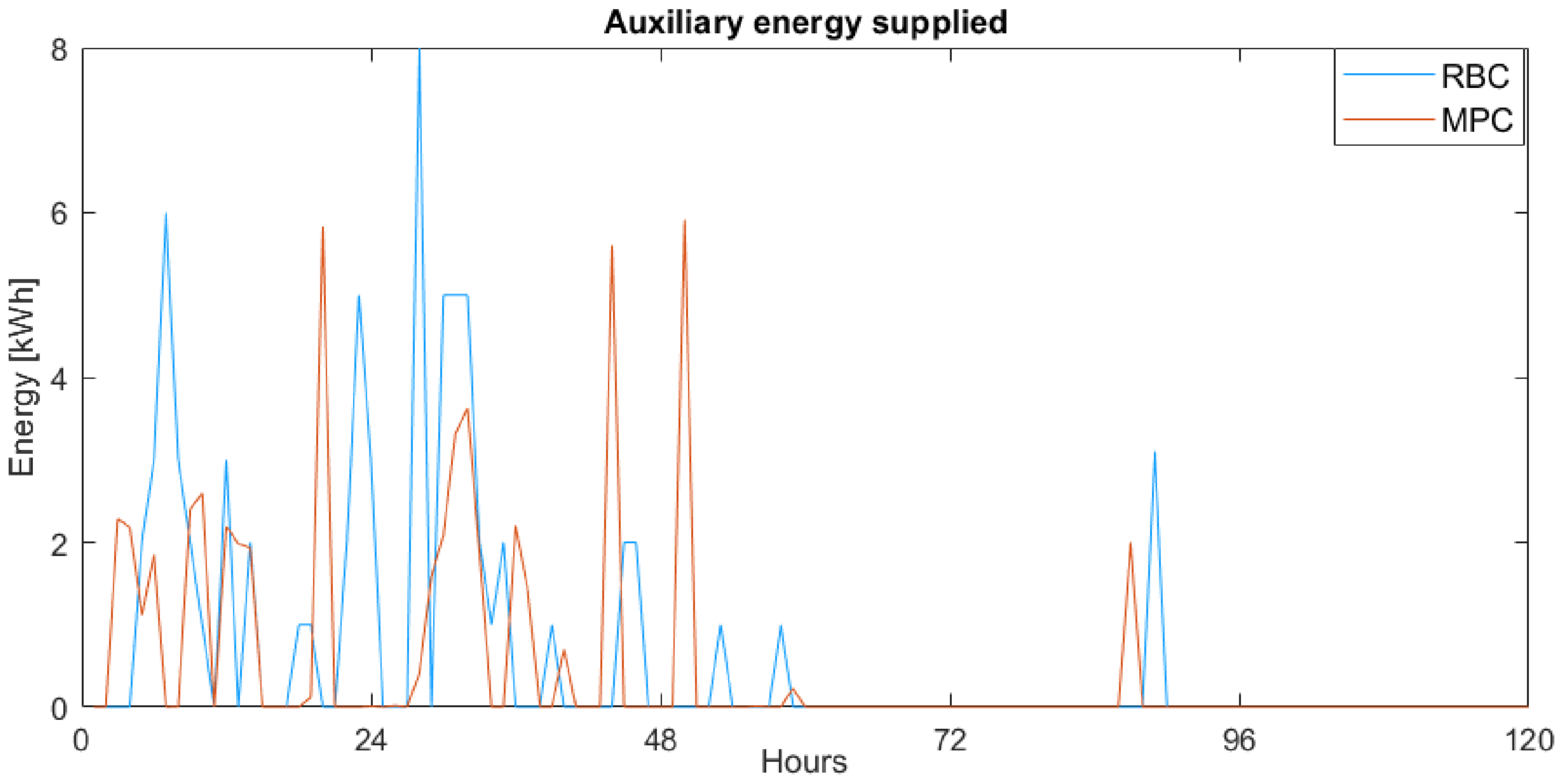
MPC vs RBC

1. Energy supplied by HP
2. Ability to maintain comfort

Comparitive study: Energy savings potential

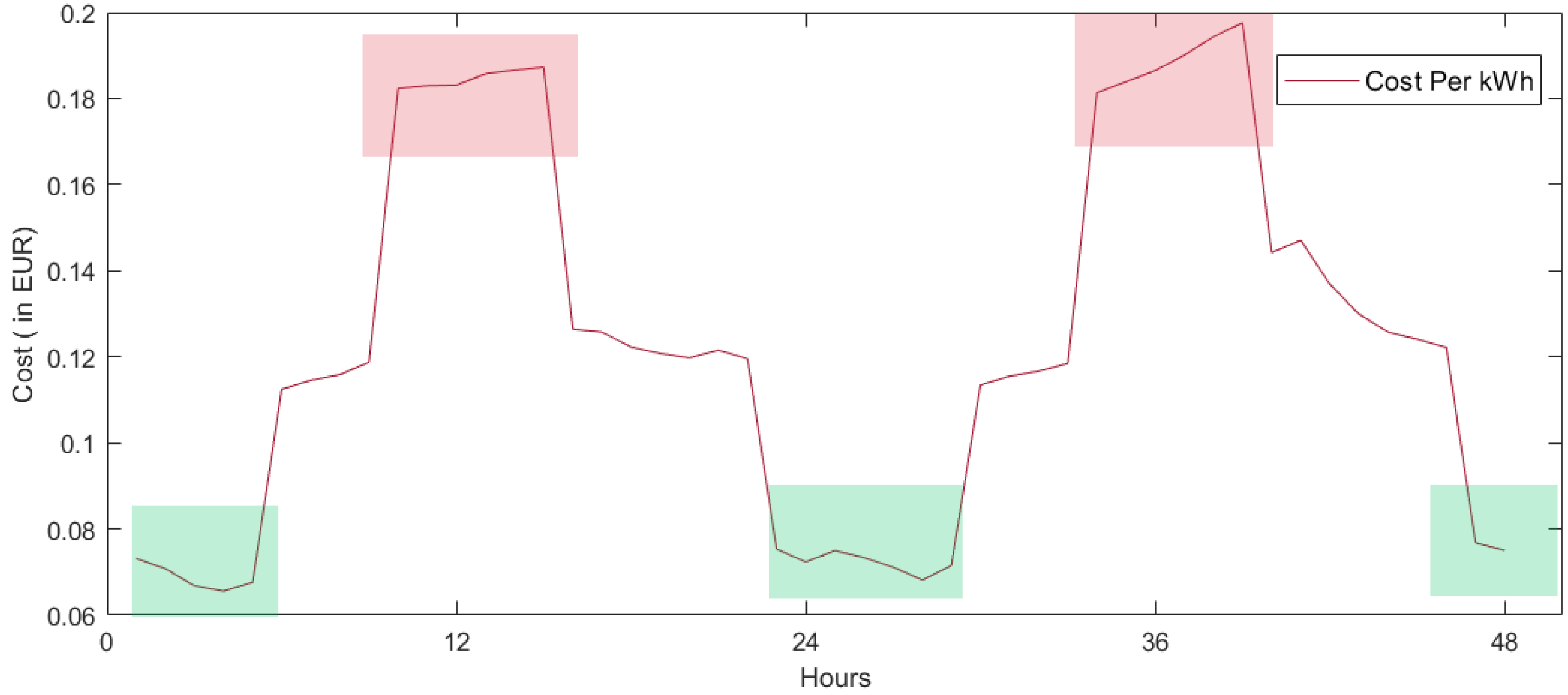
Actual test performed during April 2023 with same temperature limits





Assessment Criteria	RBC	MPC
Energy consumption [kWh]	69	53.4
Total temperature violations $\sum e$ [K]	3.89	3.21

Energy flexibility



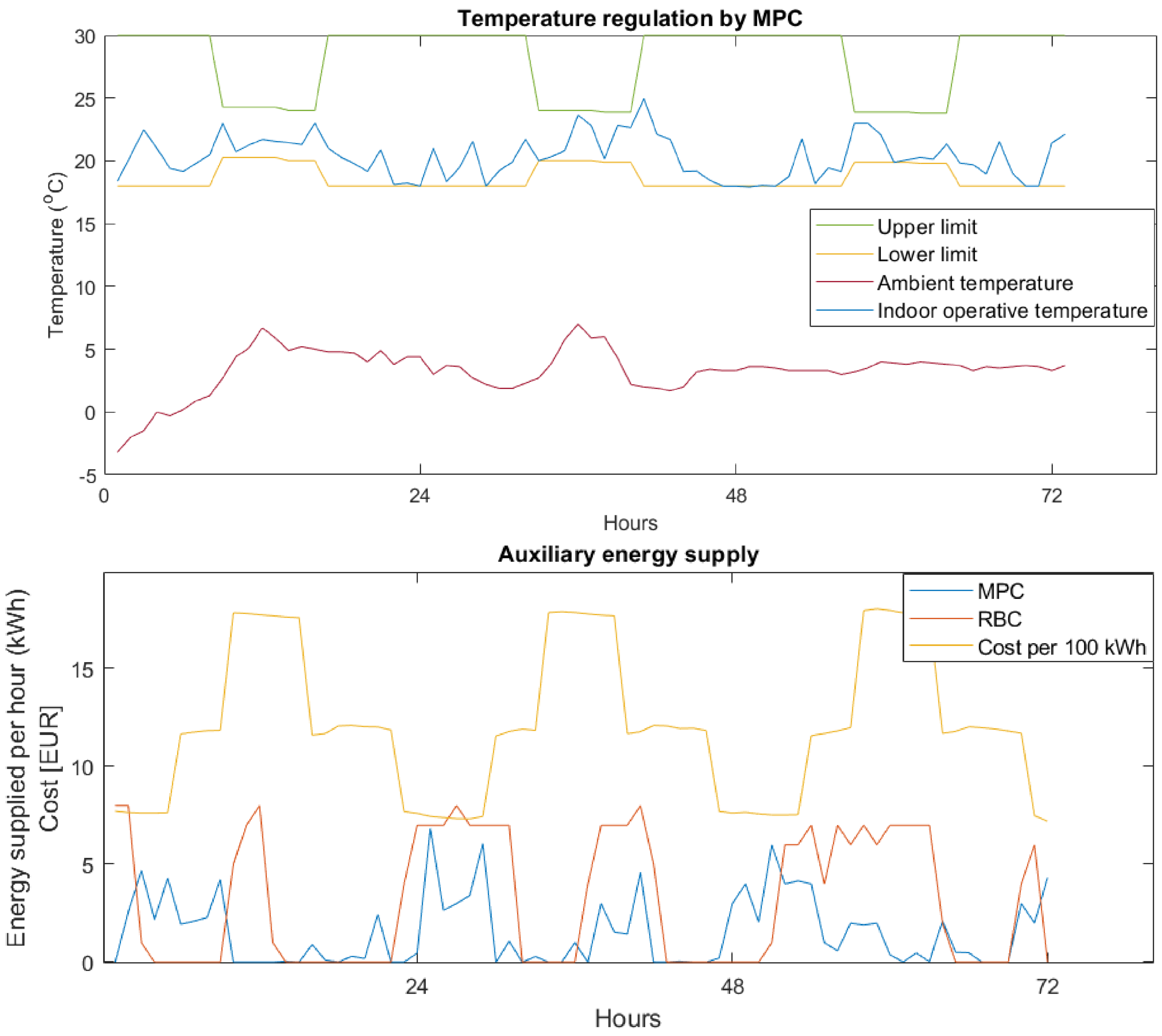
Cost of Electricity during a period of 2 days (source)

Hence, objective needs to be modified

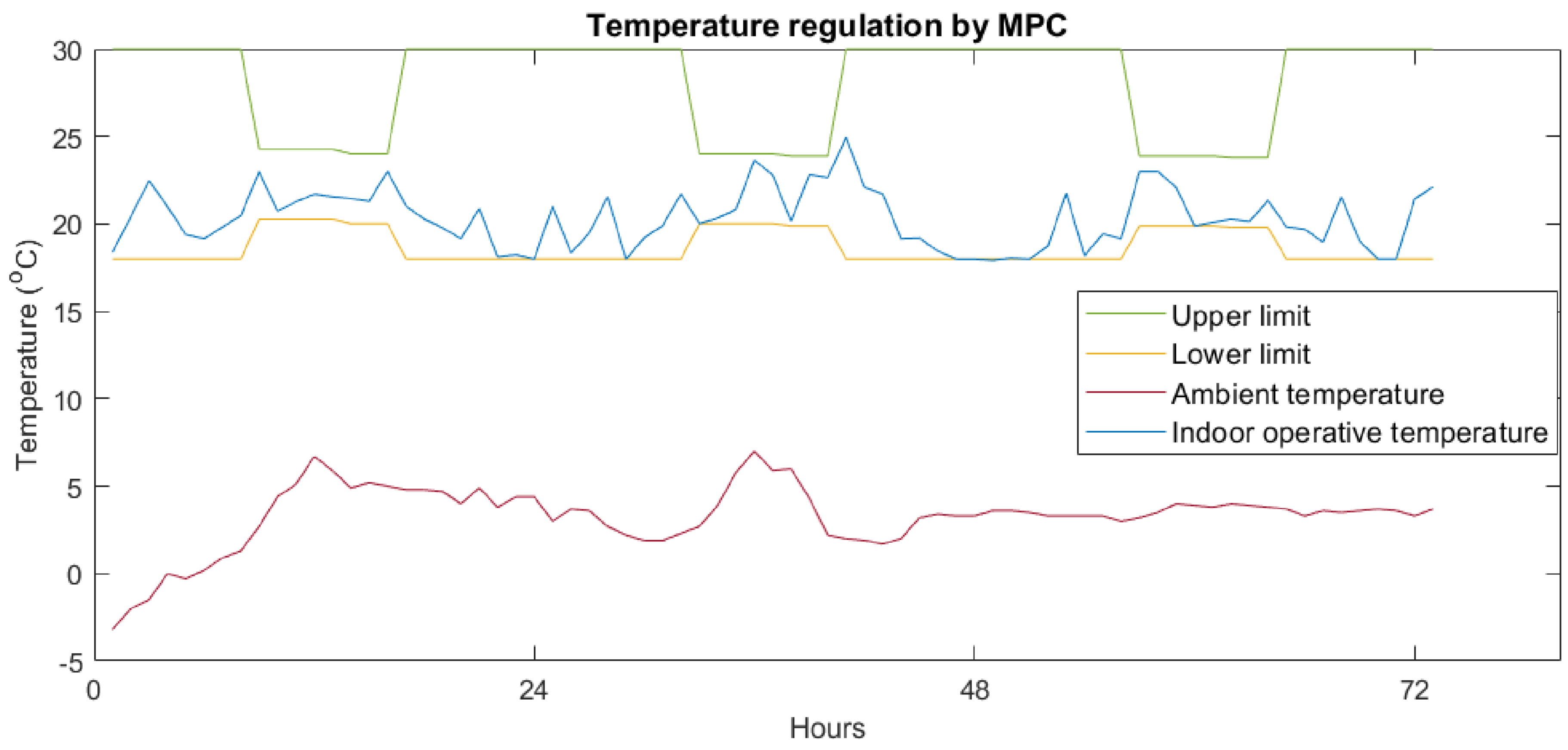
$$Q = Cost_{timestep} * \dot{m}c_p|(T_{hp} - T_{mix})|$$

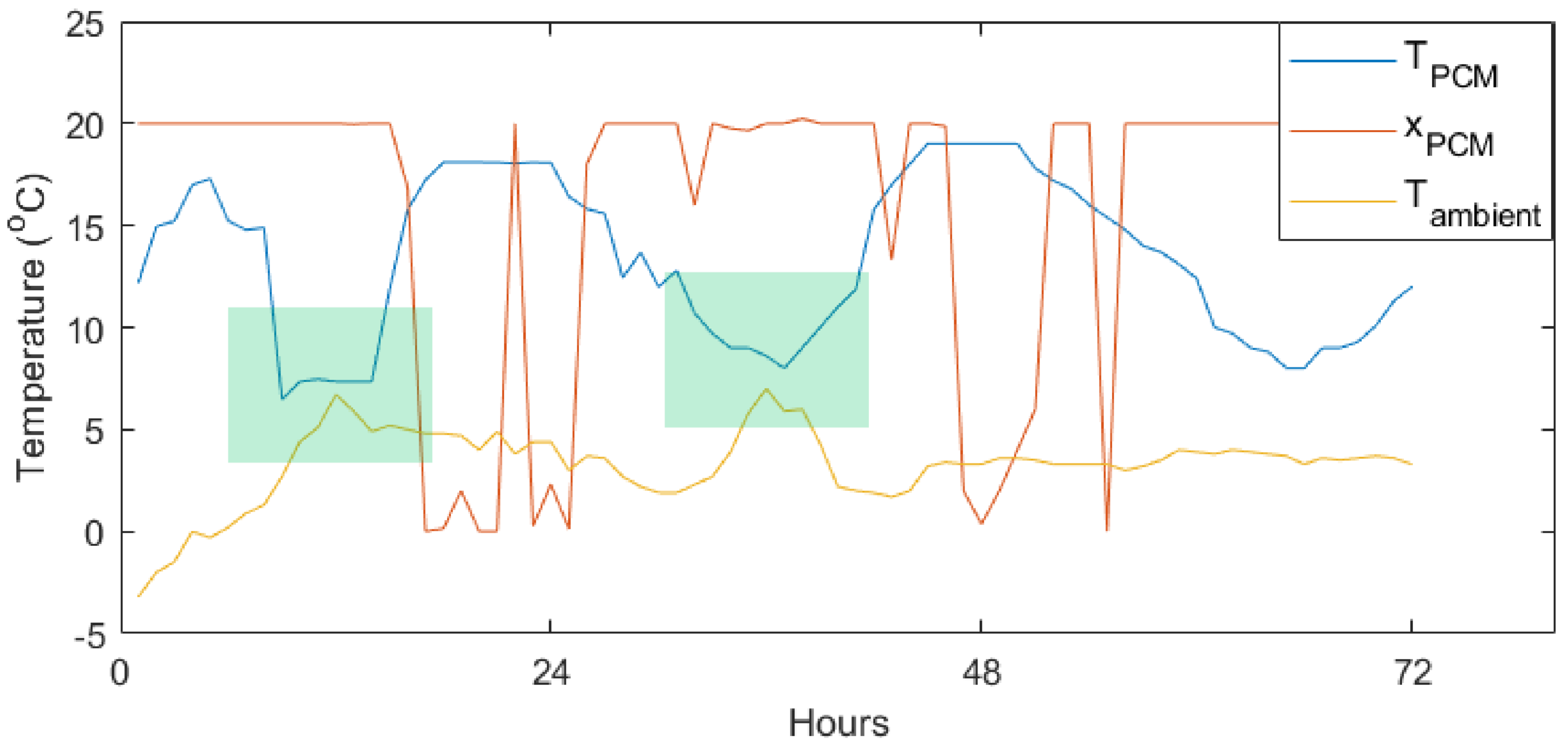
To understand the dynamics closely, a period of 3 days in chosen for Summer and Winter

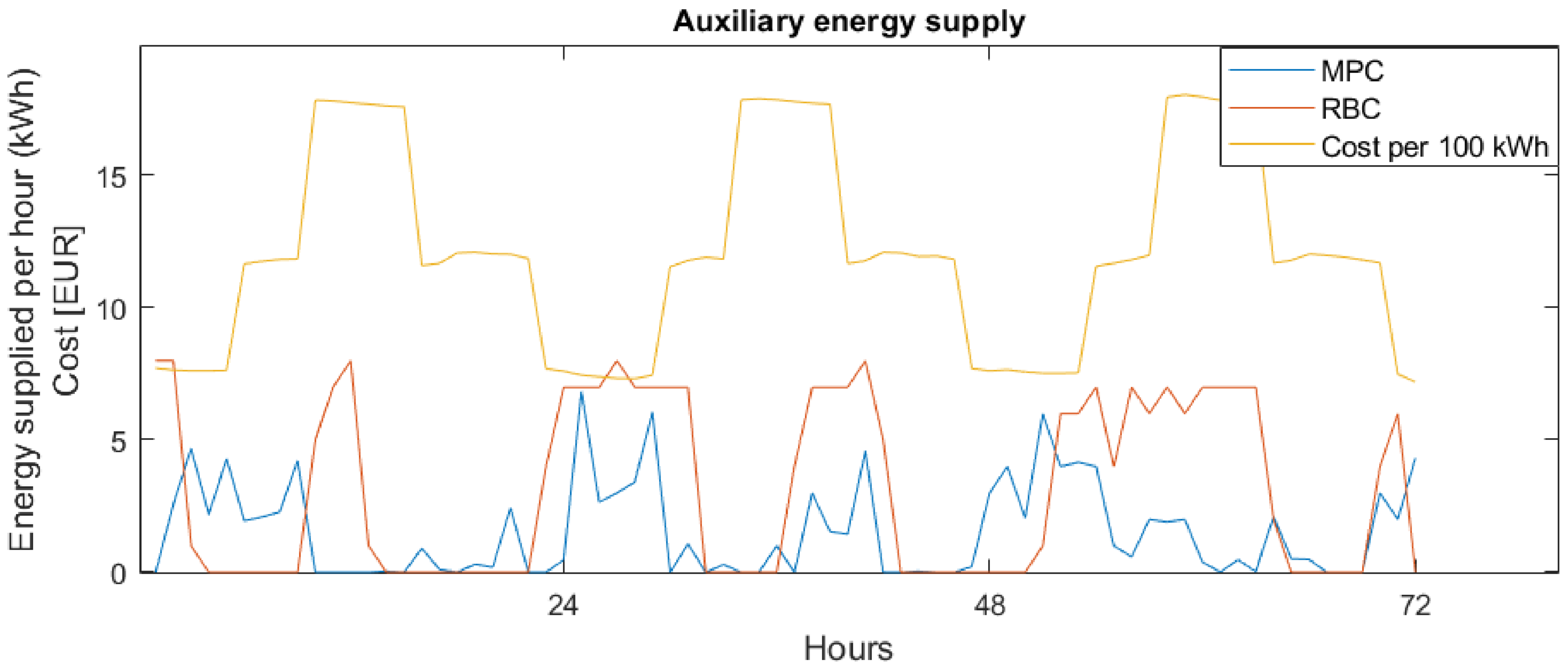
Energy flexibility potential : Representative study [Winter]



Energy flexibility potential : Representative study [Winter]

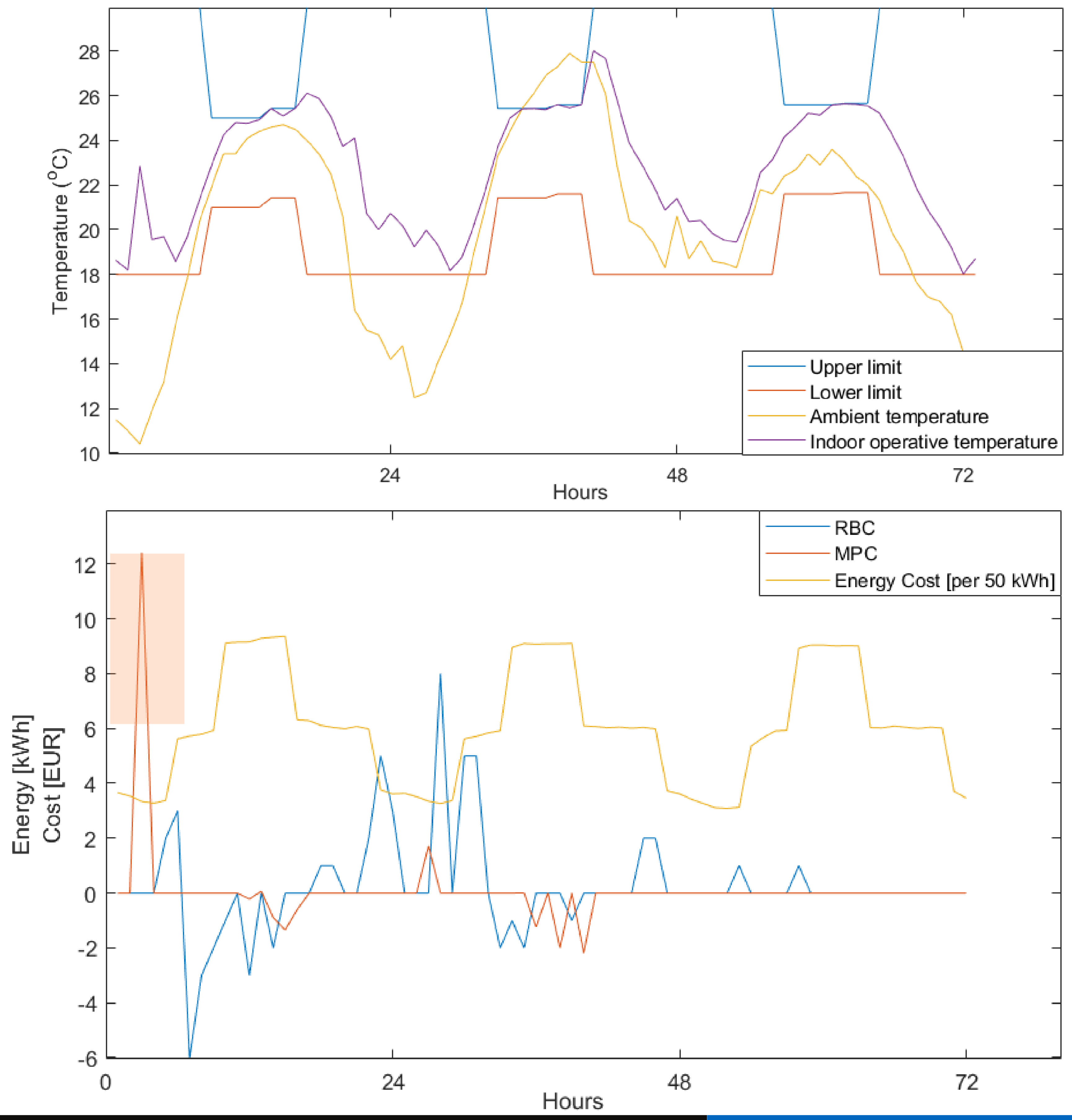




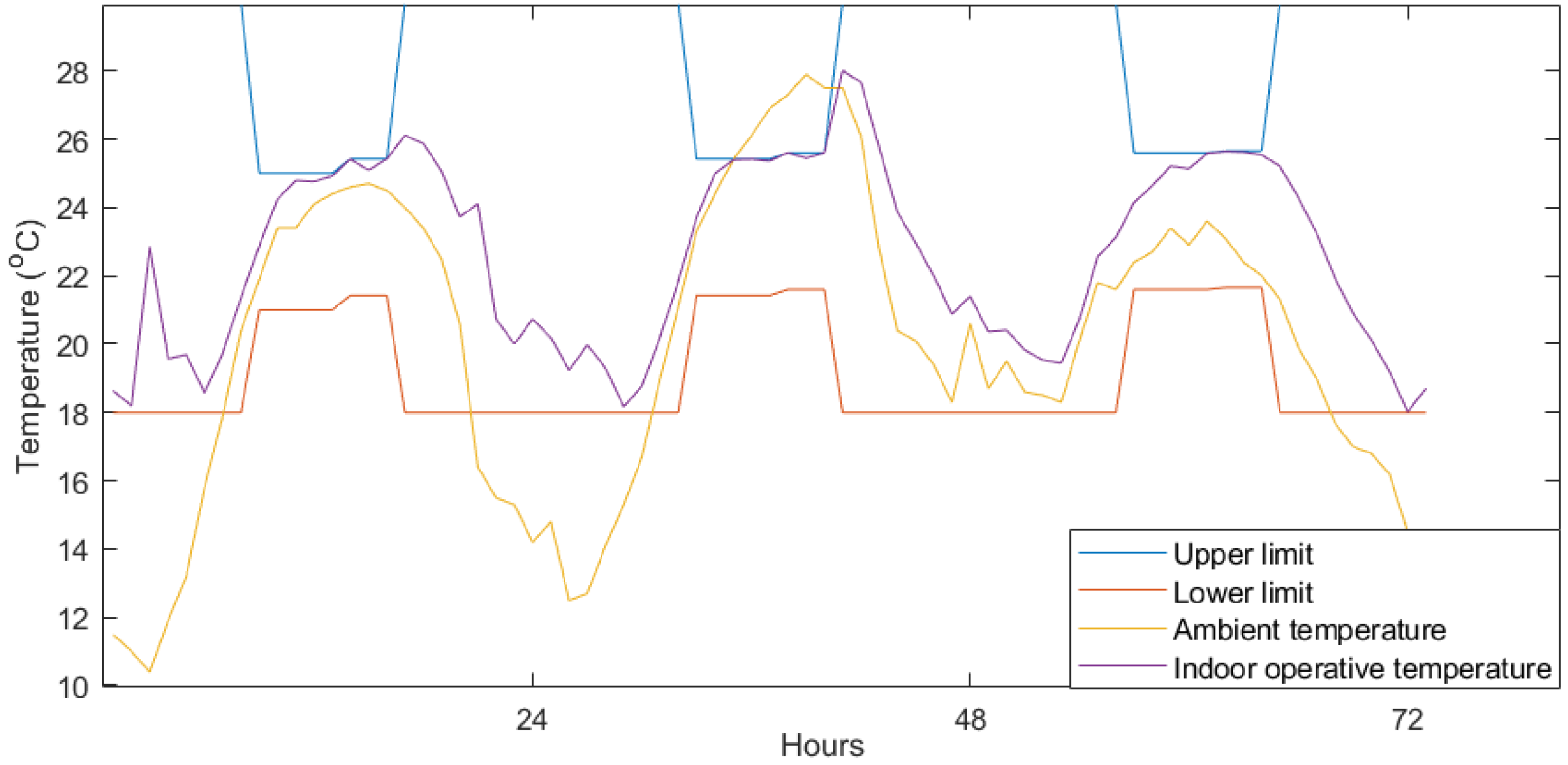


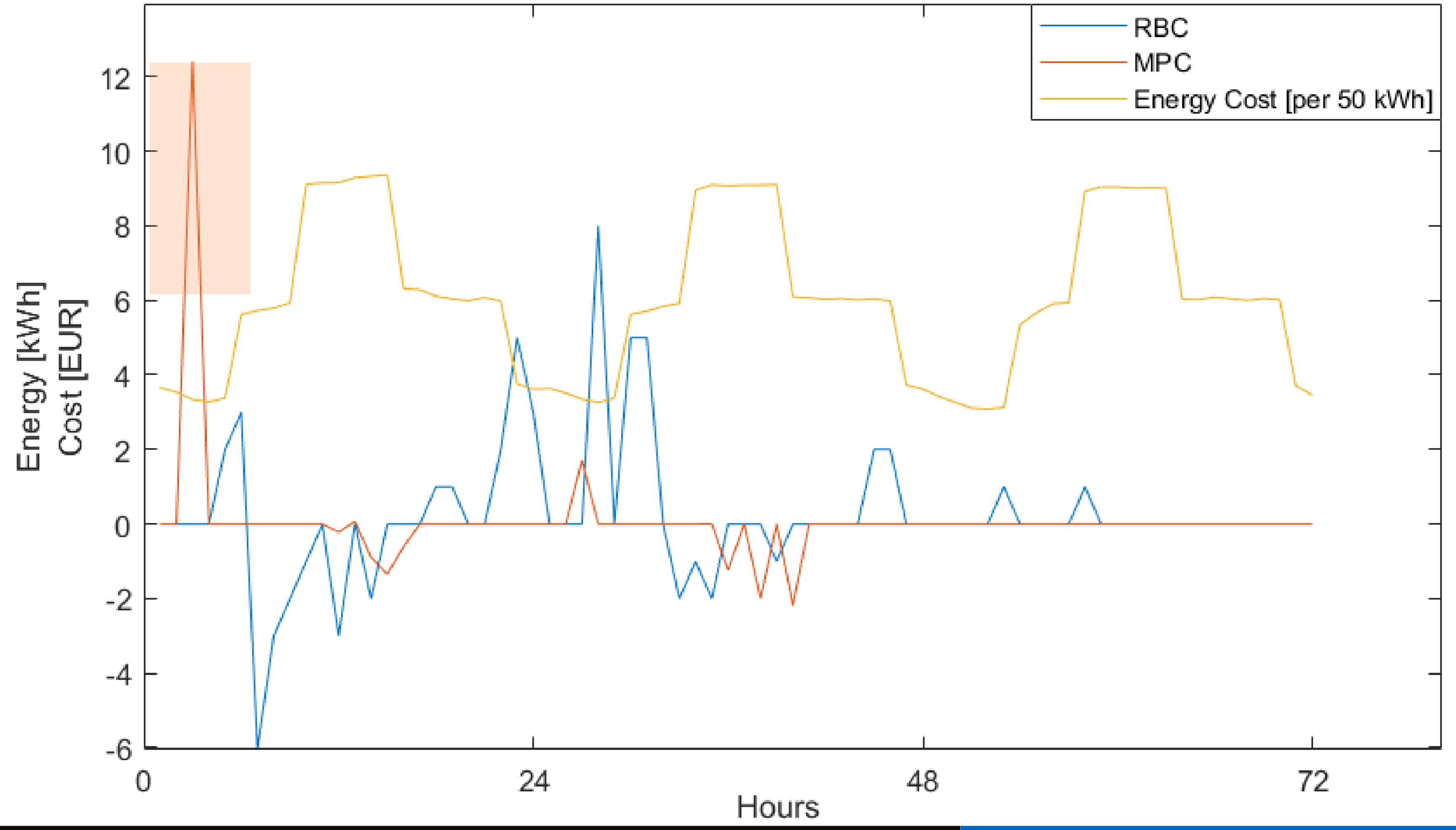
Assessment Criteria	Rule-Based Controller	MPC
Energy supplied by heatpump [kWh]	216	117
Estimated cost of electricity [EUR]	27.9	12.7

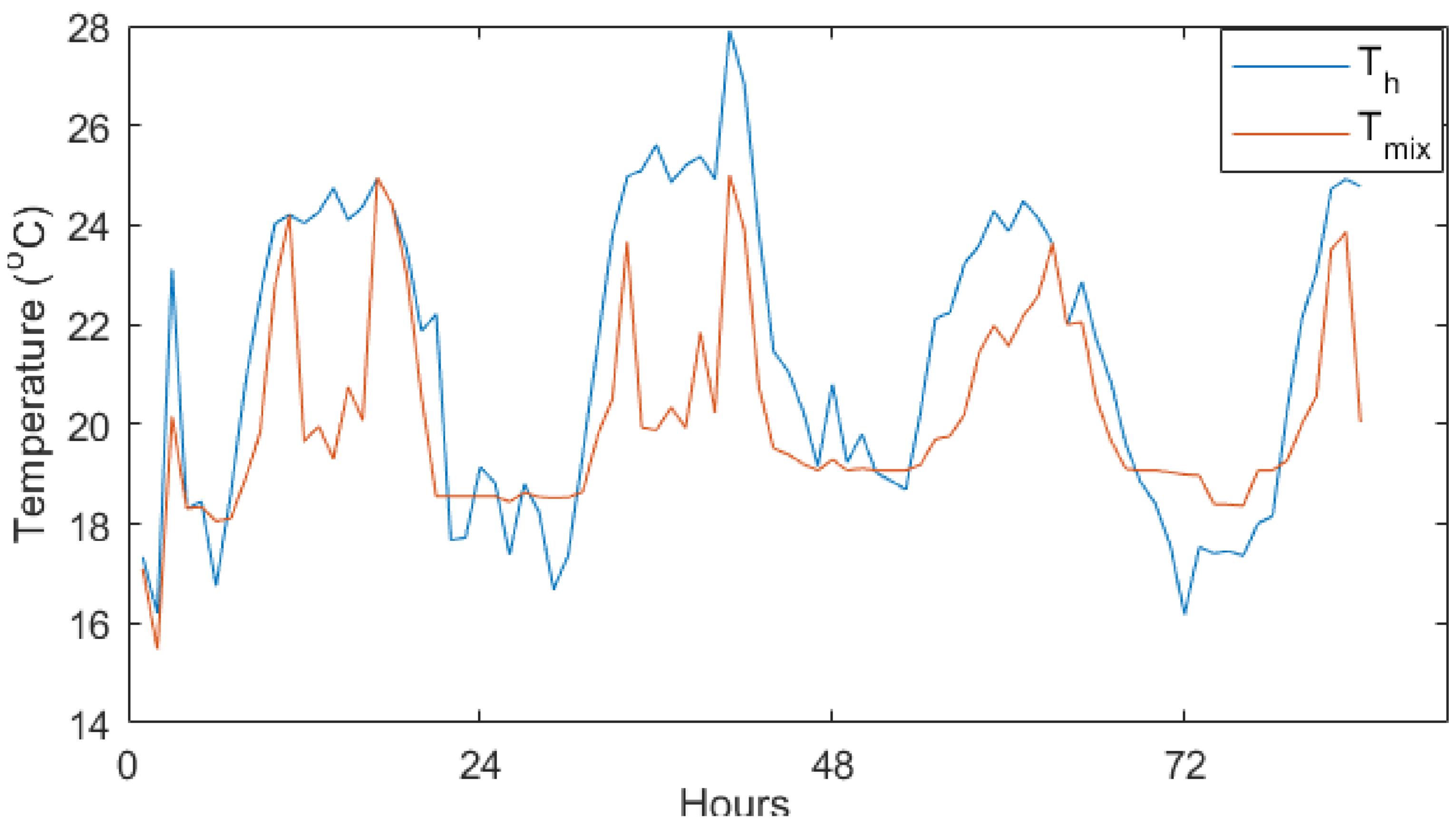
Energy flexibility potential : Representative study [Summer]



Energy flexibility potential : Representative study [Summer]



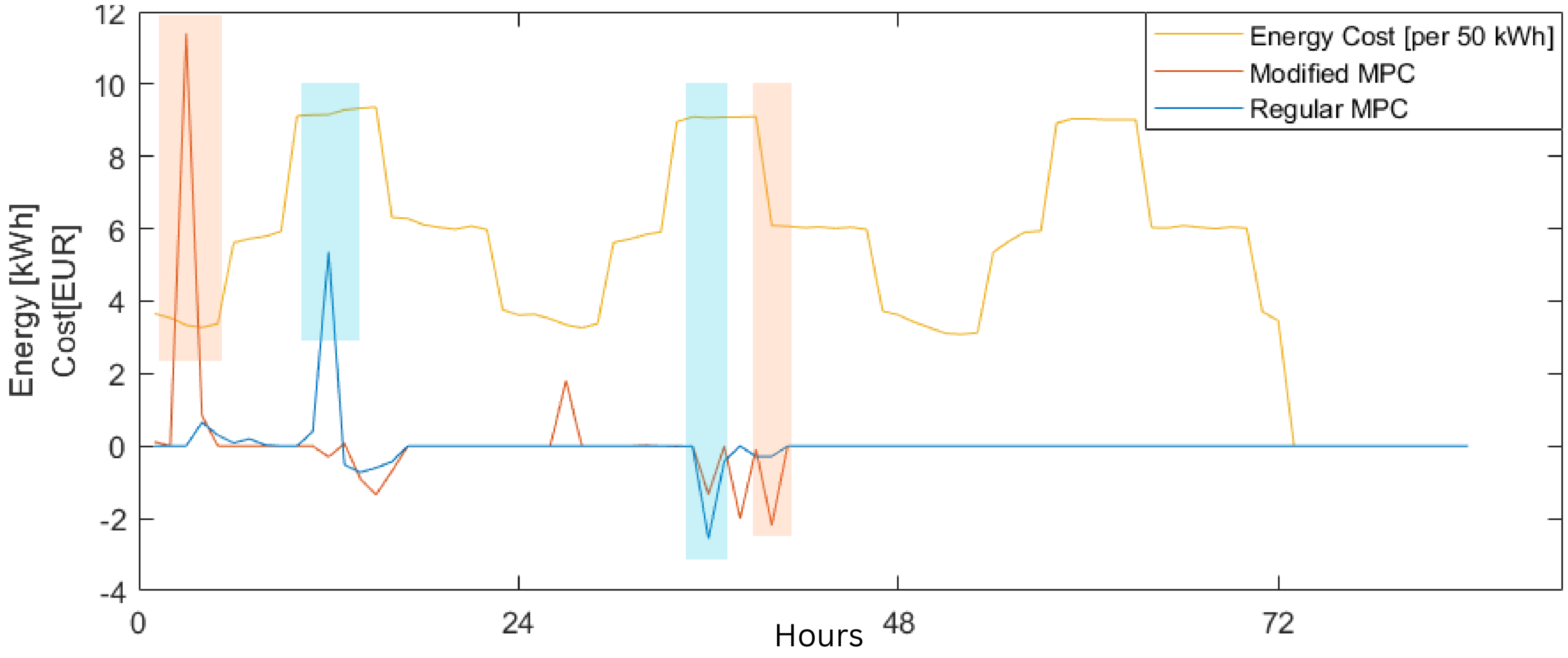




Assessment Criteria	Rule-Based Controller	MPC
Energy supplied by heatpump [kWh]	42	21.8
Estimated cost of electricity [EUR]	5.98	3.45

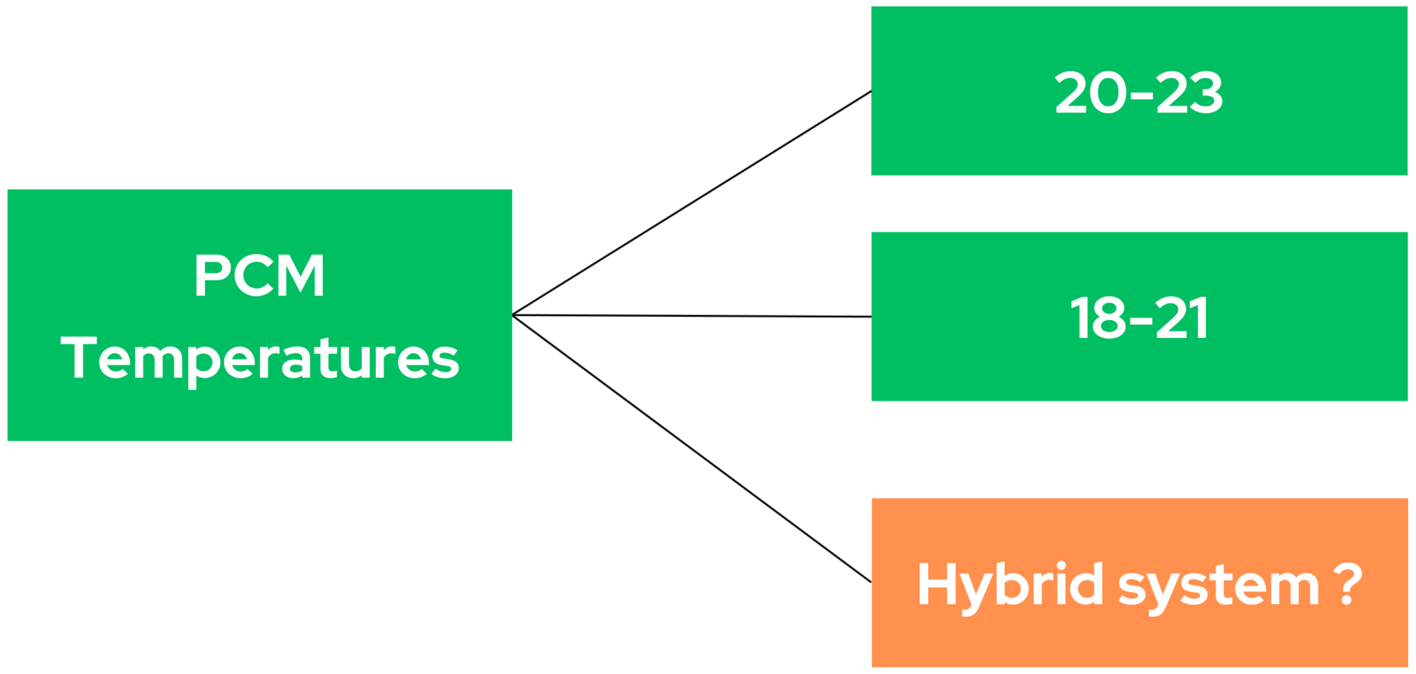
Cost vs Energy : A topic of discussion

	Minimizes Energy	Minimizes Cost
Season	Regular MPC	Modified MPC
Energy supplied by heatpump in summer [kWh]	7.2	21.8
Energy supplied by heatpump in winter [kWh]	98	117



PHASE 4: MODIFICATIONS

Optimization to PCM temperature



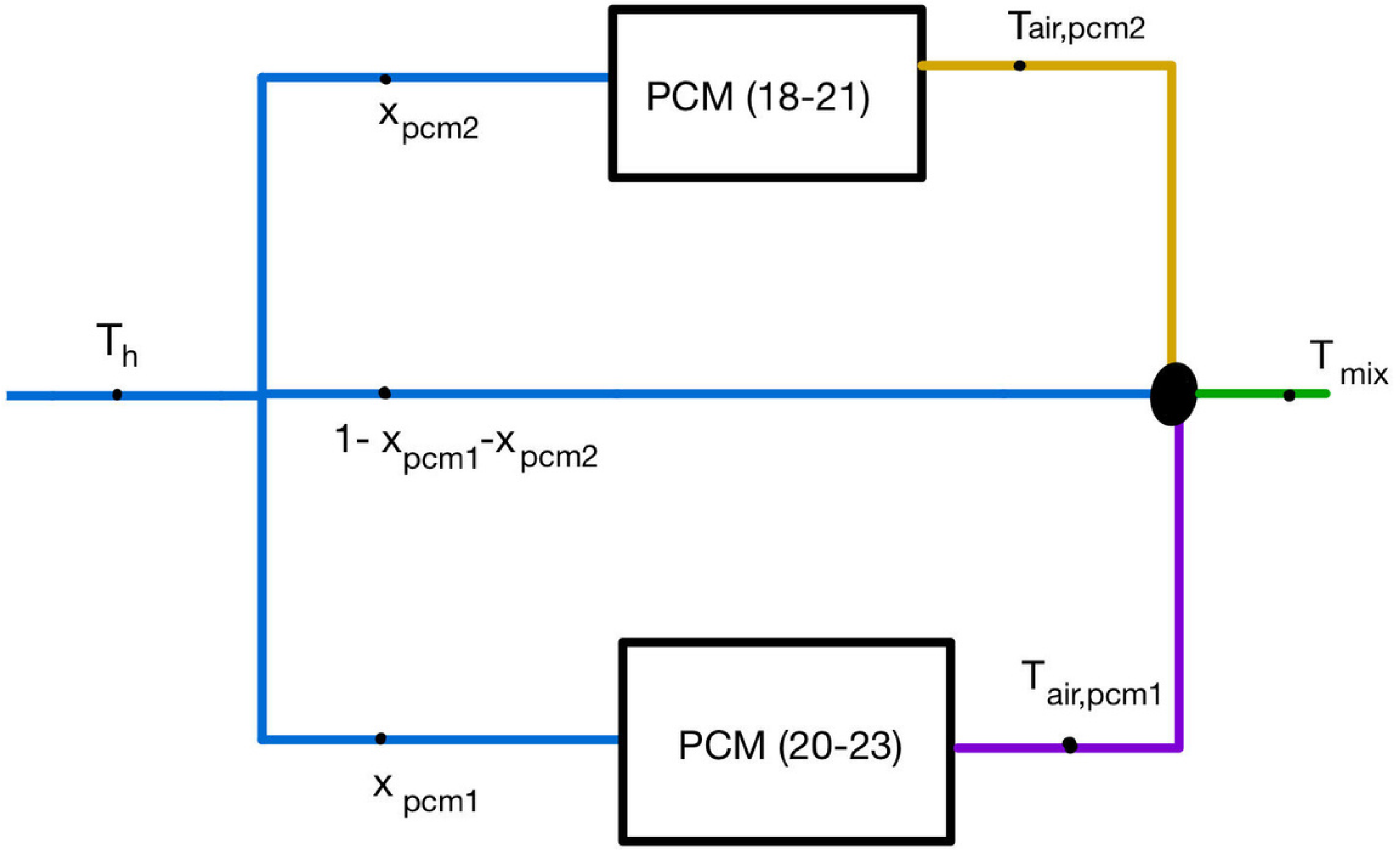
To be sufficiently representative, a period of **20 days** was studied for each season

Results

	Assessment Criteria	18-21^oC	20-23^oC
Winter	Energy supplied by Heatpump [kWh]	1140	1846
Summer	Energy supplied by Heatpump [kWh]	152	96
Autumn	Energy supplied by Heatpump [kWh]	418	364
Spring	Energy supplied by Heatpump [kWh]	878	1364

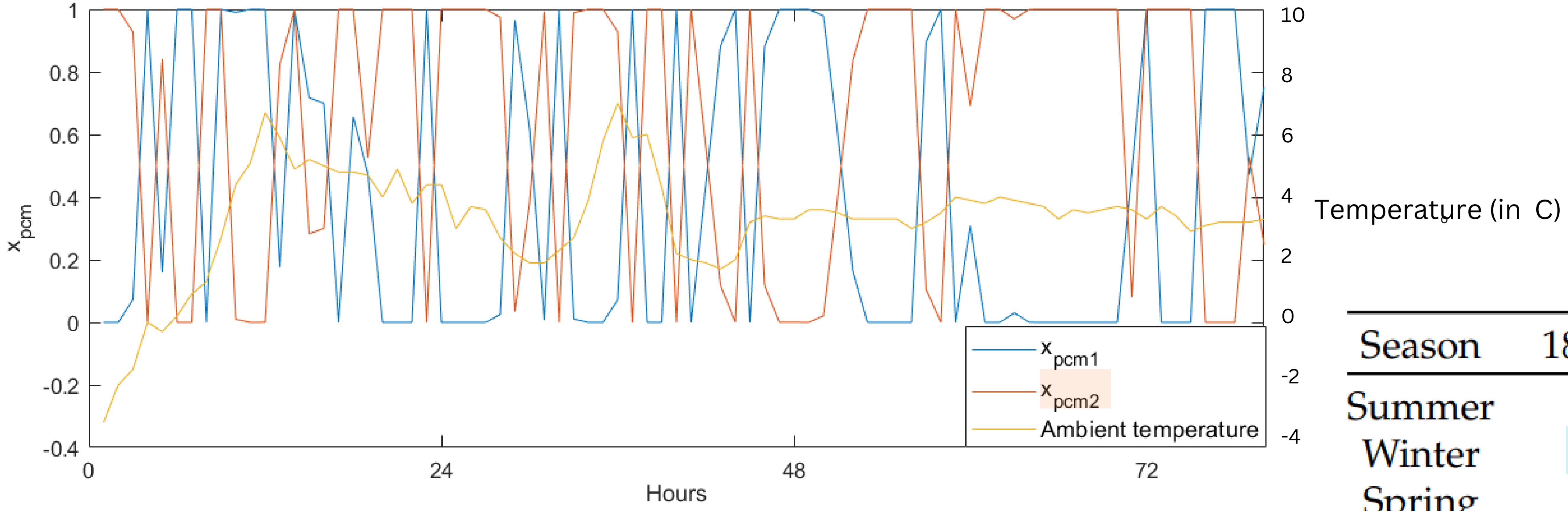
Best of both worlds?

Hybrid Configuration

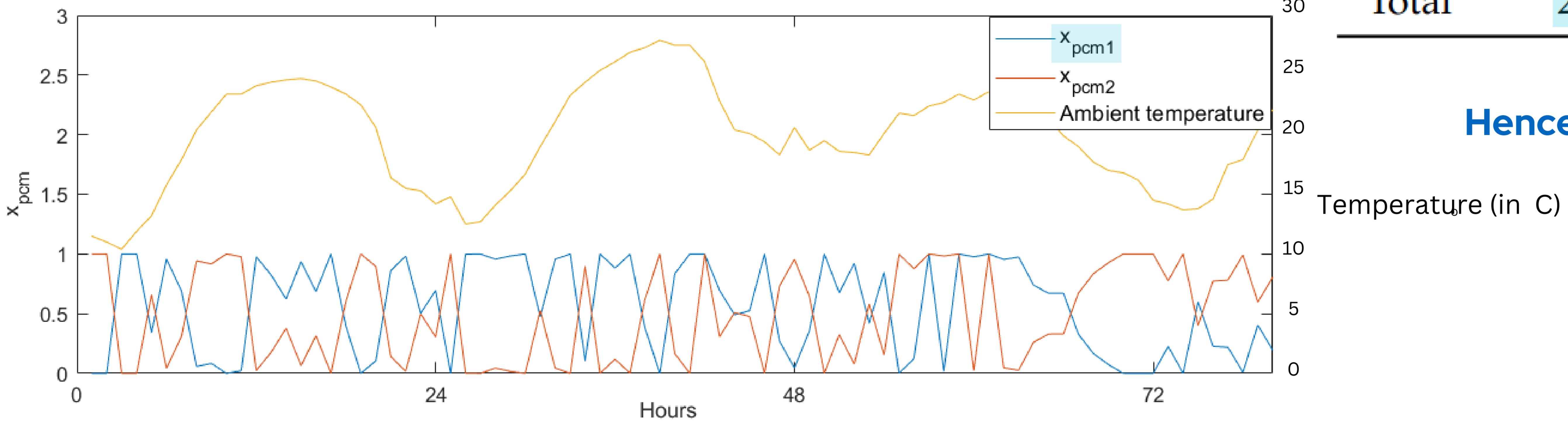


$$T_{mix} = x_{pcm1} T_{air,pcm1} + x_{pcm2} T_{air,pcm2} + (1 - x_{pcm1} - x_{pcm2}) T_h$$

Winter



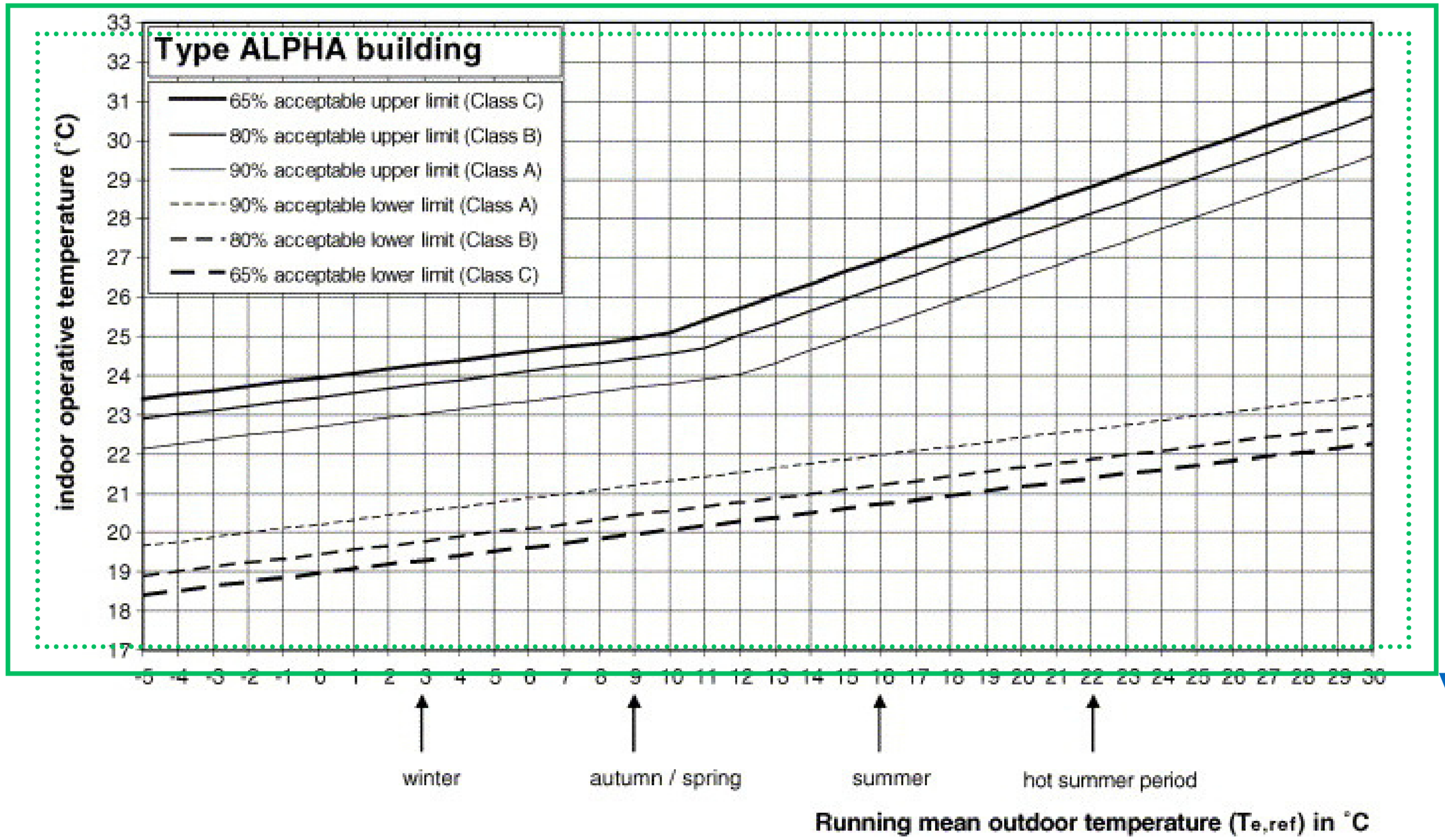
Summer



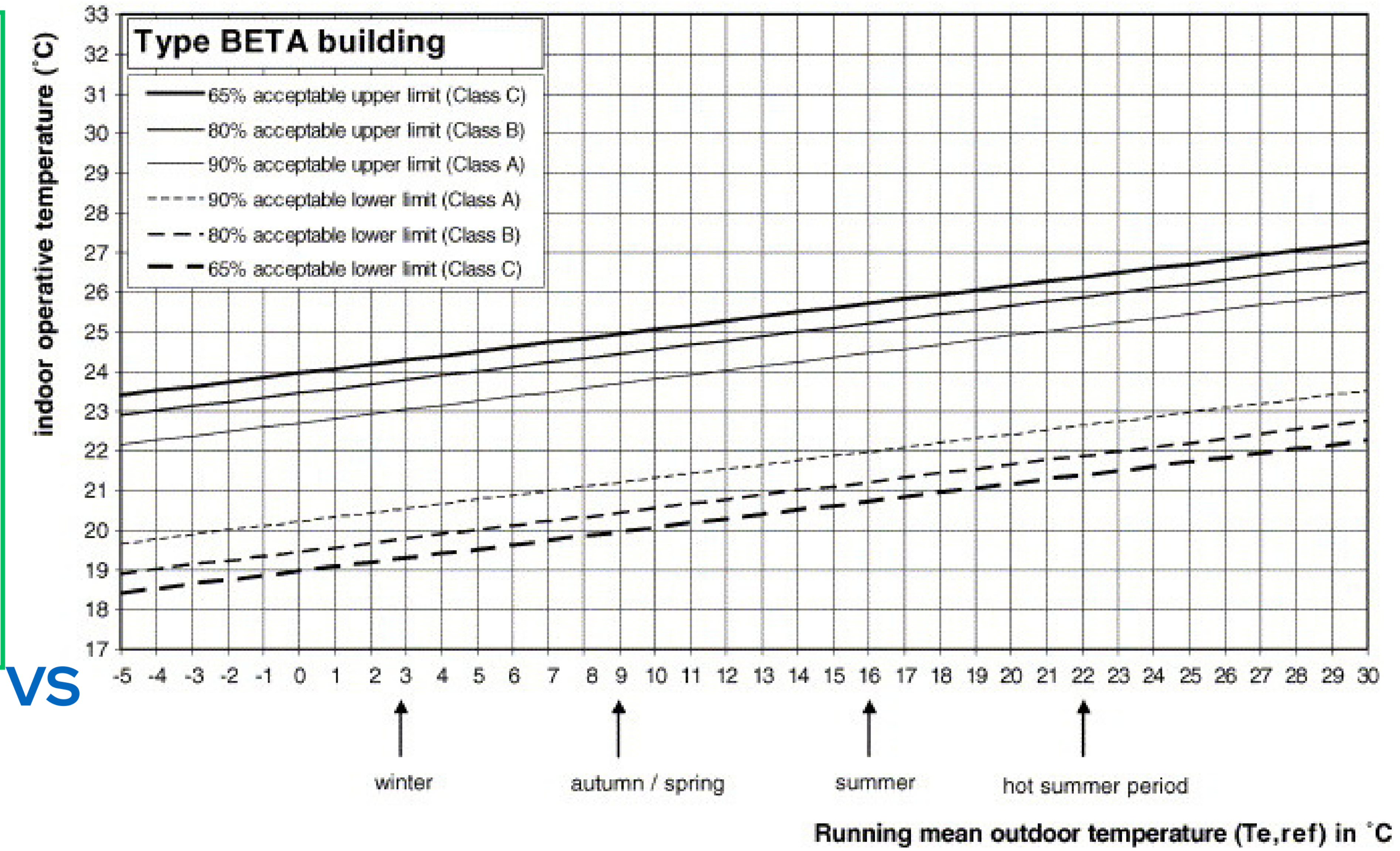
Season	18-21^{o}C	20-23^{o}C	Hybrid system
Summer	152	96	112
Winter	1140	1846	1267
Spring	878	1364	924
Autumn	418	364	378
Total	2588	3670	2681

Hence, 18-21 performs better!

Alternative thermal comfort model (Alpha)



VS

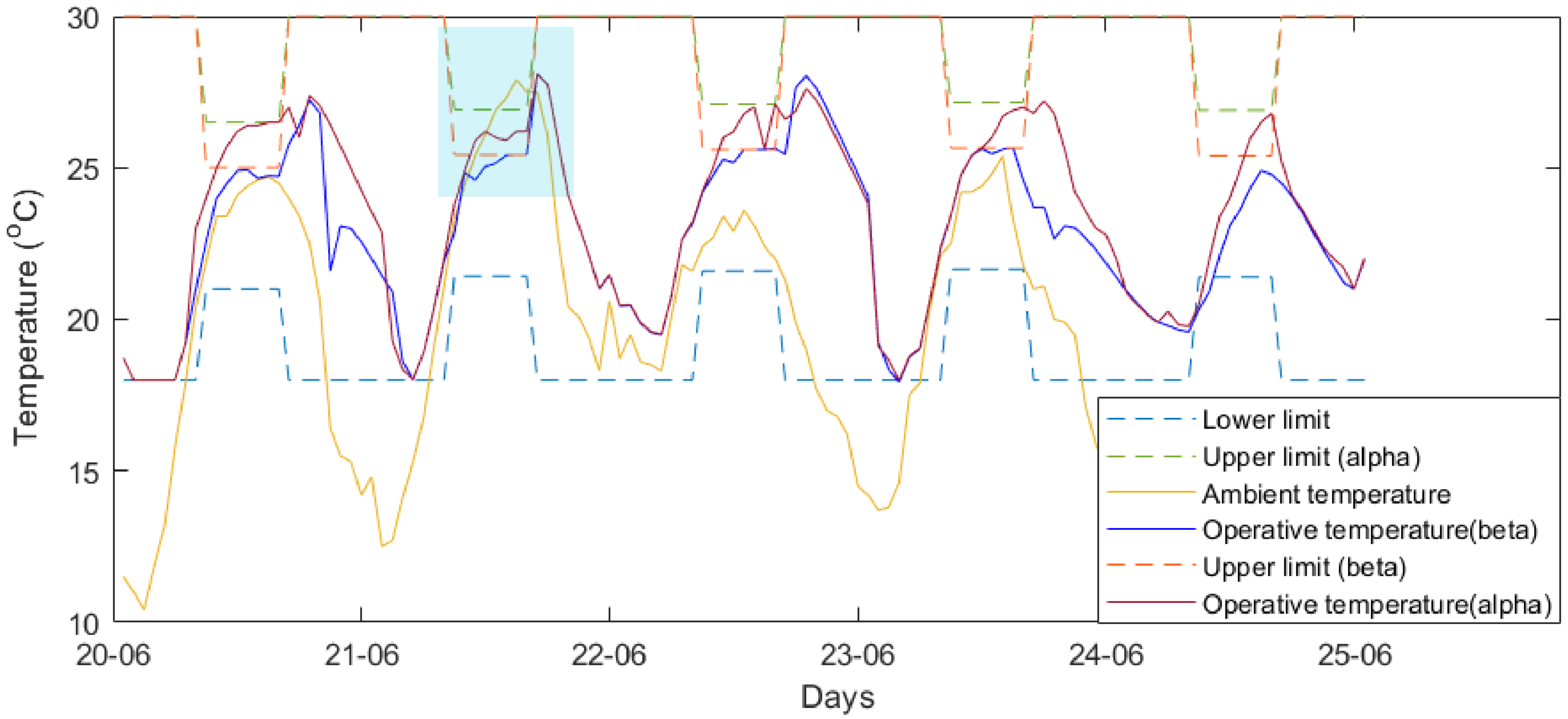


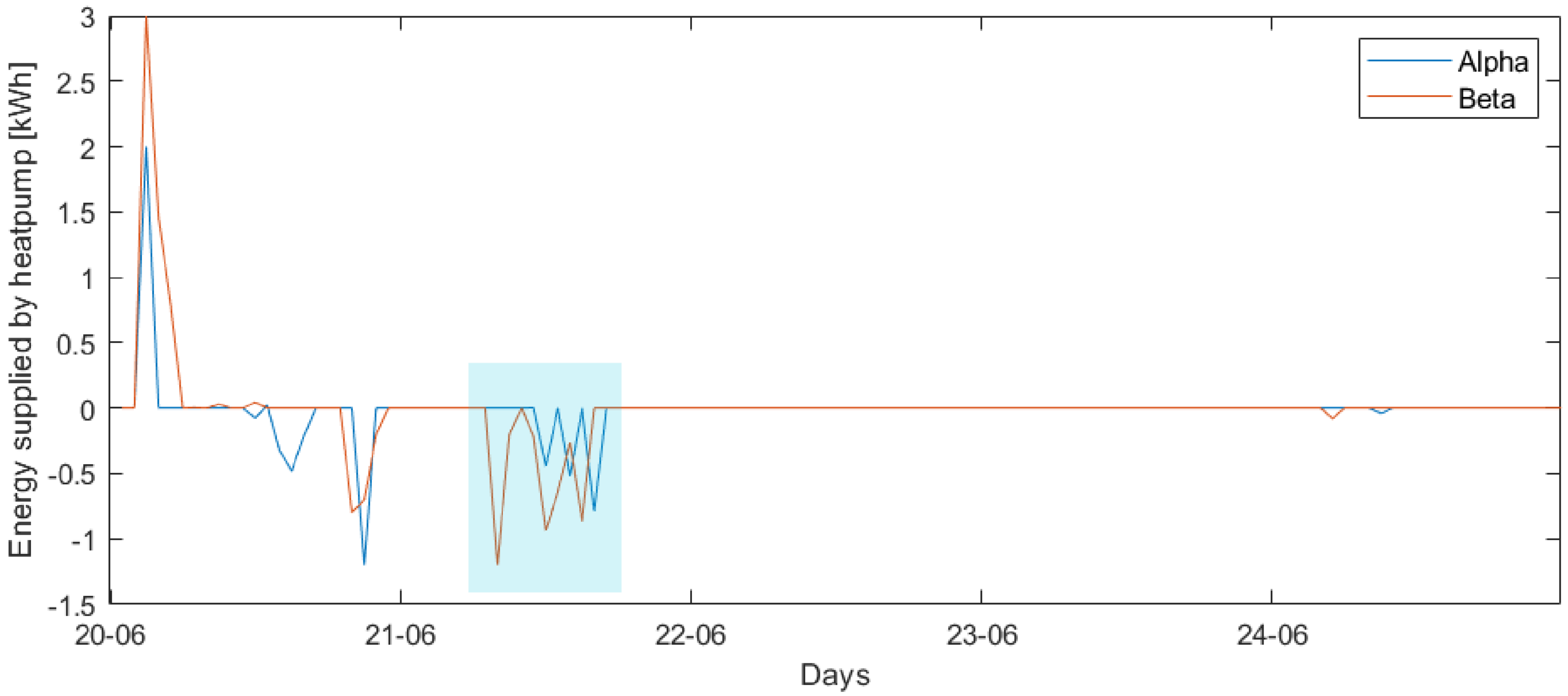
$$T_{operative} = 21.45 + 0.11 * T_{e,ref}$$

$$\begin{cases} \text{Lower limit} & T_{operative,hour} - 2^oC \\ \text{Upper limit} & T_{operative,hour} + 0.21 * (T_{e,ref} - 11) + 2^oC \end{cases}$$

Results of Alternative thermal comfort model

Would make the biggest difference in Summer : 2O June 2021 to 25 June 2021





Assessment Criteria	Beta	Alpha
Energy supplied by Heatpump [kWh]	8.5	7.2
$\sum$ error [^{o}C]	4.61	4.82

Conclusions

- MPC is able to accurately predict and control the temperature of the CCC

- MPC saves around 22.6% of the total energy supplied during the actual test period

- The energy flexibility of the building is studied in two seasons:
    - In Winter, PCM is heat loaded during the night when affordable energy is available
    - In summer, PCM is cold-loaded during the night, and sky windows are used for ventilation

- A lower PCM temperature performs better

- Flexible temperature limits can be particularly advantageous during summer

Roof and Ceiling

$$\Delta T_r = (\dot{Q}_{sol} - \dot{Q}_{cond} - \dot{Q}_{rad} - \dot{Q}_{conv})\frac{\Delta t}{\rho V c_p}$$

$$\dot{Q}_{sol} = I_o A_r \alpha_r$$

$$\dot{Q}_{cond} = \frac{\kappa_{ins}.A(T_r - T_c)}{d}$$

$$\dot{Q}_{rad} = \epsilon\sigma A({T_r}^4 - {T_{sky}}^4)$$

$$\dot{Q}_{conv} = \bar{h}_{r,a}.A(T_r - T_a)$$

$$\bar{h}_{r,a} = \frac{Nu.\lambda_{air}}{l}$$

$$l = \frac{A}{2X + 2Y}$$

$$Nu = \begin{cases} 0.664Re^{0.33}Pr^{0.33} & \text{Re} < 5000 \\ 0.037Re^{0.62}Pr^{0.333} & 5000 < \text{Re} < 100000 \\ 0.026Re^{0.8}Pr^{0.333} & \text{Re} > 100000 \end{cases}$$

$$\Delta T_c = (-\dot{Q}_{cond} - \dot{Q}_{conv})\frac{\Delta t}{\rho V c_p}$$

$$\dot{Q}_{cond} = \kappa.A(T_c - T_r)$$

$$\dot{Q}_{conv} = \bar{h}_{c,z}.A(T_c - T_z)$$

$$\bar{h}_{c,z} = \frac{\vec{Nu}\lambda_{air}}{l}$$

$$l = \frac{A}{2X + 2Y}$$

$$\vec{Nu} = \begin{cases} 0.54Ra^{0.25} & \text{T}_c < \text{T}_z \text{ and Ra} \leq 10^7 \\ 0.15Ra^{0.33} & \text{T}_c < \text{T}_z \text{ and Ra} > 10^7 \\ 0.27Ra^{0.25} & \text{T}_c > \text{T}_z \end{cases}$$

Four triple-glazed walls

$$\Delta T_{i,j} = (\dot{Q}_{sol} - \dot{Q}_{rad} - \dot{Q}_{conv})\frac{\Delta t}{\rho V c_p}$$

$$\dot{Q}_{sol} = \begin{cases} (I_{o,b}\alpha_o + (I_{o,r}I_{o,d})\alpha)A & \text{j=1} \\ (I_{o,b}\xi_o\alpha_o + (I_{o,r}I_{o,d})\xi\alpha)A & \text{j=2} \\ (I_{o,b}\xi_o^2\alpha_o + (I_{o,r}I_{o,d})\xi^2\alpha)A & \text{j=3} \end{cases}$$

$$\dot{Q}_{conv} = \begin{cases} A(\bar{h}_{1,a}(T_{i,1} - T_a) + \bar{h}_{1,2}(T_{i,1} - T_{i,2})) & \text{j=1} \\ A(\bar{h}_{2,1}(T_{i,2} - T_{i,1}) + \bar{h}_{2,3}(T_{i,2} - T_{i,3})) & \text{j=2} \\ A(\bar{h}_{3,2}(T_{i,3} - T_{i,2}) + \bar{h}_{3,z}(T_{i,3} - T_z)) & \text{j=3} \end{cases}$$

$$\dot{Q}_{rad} = \begin{cases} \sigma A(\epsilon(T_{i,1}^4 - T_{sky}^4) + \mathcal{F}(T_{i,1}^4 - T_{i,2}^4)) & \text{j=1} \\ \sigma A\mathcal{F}(2T_{i,2}^4 - T_{i,1}^4 - T_{i,3}^4) & \text{j=2} \\ \sigma A\mathcal{F}(T_{i,3}^4 - T_{i,2}^4) & \text{j=3} \end{cases}$$

$$\bar{h}_{j,k} = \begin{cases} \frac{Nu_j.\lambda_{air}}{Y} & \text{if k=a,z and j} \neq \text{k} \\ \frac{Nu_k.\lambda_{Argon}}{Y} & \text{if k=1,2,3 and j} \neq \text{k} \end{cases}$$

$$\mathcal{F} = \frac{1}{\frac{1}{\epsilon} + \frac{1}{\epsilon_{low}} - 1}$$

Chilton-Colburn for k=a $\quad Nu_k = 0.664Re^{0.5}Pr^{0.333}$

McGregor for k=1,2,3: $\quad Nu_k = 0.42Pr^{0.012}Ra^{0.25}(\frac{Y}{D})^{-0.3}$

Churchill Chu for k=z: $\quad Nu_k = \begin{cases} 0.68 + (\frac{0.67Ra^{0.25}}{1+(\frac{0.492}{Pr})^{0.5625}})^{0.4444} & \text{Ra} < 10^9 \\ 0.825 + (\frac{0.387Ra^{0.167}}{1+(\frac{0.492}{Pr})^{0.5625}})^{0.5926} & \text{Ra} \geq 10^9 \end{cases}$

Raised and basement floor

$$\Delta T_{rf} = (\dot{Q}_{sol} - \dot{Q}_{conv})\frac{\Delta t}{\rho V c_p}$$

$$\dot{Q}_{sol} = x_h I_o A_{floor}\xi_0^3\alpha$$

$$\dot{Q}_{conv} = \bar{h}_{rf,z}.A(T_rf - T_z) + \bar{h}_{rf,deck}.A(T_{rf} - T_{deck})$$

$$\bar{h}_{rf,z} = \frac{Nu_{rf,z}.\lambda_{air}}{l} \qquad \bar{h}_{rf,deck} = \frac{Nu_{rf,deck}.\lambda_{air}}{l}$$

$$\Delta T_{bf} = (-\dot{Q}_{conv} - \dot{Q}_{cond})\frac{\Delta t}{\rho V c_p}$$

$$\dot{Q}_{cond} = \frac{\kappa A(T_{bf} - T_g)}{d}$$

$$\dot{Q}_{conv} = \bar{h}_{bf,deck}.A(T_rf - T_{deck})$$

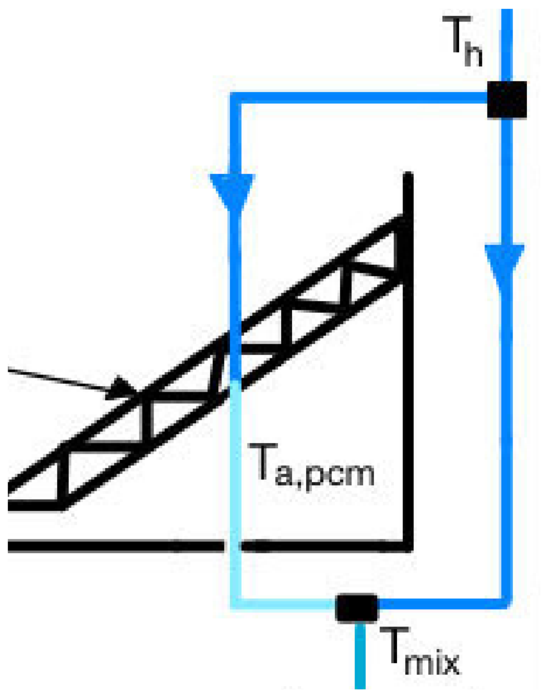
$$\bar{h}_{bf,deck} = \frac{Nu_{rf,deck}.\lambda_{air}}{l}$$

$$Nu_{rf,z} = \begin{cases} 0.54Ra^{0.25}; & \text{T}_{rf} > \text{T}_z \text{ and Ra} \geq 10^7 \\ 0.15Ra^{0.333} & \text{T}_{rf} > \text{T}_z \text{ and Ra} > 10^7 \\ 0.27Ra^{0.25} & \text{T}_{rf} < \text{T}_z \end{cases}$$

$$Nu_{rf,deck} = \begin{cases} 0.54Ra^{0.25} & \text{T}_{rf} < \text{T}_{deck} \text{ and Ra} \geq 10^7 \\ 0.15Ra^{0.333} & \text{T}_{rf} < \text{T}_{deck} \text{ and Ra} > 10^7 \\ 0.27Ra^{0.25} & \text{T}_{rf} > \text{T}_{deck} \end{cases}$$

$$Nu_{bf,deck} = \begin{cases} 0.54Ra^{0.25} & \text{T}_{bf} < \text{T}_{deck} \text{ and Ra} \geq 10^7 \\ 0.15Ra^{0.333} & \text{T}_{bf} < \text{T}_{deck} \text{ and Ra} > 10^7 \\ 0.27Ra^{0.25} & \text{T}_{bf} > \text{T}_{deck} \end{cases}$$

Modelling of PCM battery



$$\bar{Q}_{pcm} = \bar{h}_{pcm} A_{pcm} (T_{air,pcm} - T_{pcm})$$

$$\bar{h}_{pcm} = Nu \frac{\lambda_{air}}{L_{pcm}} = 16.8 W/(m^2.K)$$

Scheil-Gulliver equation $f = 1 - (\frac{\Delta T}{\Delta T_m})^{(1/n)}$

Delta T is calculated from 23

For a PCM between 20-23,

@20, f=0 (solid)

@ 21 , f=0.33

@22, f= 0.66

@23, f=1 (liquid)

$$y_{pcm} = 1 - min(1, max(0, \frac{23 - T_{pcm}}{3}))$$

$$\bar{h}_{pcm} A_{pcm} (T_{air,pcm} - T_{pcm}) = (1 - y_{pcm}) m_{pcm} c_{p,solid} \frac{dT_{pcm}}{dt} + m_{pcm} H_{pcm} \frac{dy_{pcm}}{dt} + y_{pcm} m_{pcm} c_{p,liquid} \frac{dT_{pcm}}{dt}$$

$$\bar{h}_{pcm} A_{pcm} (T_{air,pcm} - T_{pcm}) = x_{pcm} \dot{m} c_p (T_h - T_{air,pcm})$$

$$x_{pcm} T_{air,pcm} + (1 - x_{pcm}) T_h = T_{mix}$$

Inner zone

$$\Delta T_z = (\dot{Q}_{hp} + \dot{Q}_{gen} - \dot{Q}_{adv} - \dot{Q}_{vent} - \dot{Q}_{conv})\frac{\Delta t}{\rho V c_p}$$

$$\dot{Q}_{int} = 100 * N_{people}$$

$$\dot{Q}_{adv} = \dot{m} c_p (T_z - T_{deck})$$

$$\dot{Q}_{vent} = x_{sw}\left(0.65 \rho_{air} A_{sw} * 9.81 * H * \left| \frac{T_z - T_{ambient}}{T_{ambient}} x \right| \right)^{0.5} c_{p\ air}(T_z - T_{ambient})$$

$$\dot{Q}_{conv} = \bar{h}_{z,i}.A(T_z - T_i) \qquad i \in (rf, r, n, e, s, w)$$

$$\bar{h}_{z,i} = \frac{Nu_i.\lambda_{air}}{l} \quad i \in (rf, r) \qquad \frac{Nu_i.\lambda_{air}}{Y} \quad i \in (n, e, s, w)$$

$$l = \frac{A_i}{2X + 2Y} \qquad i \in (rf, r)$$

$$Nu_{z,i} = \begin{cases} \text{Chuchill and Chu eq. 4.23} & i \in (n, e, s, w) \\ \text{McAdams eq. 4.14} & i \in (c) \\ \text{McAdams eq. 4.30 and 4.31} & i \in (rf) \end{cases}$$

Heat recovery system

$$x_{rec} * 0.8(T_z - T_{amb}) = (T_h - T_{amb})$$

Heat pump

$$\dot{Q}_{hp} = \dot{m} c_p (T_{hp} - T_{mix})$$

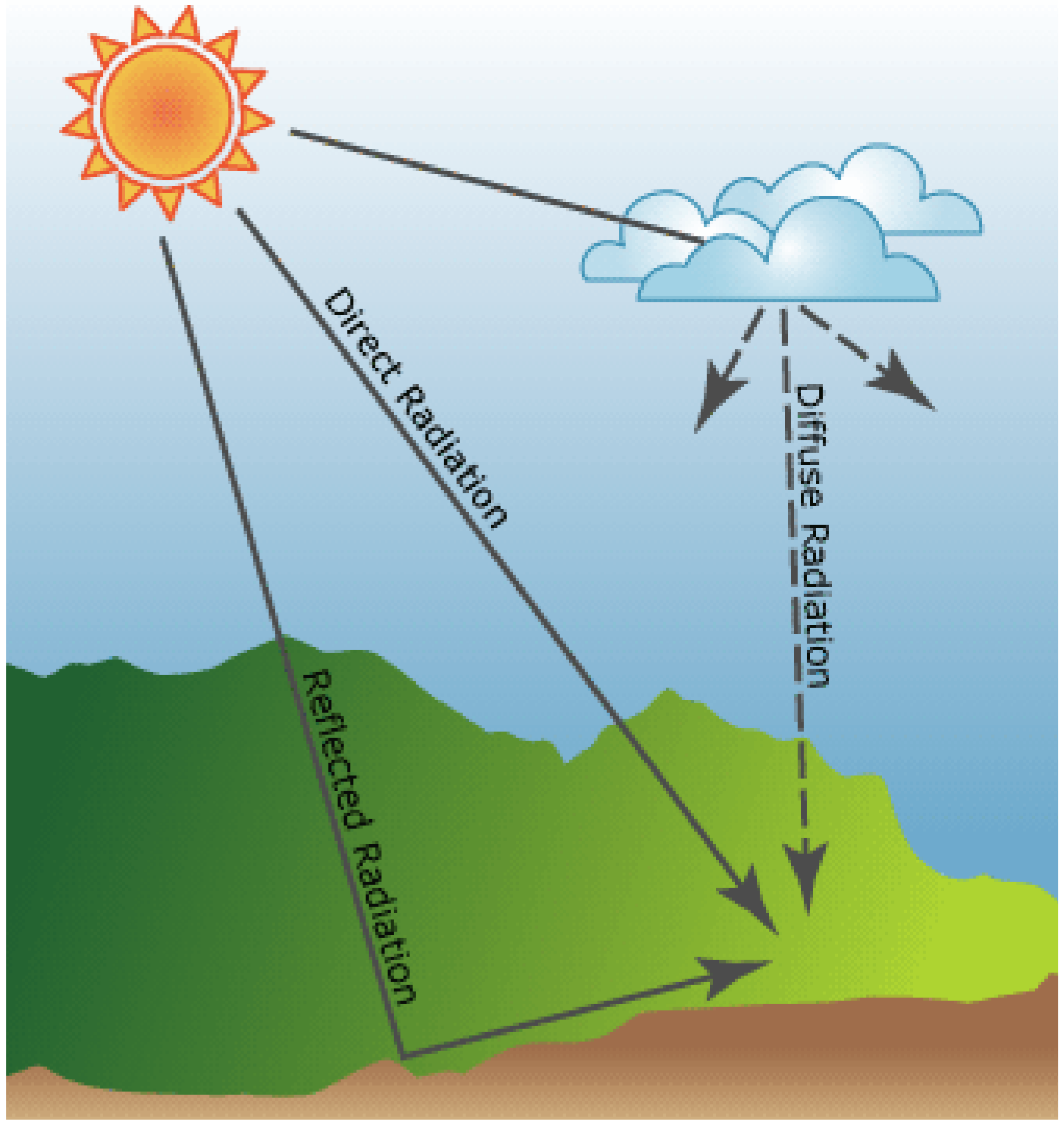
Energy flow by solar radiation

Direct beam radiation $$I_{o,b} = I_{bh}\frac{cos(\theta_n)}{cos(\theta_z)} = I_{bn}cos(\theta_n)$$

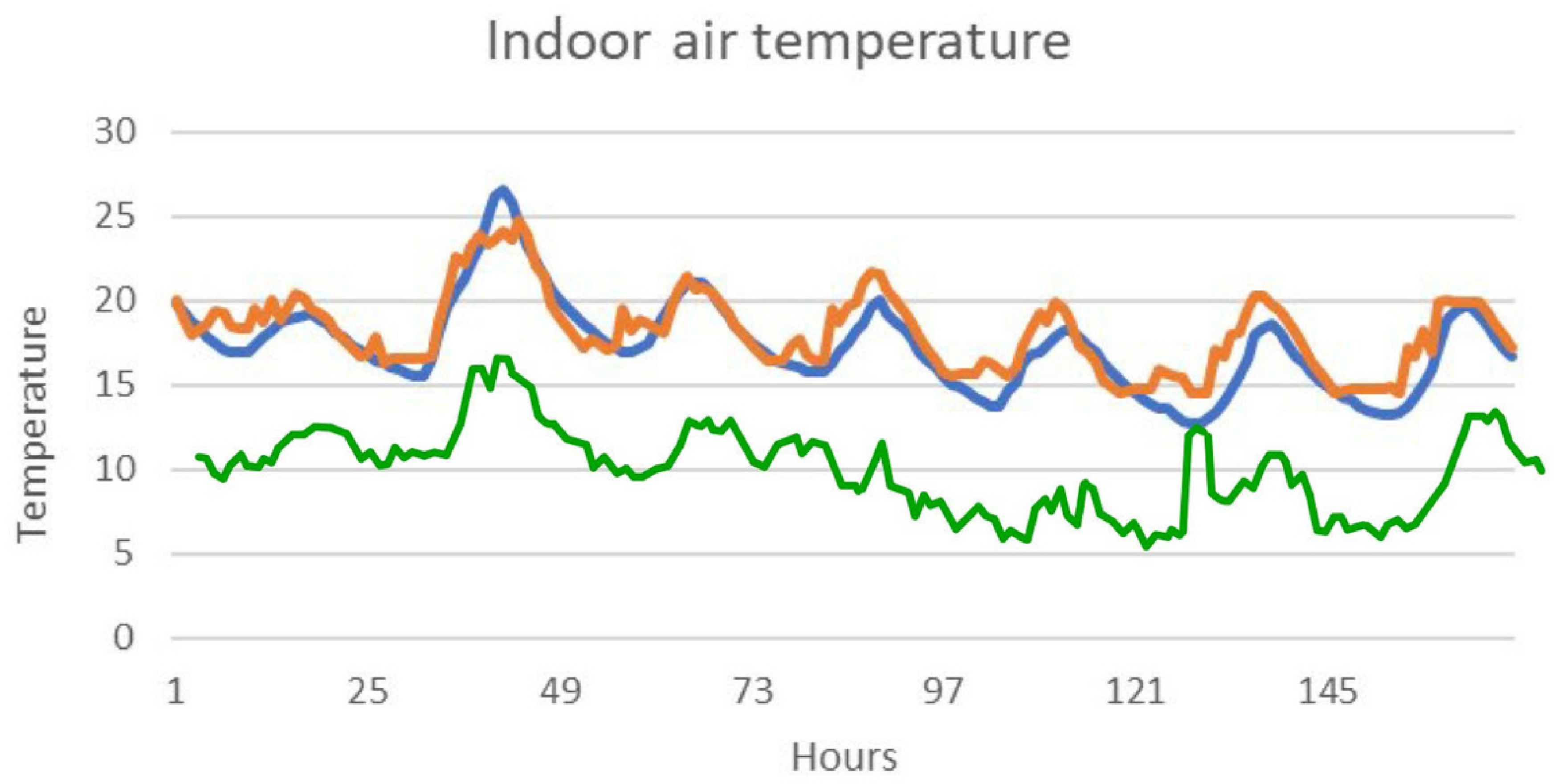
Reflected radiation $$I_{o,r} = (I_d + I_{bh})\rho_r\frac{1-cos(\beta)}{2}$$

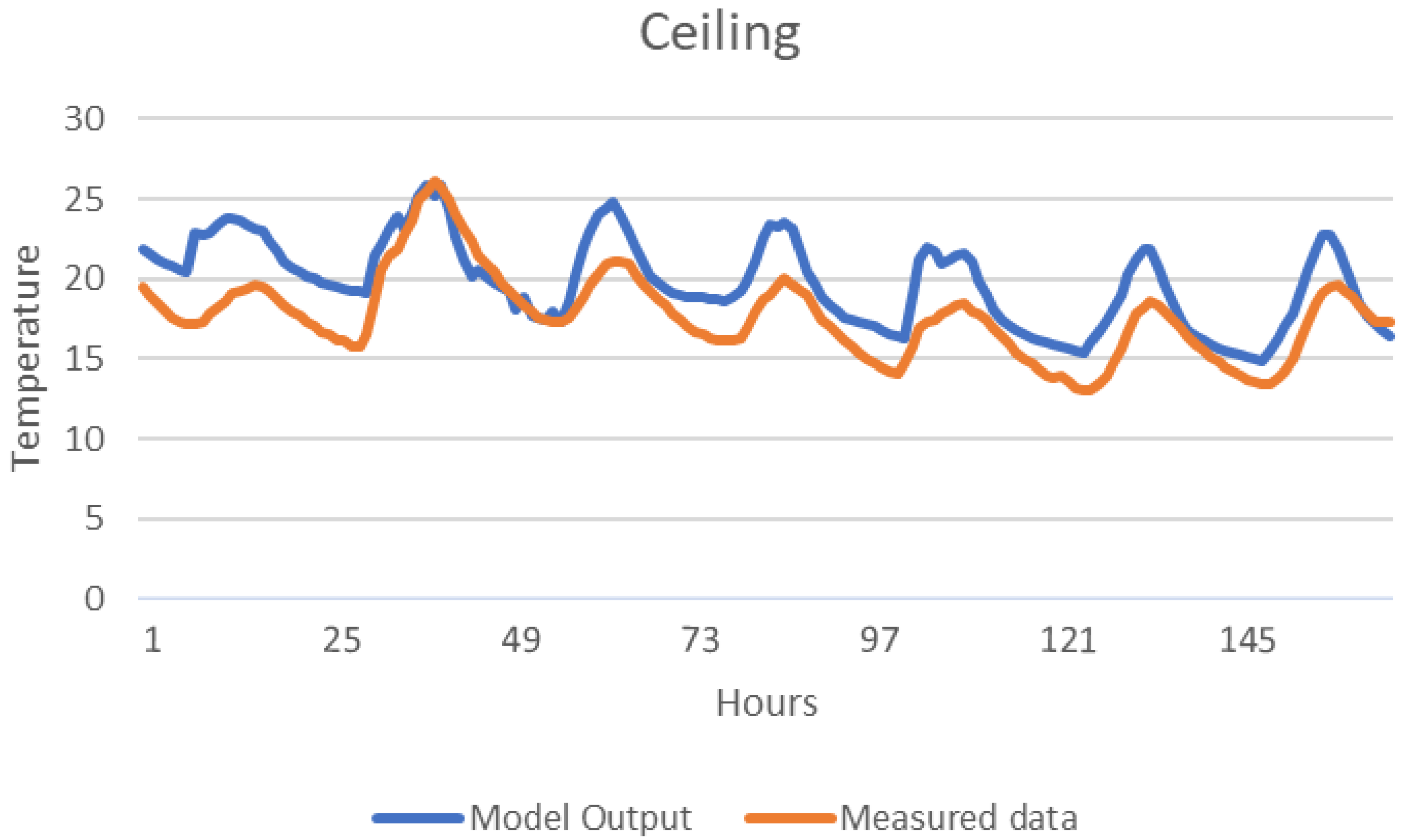
Diffused radiation $$I_{o,d} = I_{d,iso}\frac{1+cos(\beta)}{2} + I_{d,cir}\frac{cos(\theta_n)}{cos(\theta_z)} + I_{d,hor}F_{c-hor}$$

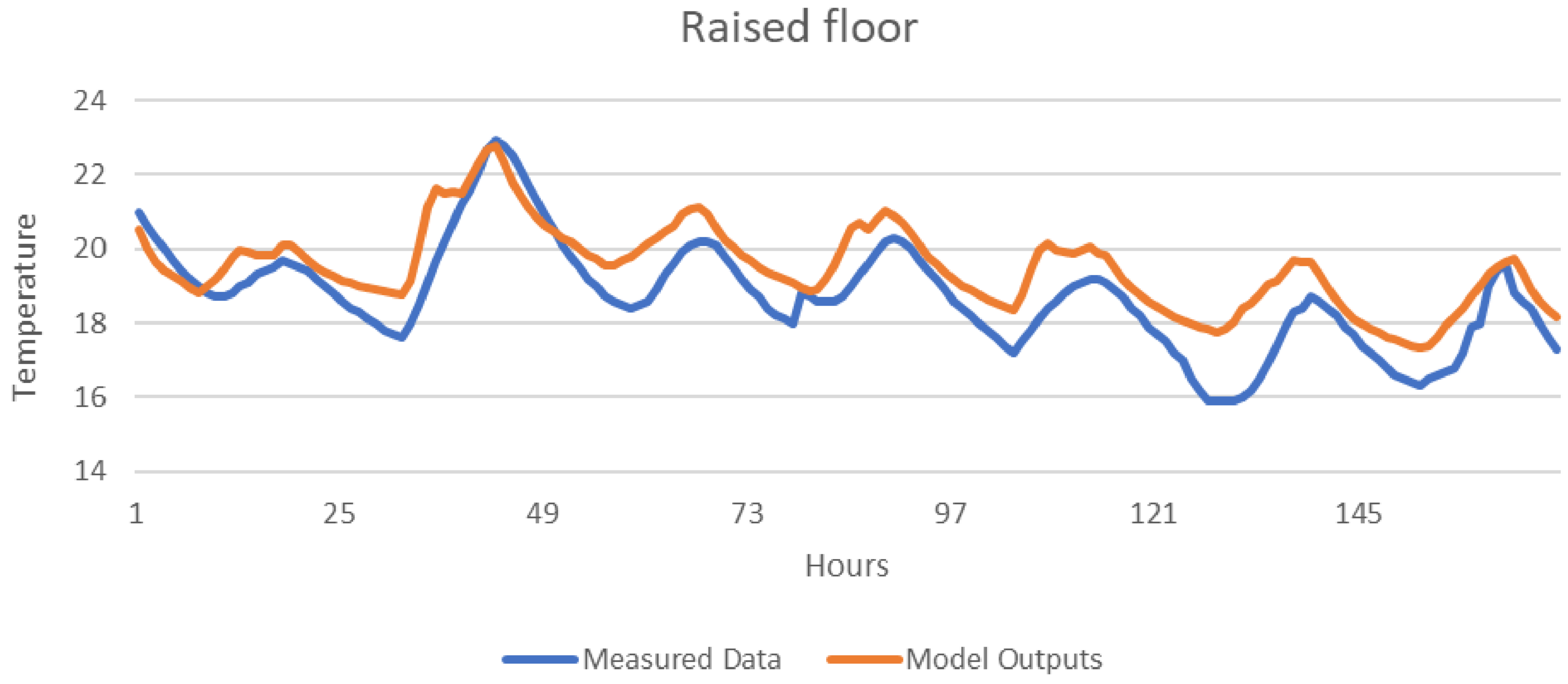
Model Name	Model Type	Complexity	Local data needed	RMSE	R^2
Liu and Jordan [30]	Isotropic	Simple	-	7	6
Koronakis [28]	Isotropic	Simple	-	6	7
Hay and Davies [23]	Anisotropic	Simple	-	5	5
Muneer [34]	Anisotropic	Moderate	-	3	4
Perez [41]	Anisotropic	Moderate	-	4	3
Perez opt.[41][15]	Anisotropic	Complex	√	2	2
MLP [15]	ANN	Complex	√	1	1

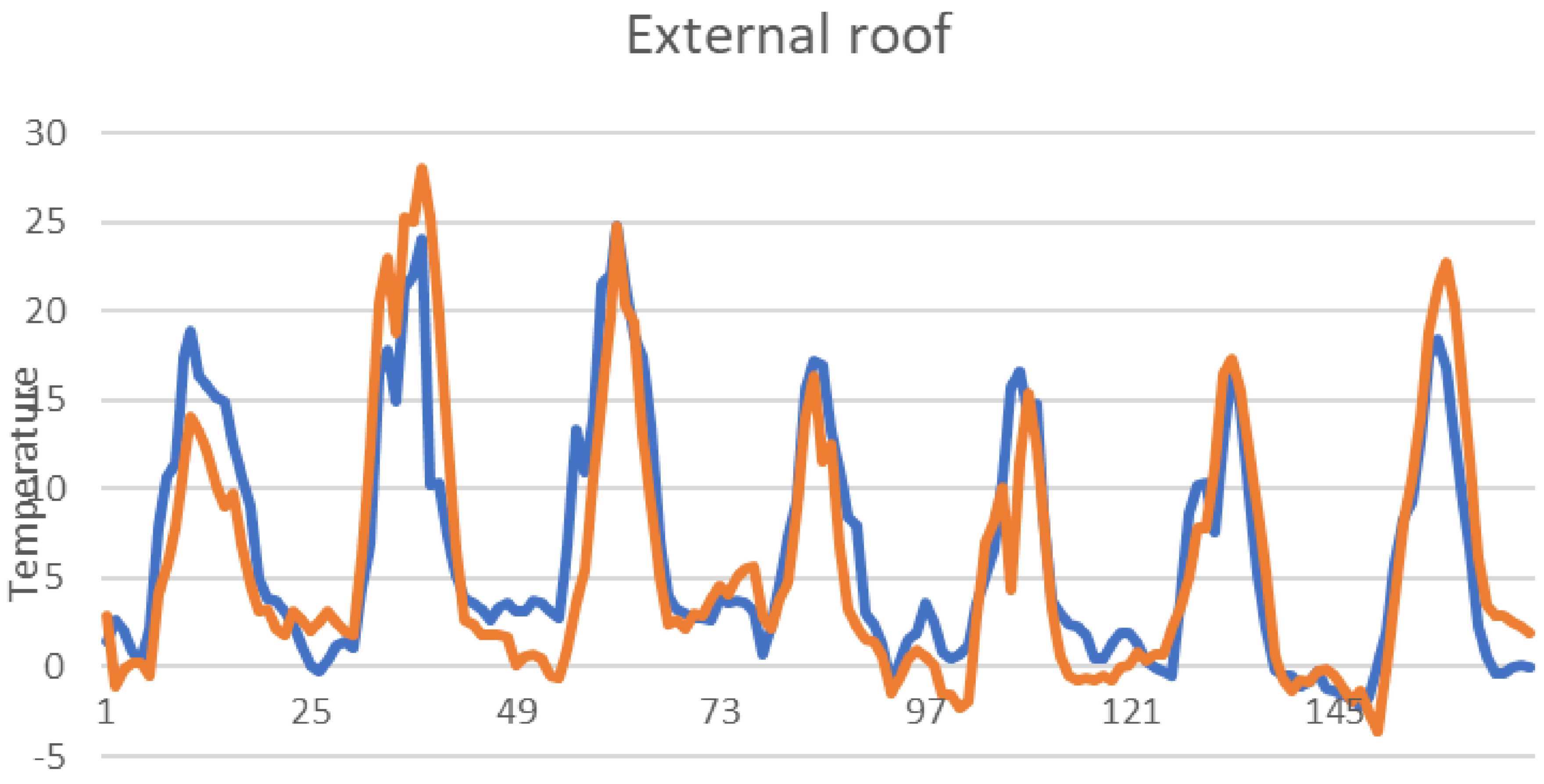


Model Validation



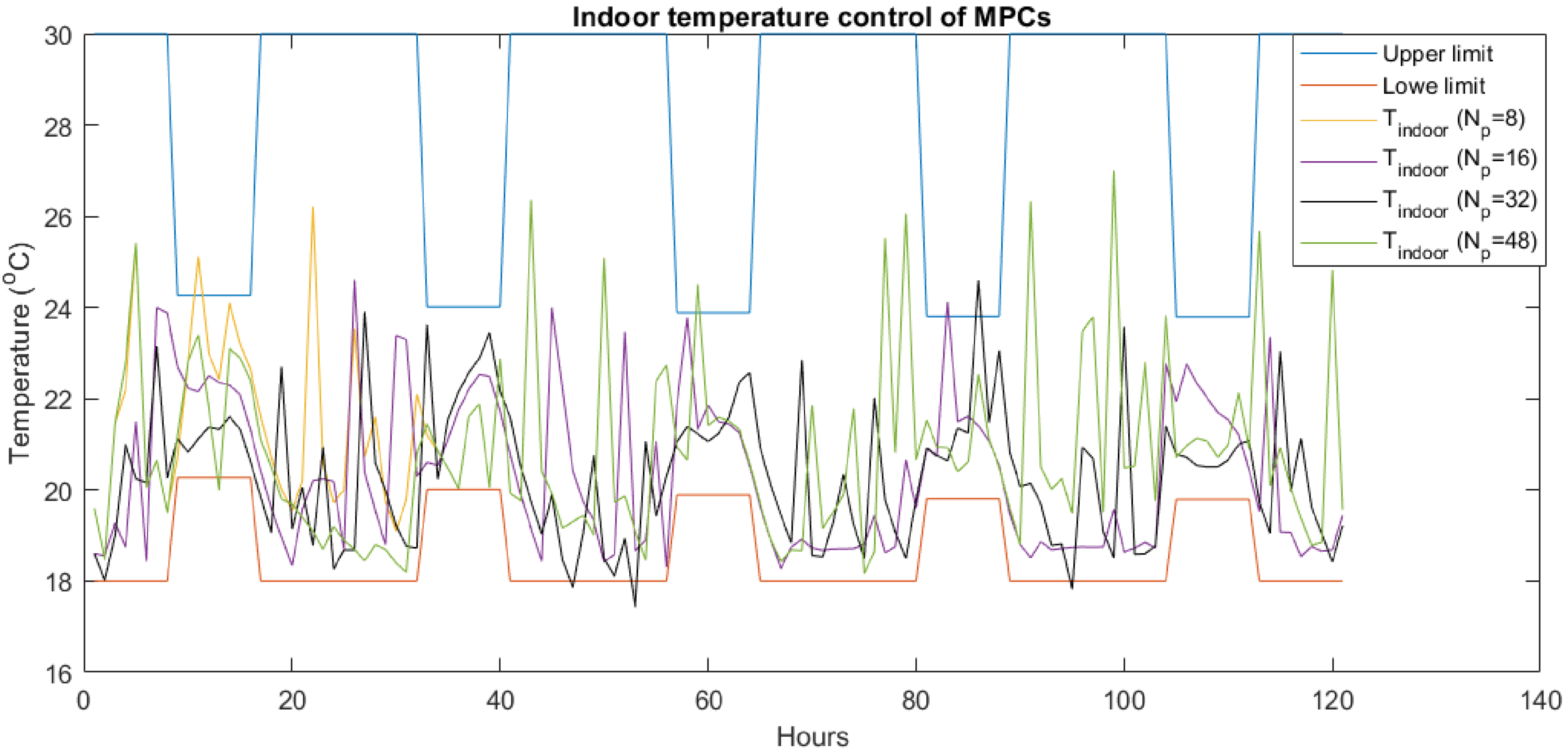






Determination of Prediction Horizon

Winter



Prediction horizon (hours)	Computational time (s)	$\sum error$ [^oC]	Energy supplied by HP [kWh]
4	40	1.82	148
8	261	0.16	144
16	492	0.68	138
24	1206	0.36	137

Summer

Prediction horizon (hours)	Computational time (s)	$\sum error$ [^oC]	Energy supplied by HP [kWh]
4	39	12.62	23.76
8	168	4.72	21.89
16	361	5.92	10.67
24	1092	4.61	8.58

Spring

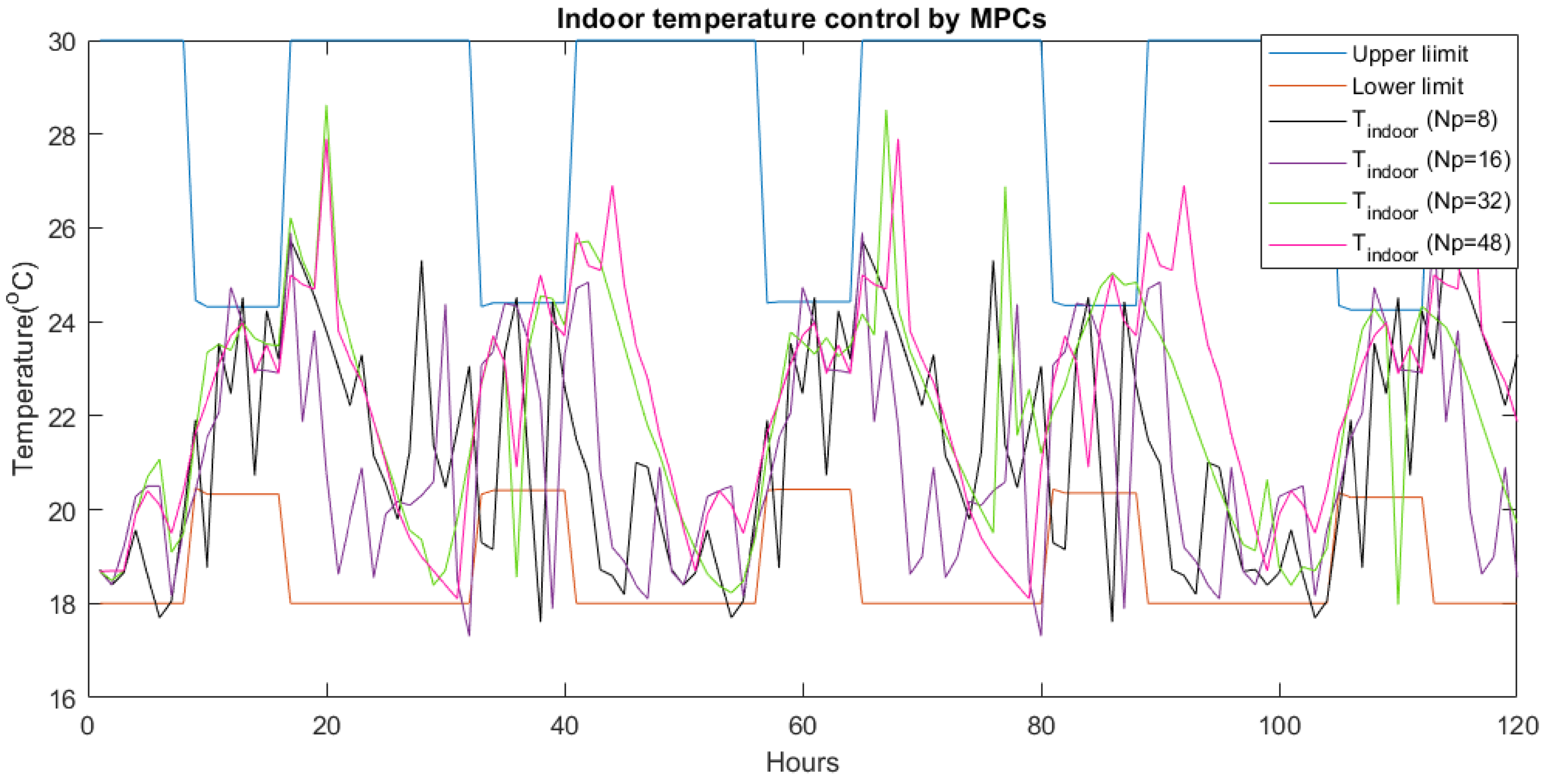
Prediction horizon (hours)	Computational time (s)	$\sum error$ [^oC]	Energy supplied by HP [kWh]
4	51	9.61	74
8	178	6.81	72
16	454	4.81	68
24	1125	0.81	67

Autumn

Prediction horizon (hours)	Computational time (s)	$\sum error$ [^oC]	Energy supplied by HP [kWh]
4	42	11.82	108
8	198	8.21	102
16	392	3.42	94
24	982	2.21	93

Determination of Prediction Horizon

Spring



Prediction horizon (hours)	Computational time (s)	$\sum error$ [^oC]	Energy supplied by HP [kWh]
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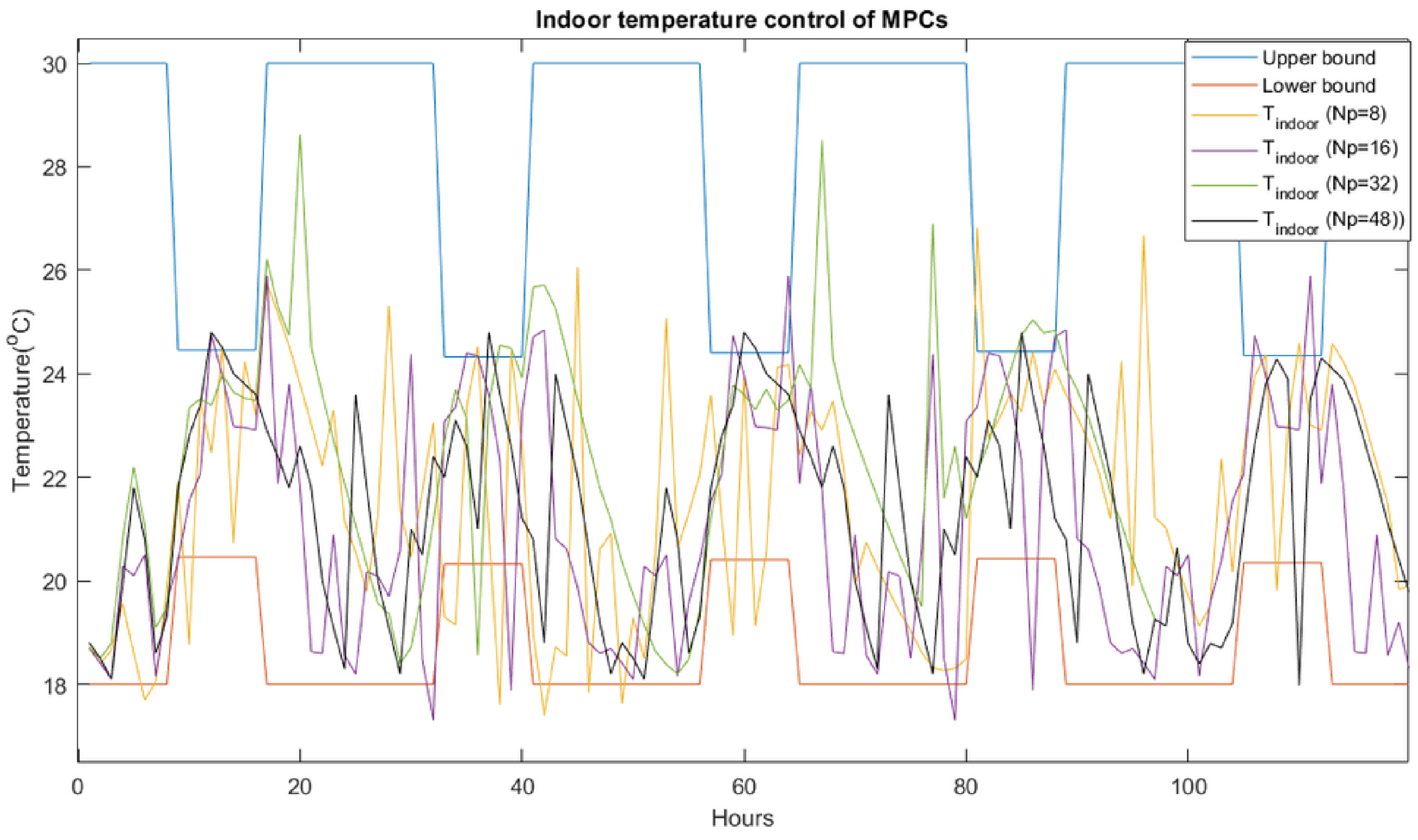
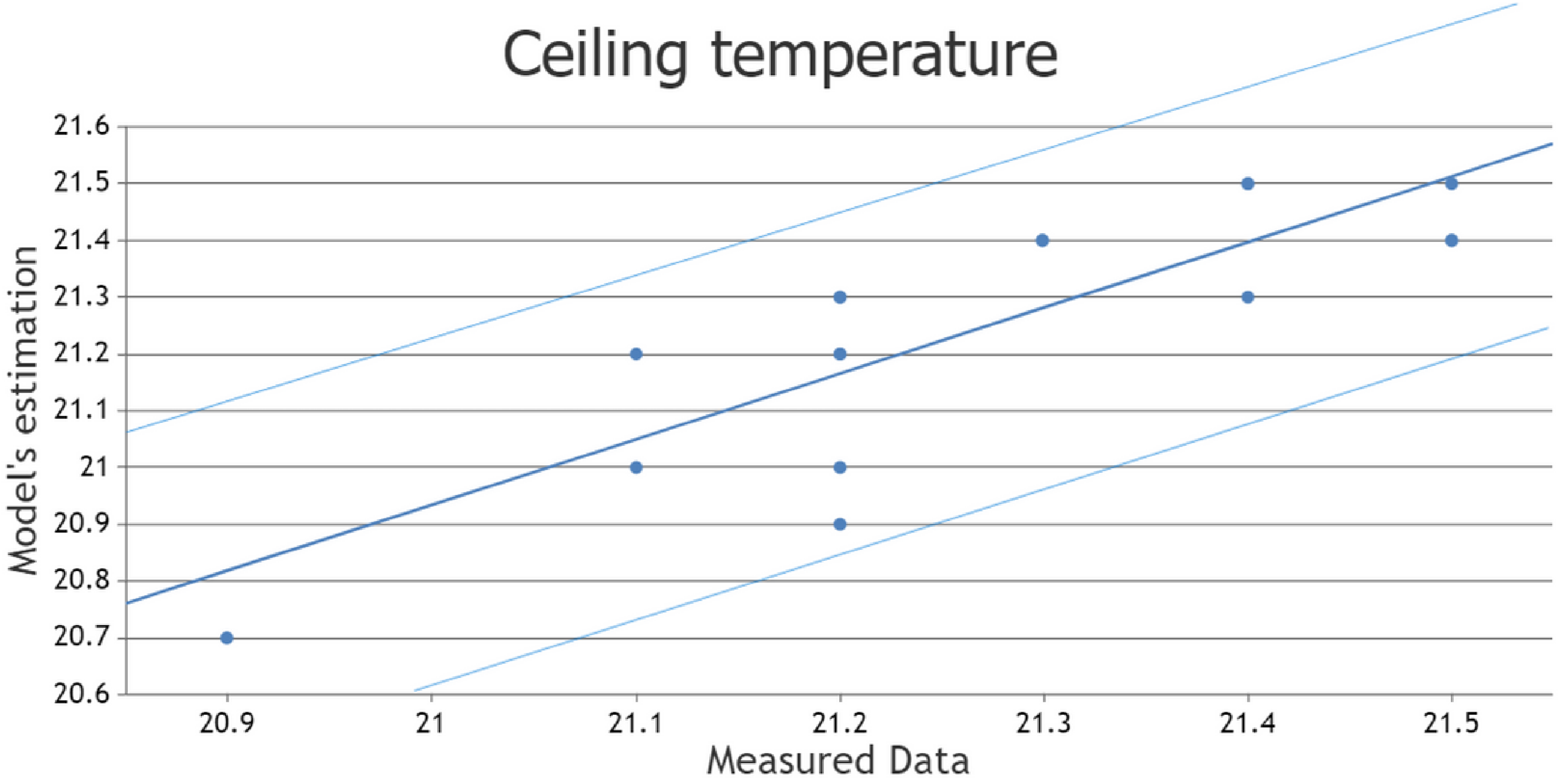
Autumn

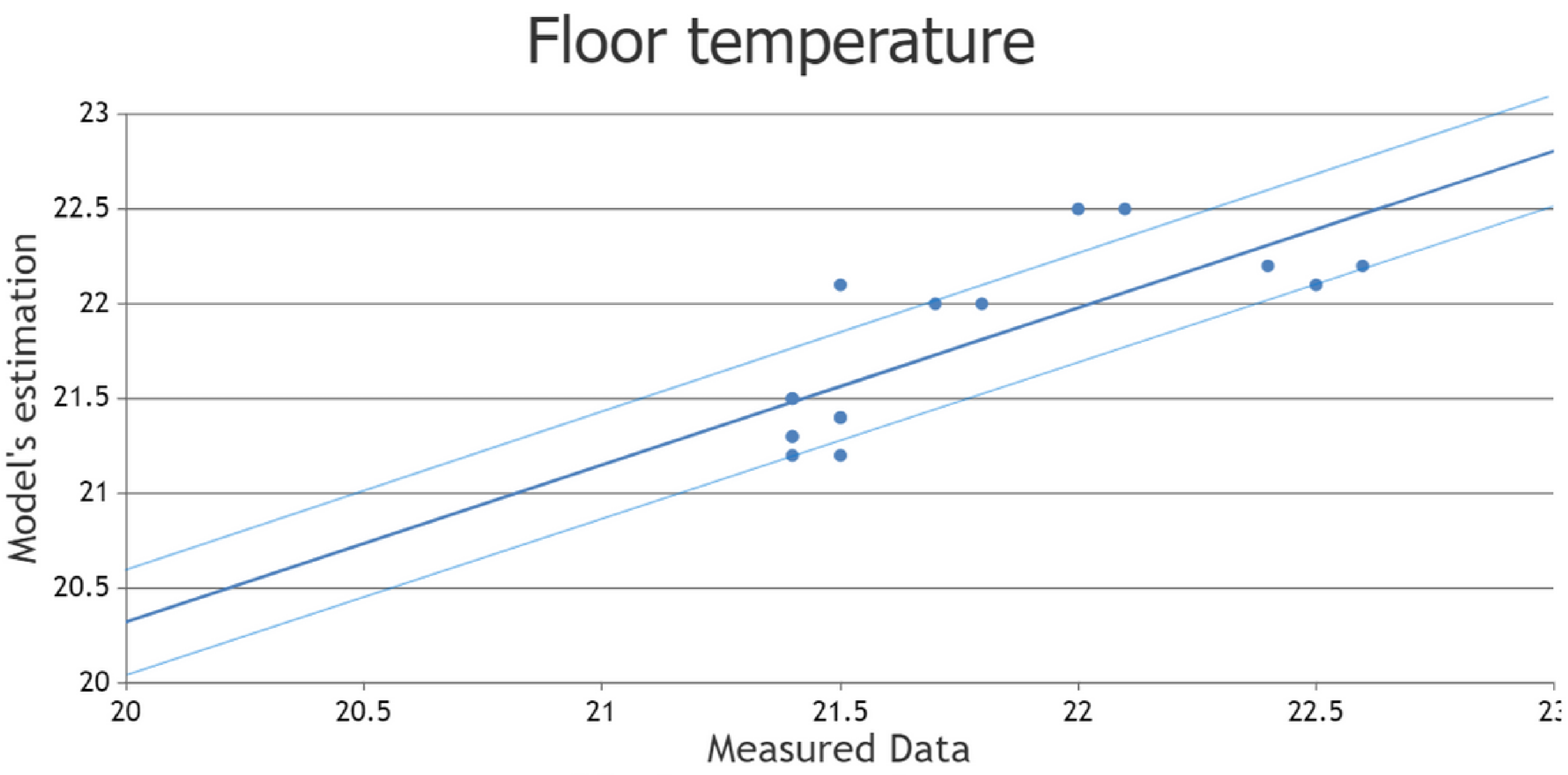


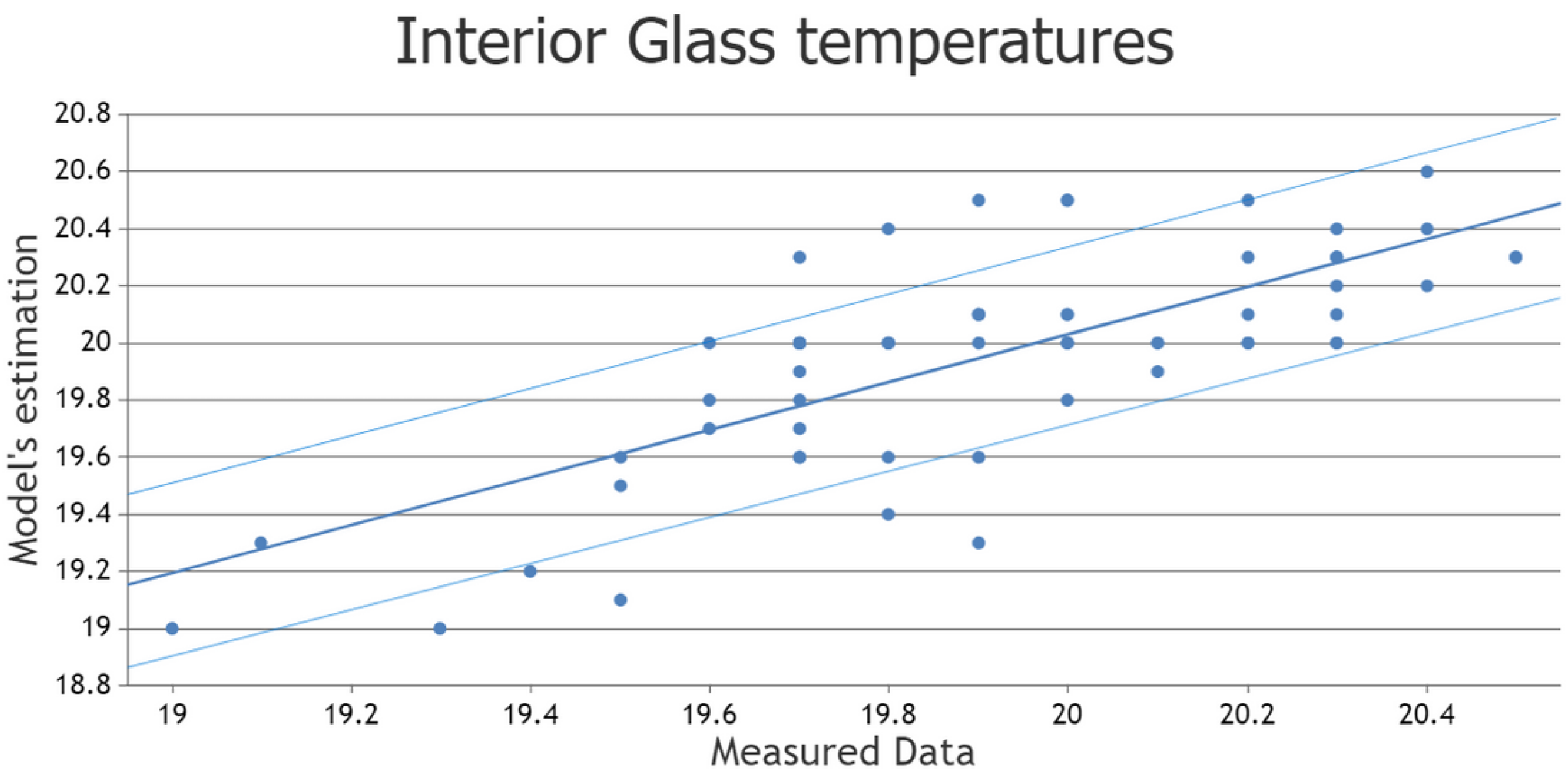
Prediction horizon (hours)	Computational time (s)	$\sum error$ [^oC]	Energy supplied by HP [kWh]
4	42	11.82	108
8	198	8.21	102
16	392	3.42	94
24	982	2.21	93

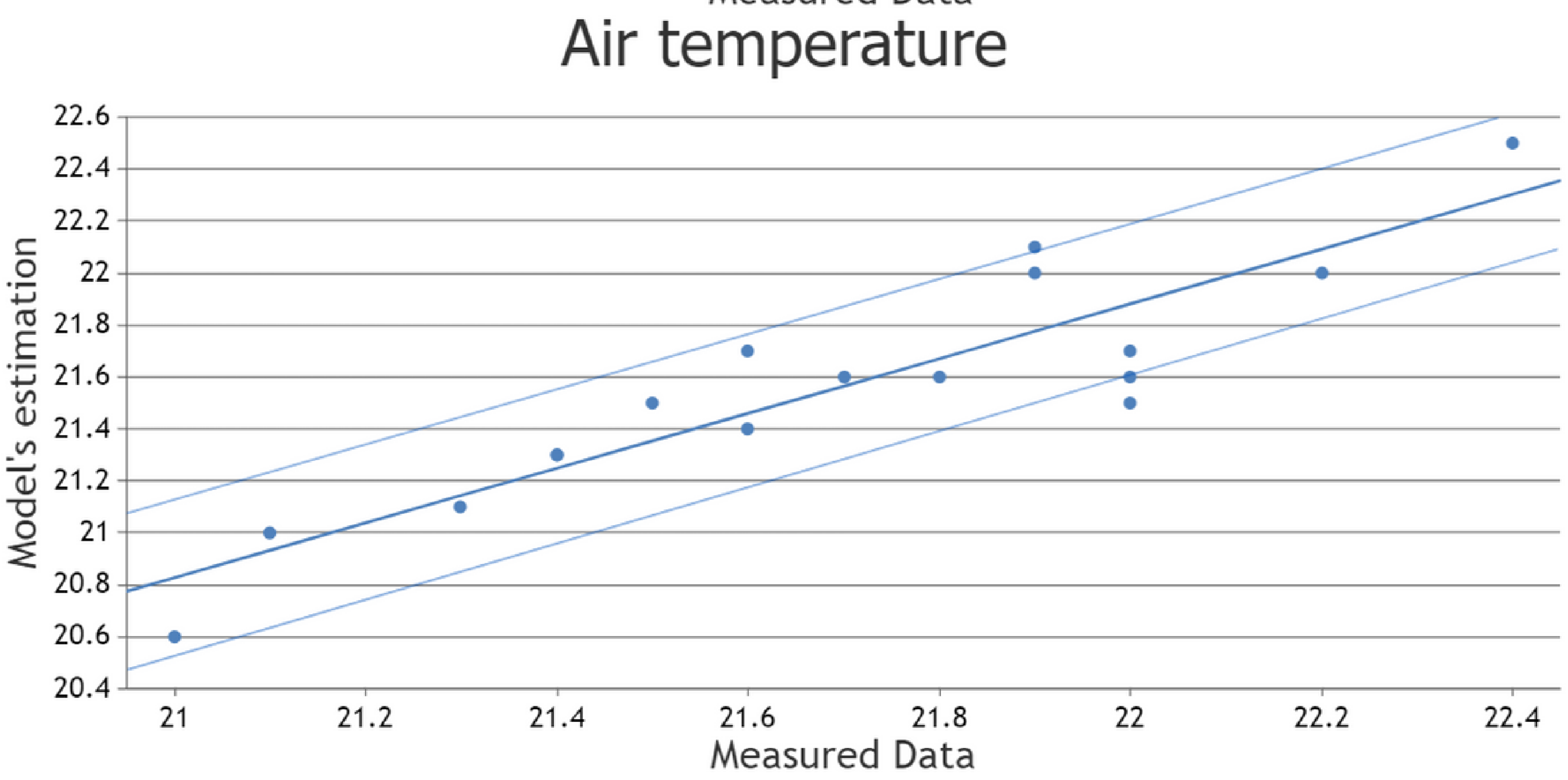
Hence, prediction horizon = 24 hours

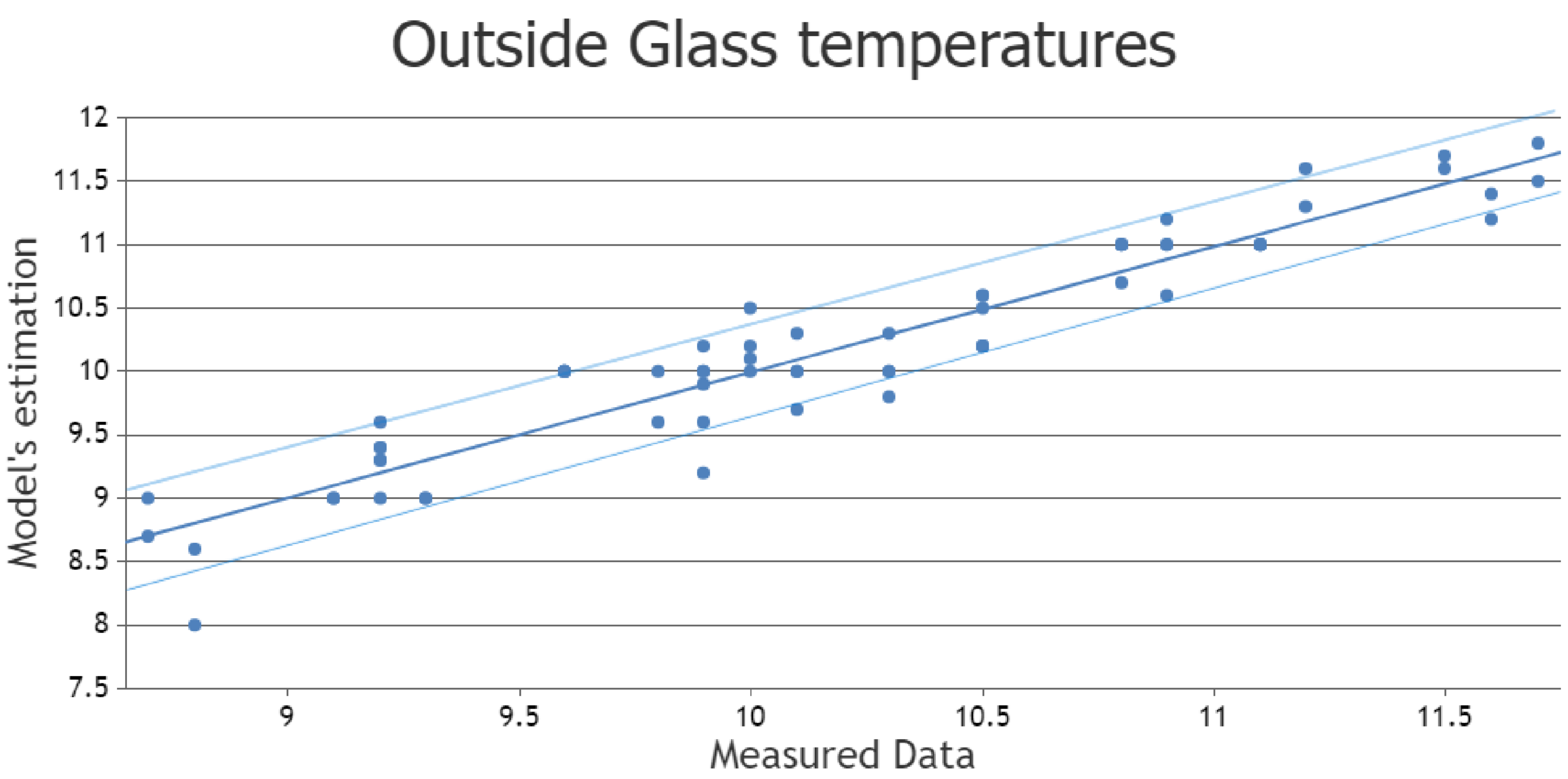
Experimental Validation of MPC

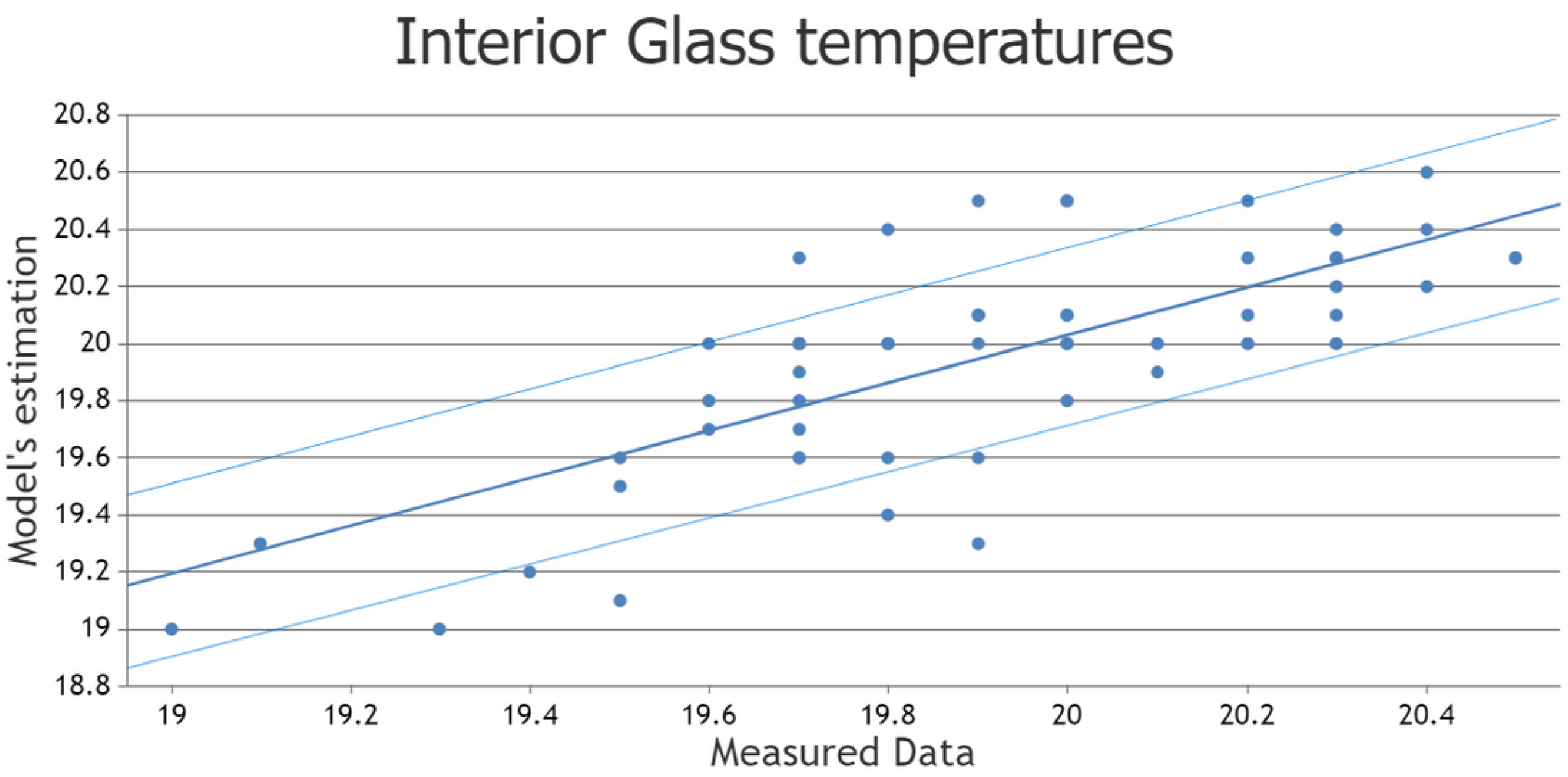












State	T_z	T_c	$T_{interiorglass}$	$T_{outsideglass}$	T_{floor}
RMSE [K]	0.23	0.12	0.26	0.23	0.29

MPC Problem setup

Matrix Formulation

$$x_{k+1} = \mathcal{A}(x_k, p_k)x_k + \mathcal{B}(x_k, p_k)u_k + d_k$$

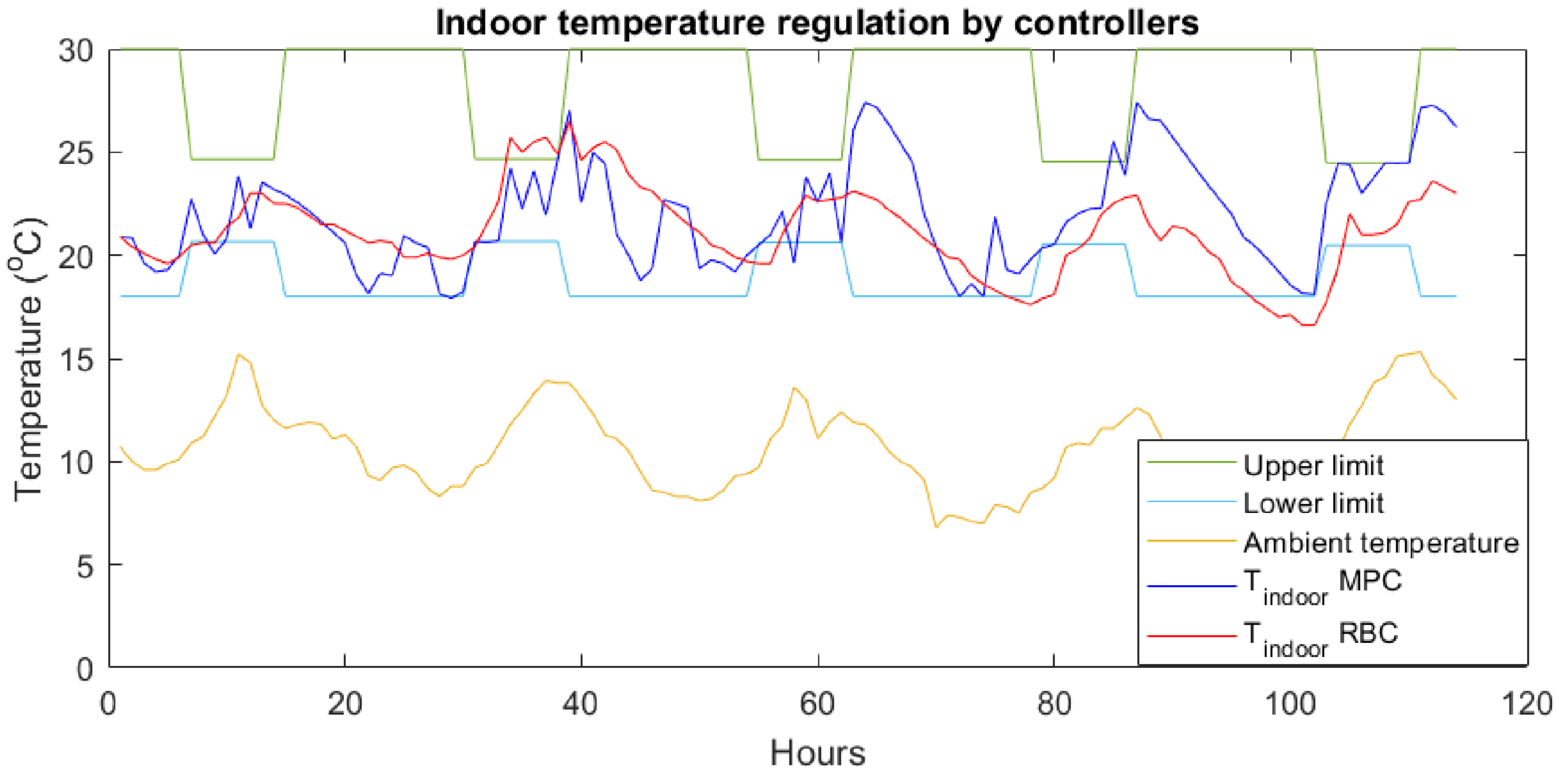
$$y_k = \mathcal{C}(x_k, p_k)x_k + \mathcal{D}(x_k, p_k)u_k$$

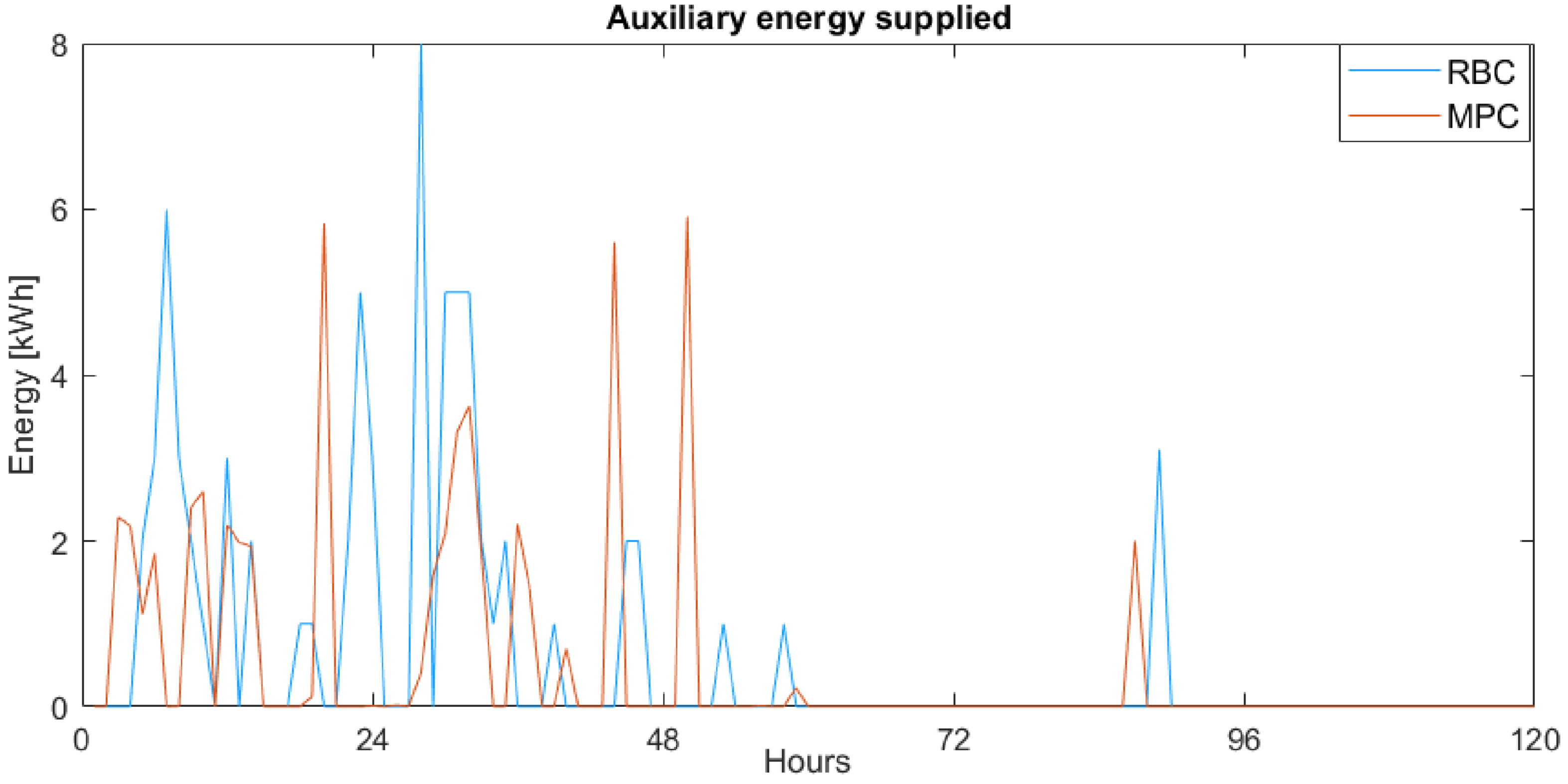
where:

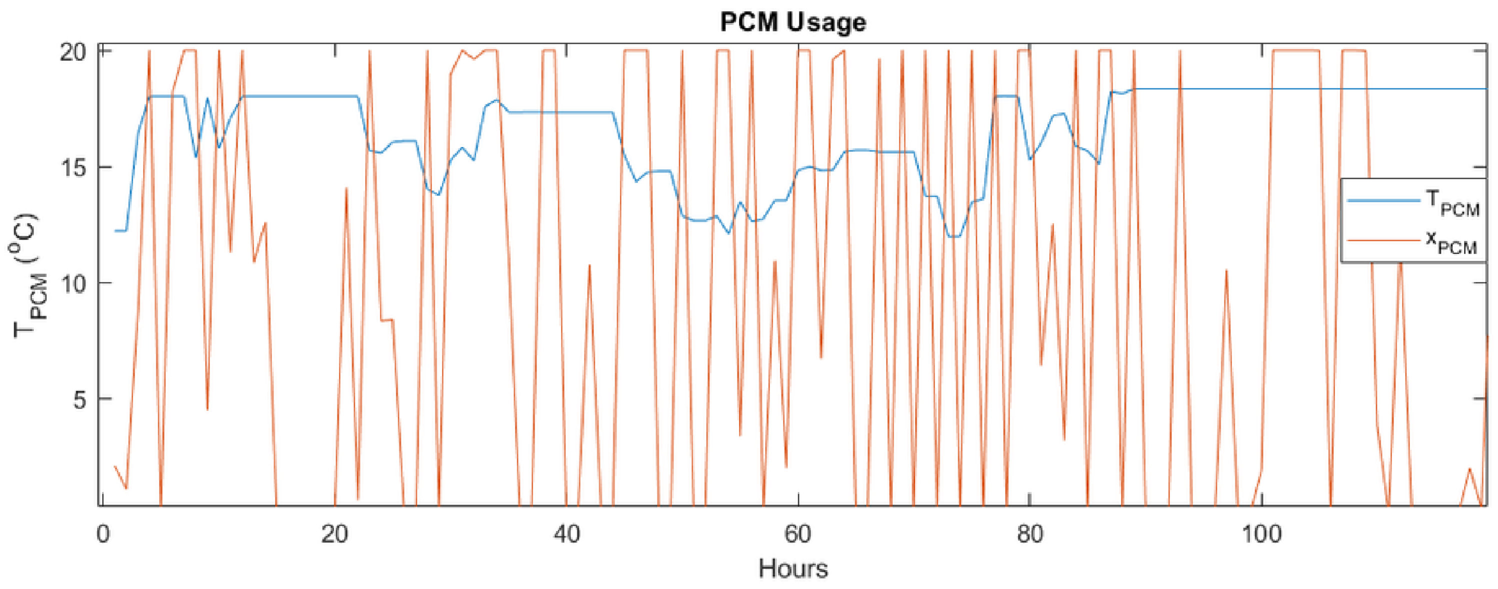
- x_k : Indoor temperature at time k
- u_k : Control input vector at time k
- y_k : Measured or observed temperature at time k
- d_k : Disturbances to the model

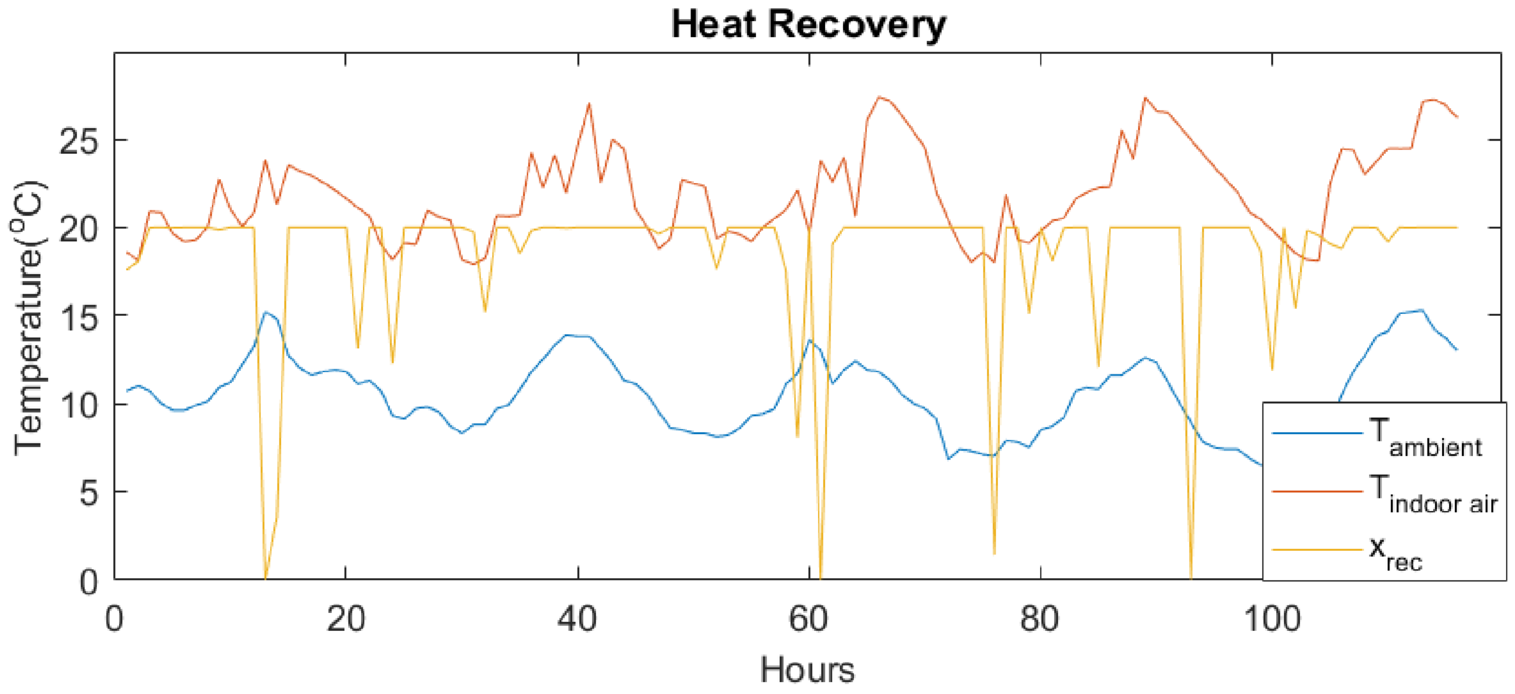
Comparitive study: Energy savings potential

Actual test performed during April 2023 with same temperature limits



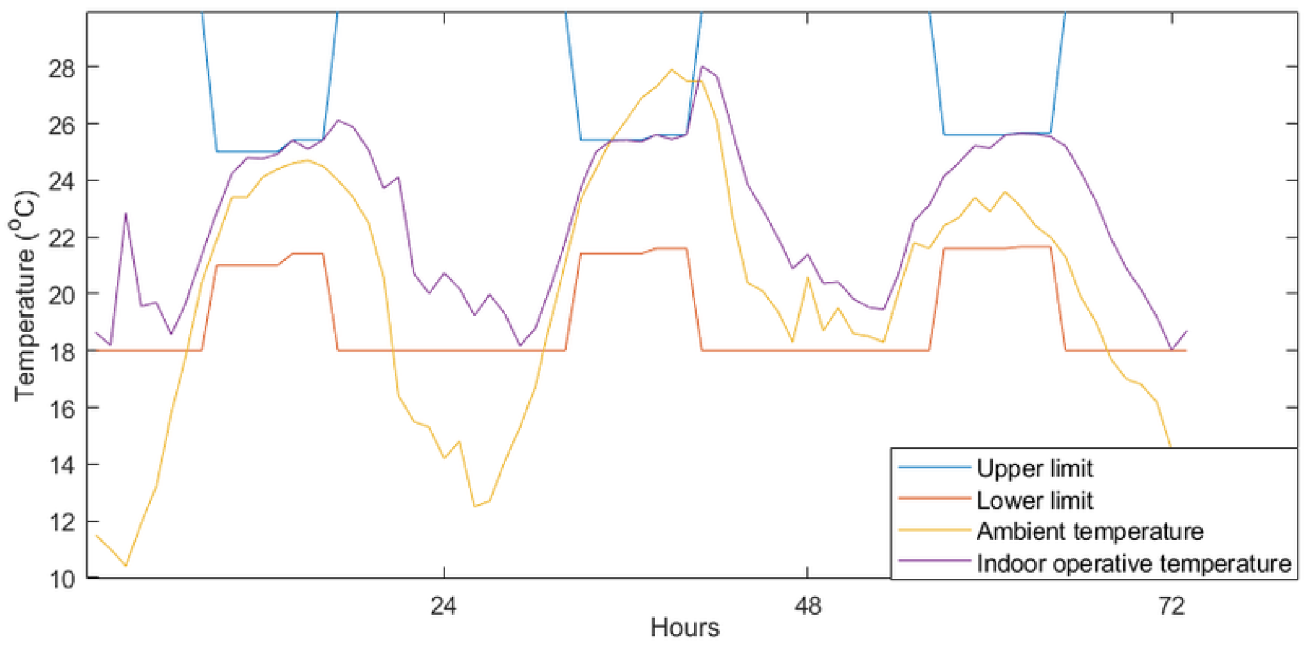


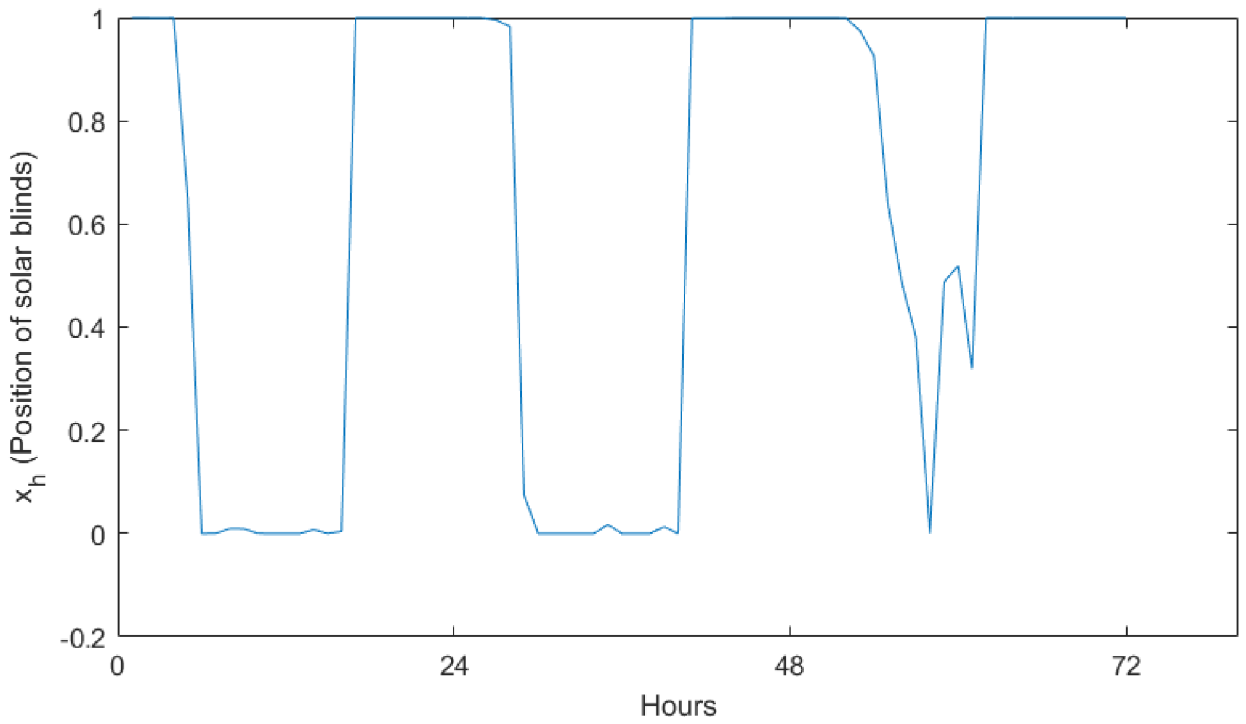


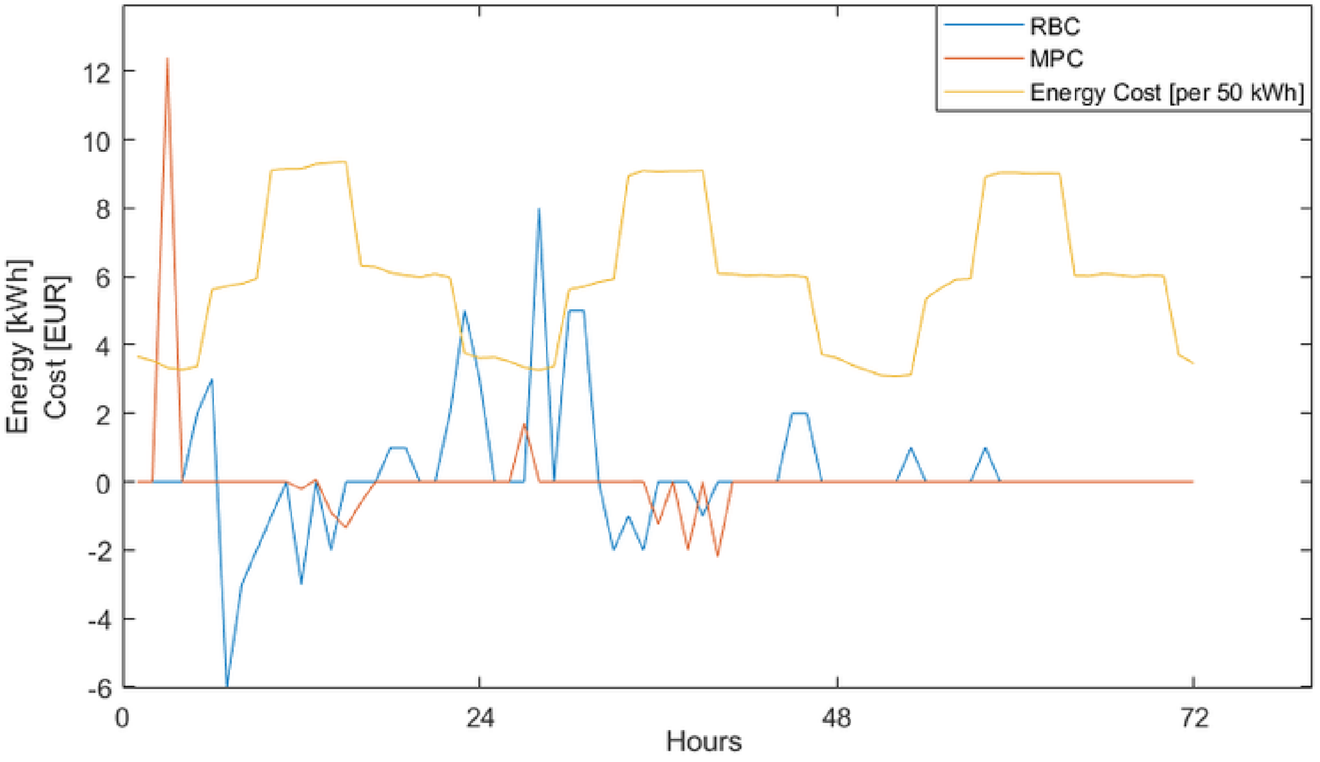


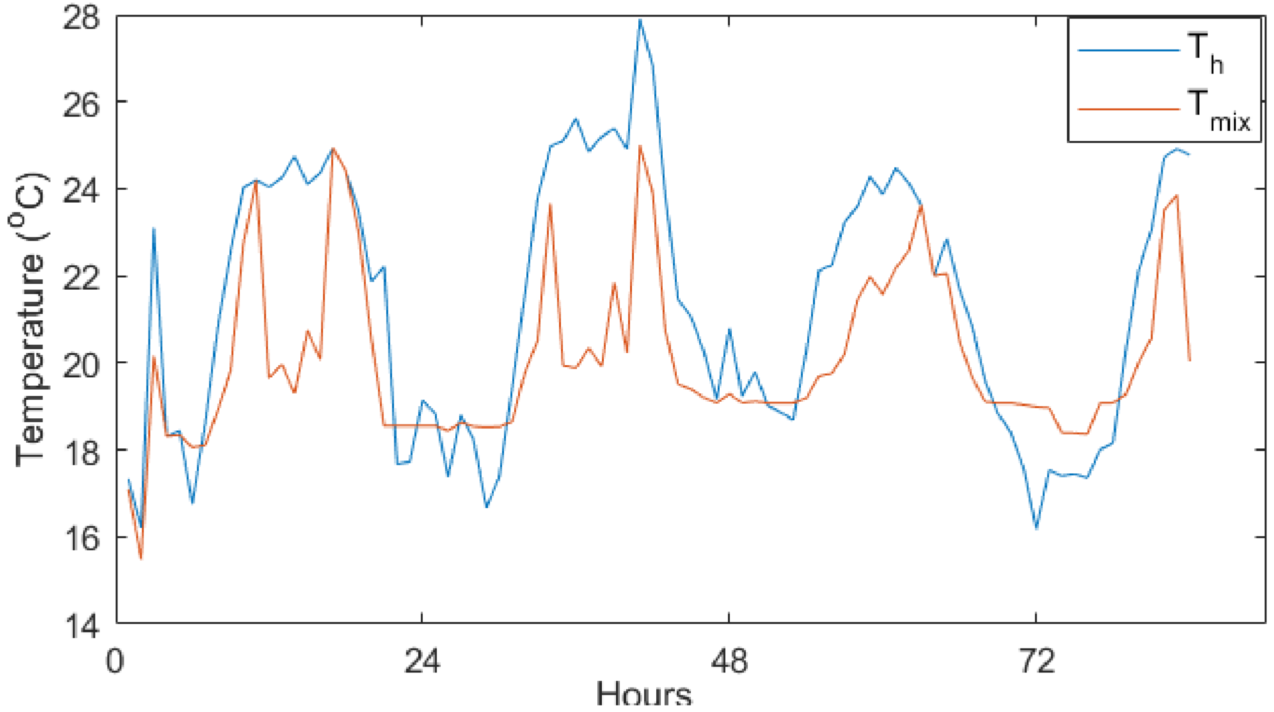
Assessment Criteria	RBC	MPC
Energy consumption [kWh]	69	53.4
Total temperature violations $\sum e$ [K]	3.89	3.21

Energy flexibility potential : Representative study [Summer]

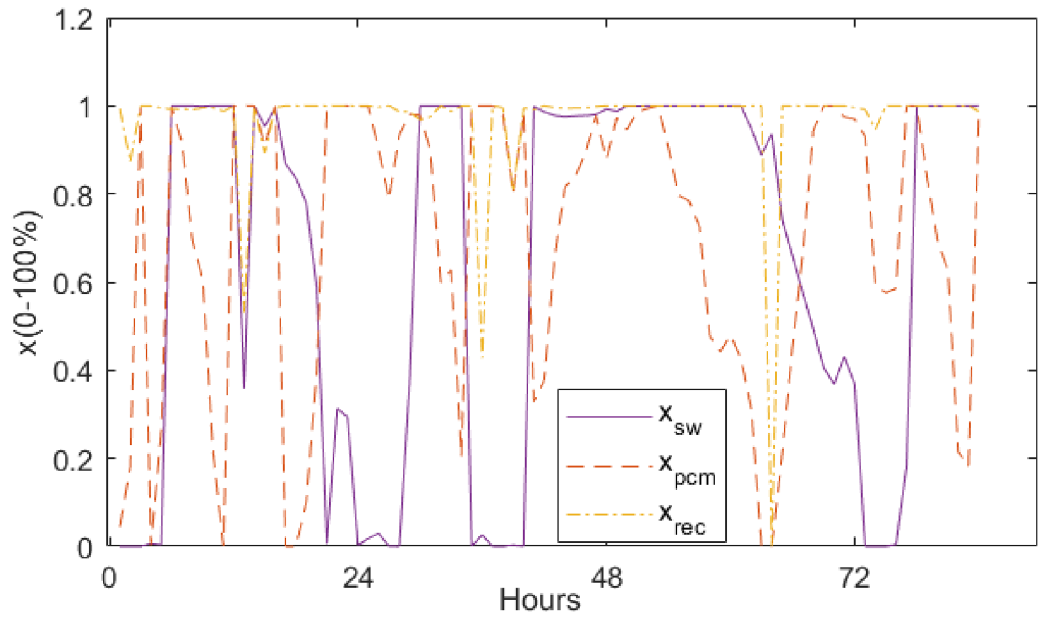




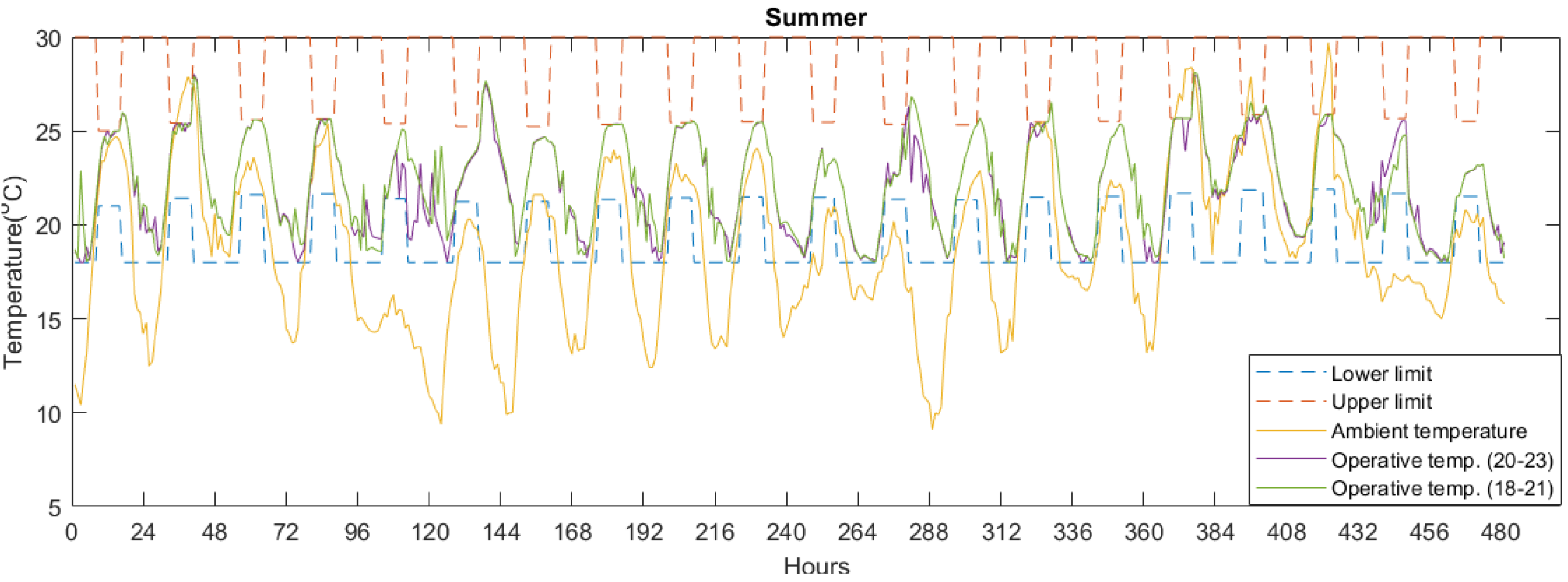


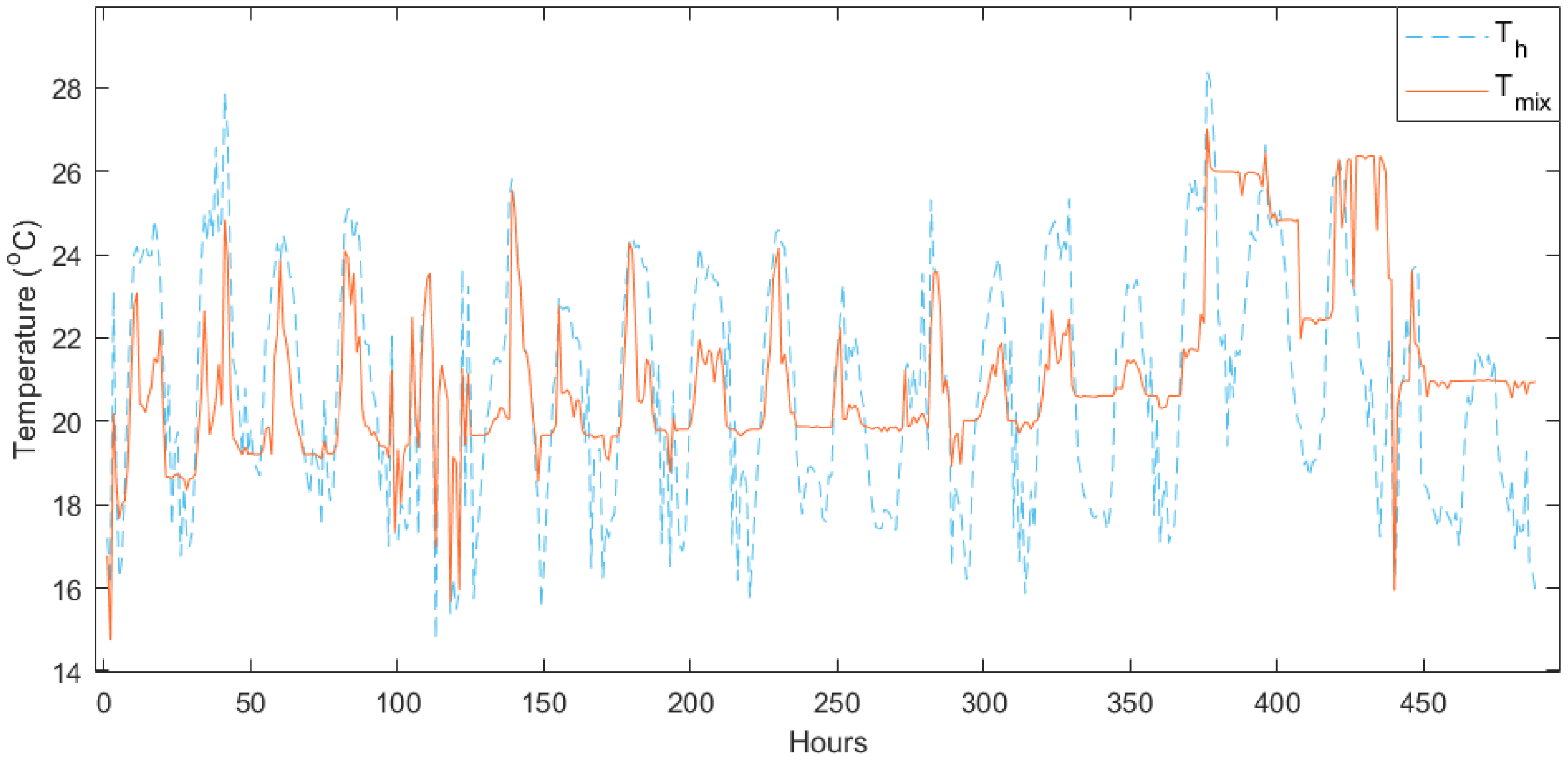


Assessment Criteria	Rule-Based Controller	MPC
Energy supplied by heatpump [kWh]	42	21.8
Estimated cost of electricity [EUR]	5.98	3.45

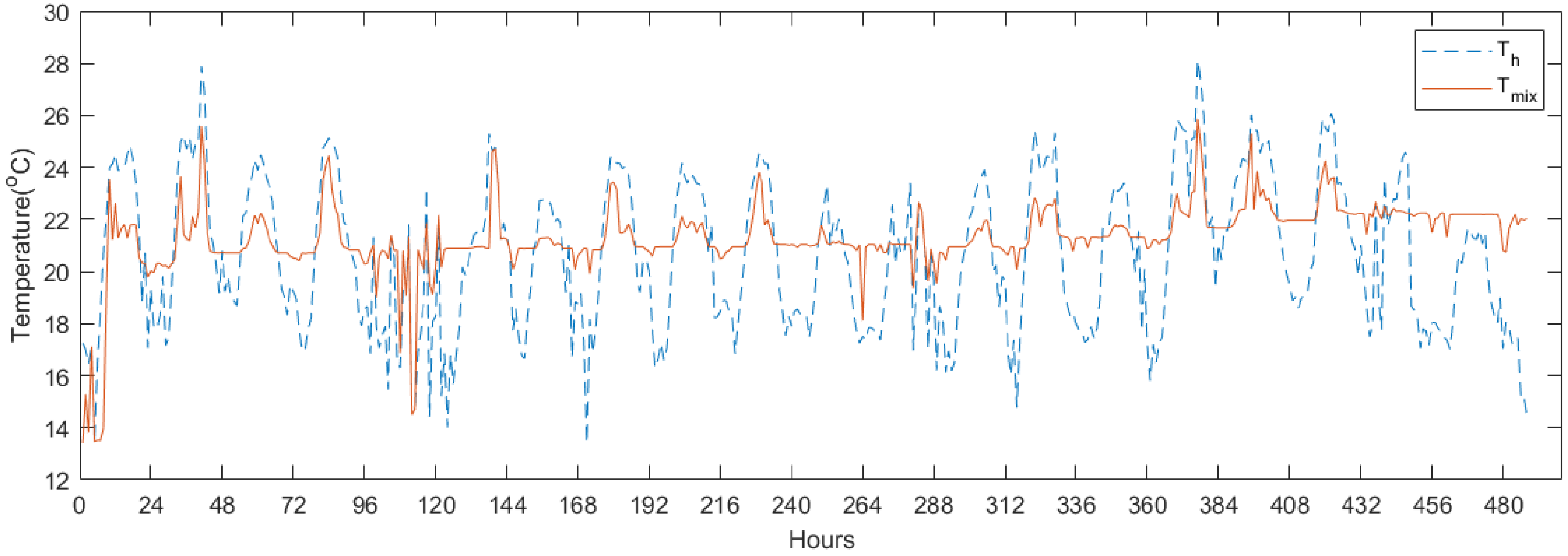


Optimization to PCM configuration: Summer





Utilization of PCM (18-21^{o}C)



Utilization of PCM (20-23^{o}C)