# Energy Flow Modeling of Night Storage Heaters and Its Usage for Sector Coupling

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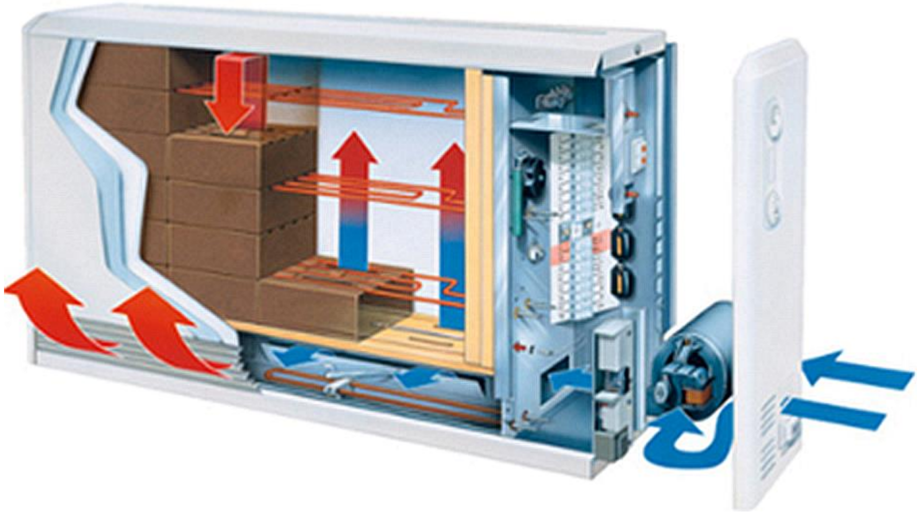
# Outline

- Introduction – Night Storage Heaters
- Challenge – Modeling the Room Temperature
- Test Setup Room
- Energy Transport
- Parameter Estimation
- Simulation Results
- Outlook

# Introduction – Night Storage Heaters

- Widely build in Germany in the 1950th and 1960th
- Cheap electric energy was available during the night



- Today still in use in Germany
- Approx. 1.5 million apartments

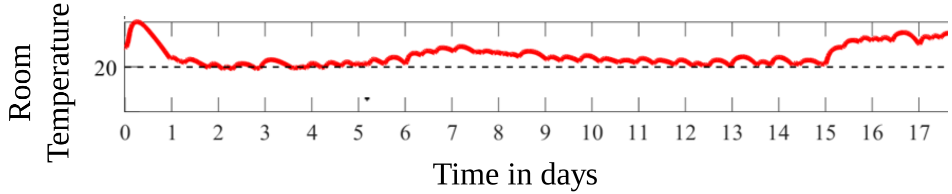
- Quite expensive compared to heating with fossil fuels due to taxes and fees
- If electric energy has an significant share of coal and gas, NSH will pollute much more $CO_2$ than natural gas

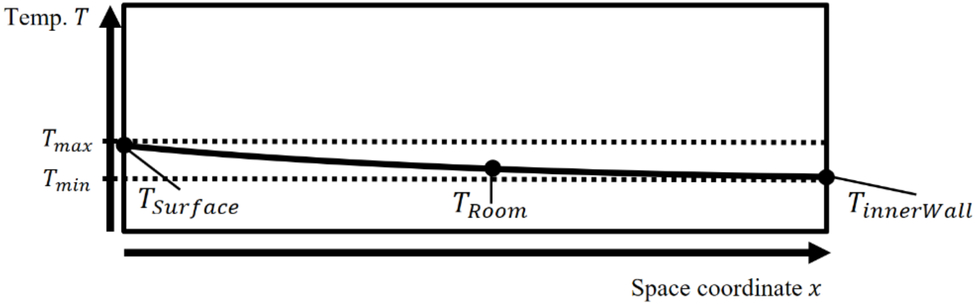
# Challenge – Modeling the Room Temperature

- Volatile Electric Energy Prices could help to
  - improve the home comforts temperatures with NSH, and
  - reduce heating costs.

- With a room temperature model with two input parameters
  - Electric Power Supply
  - Ambient temperature

  the room temperature could be simulated over a long period of time.



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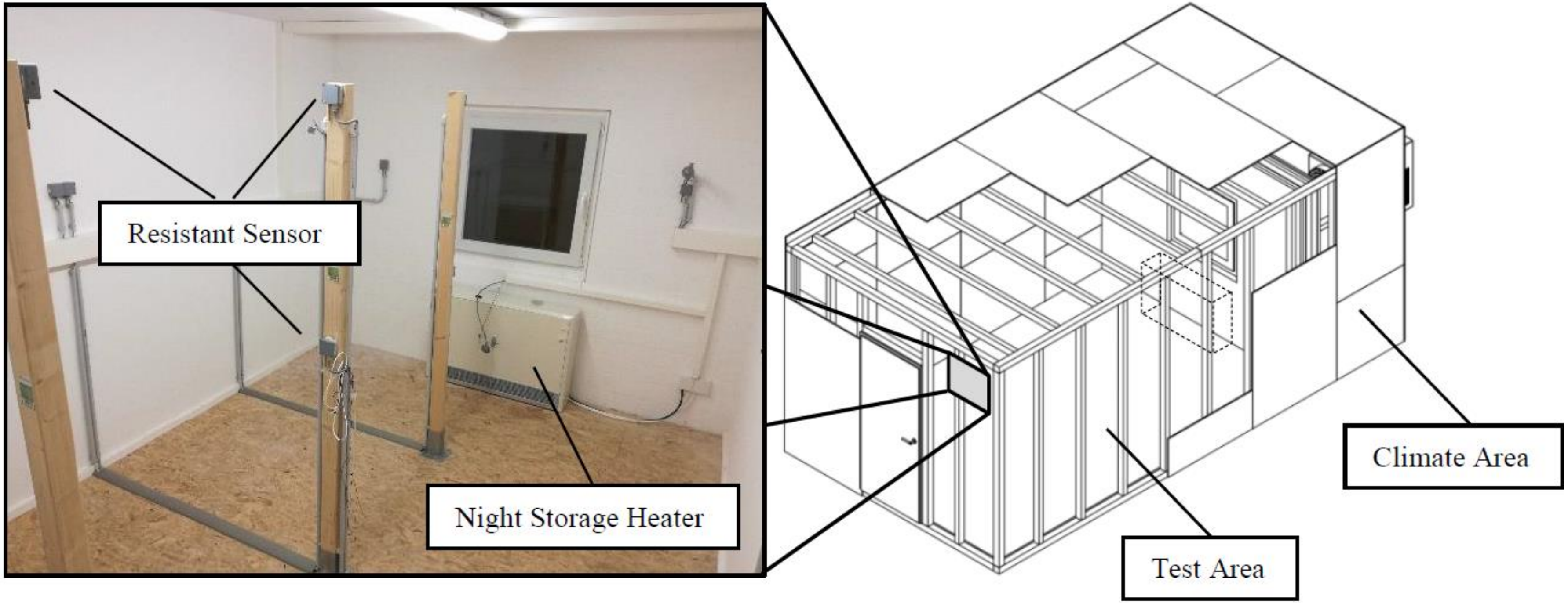
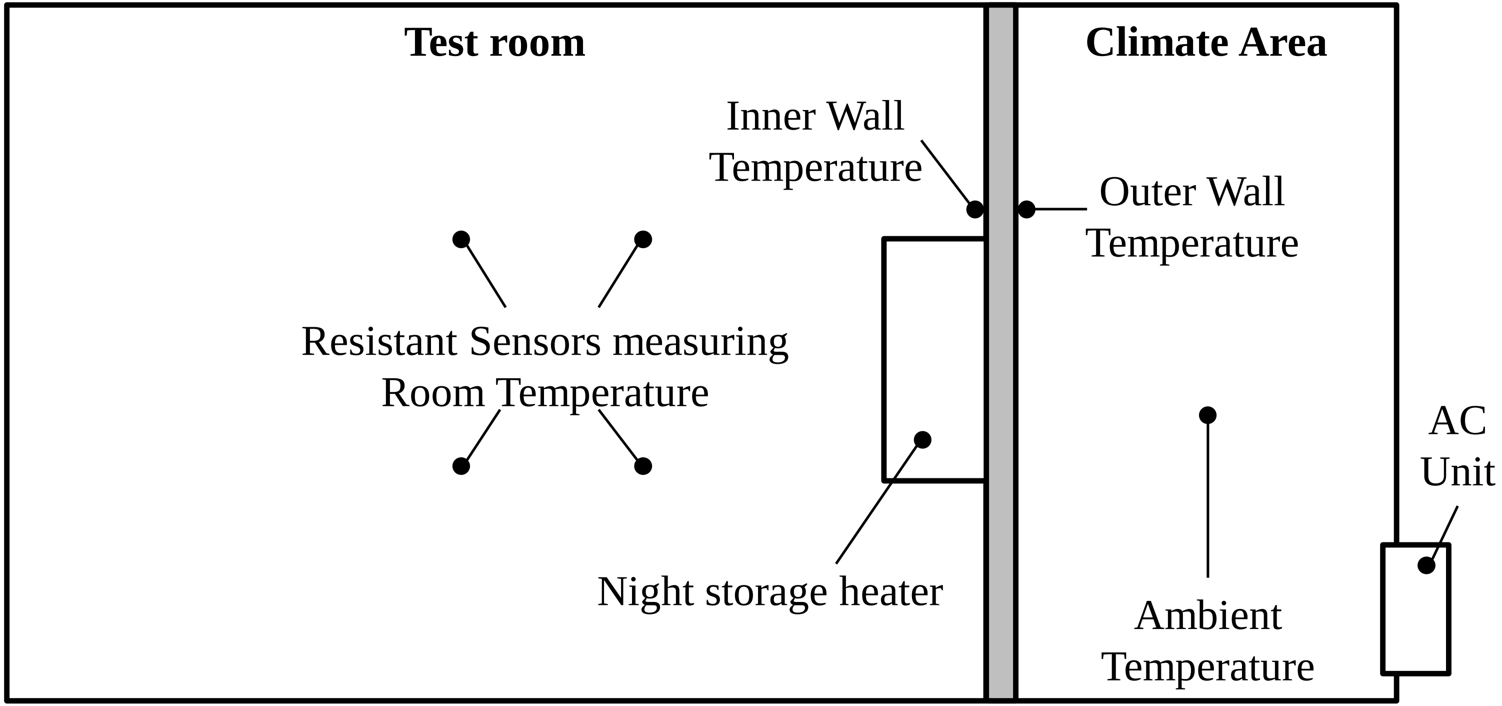
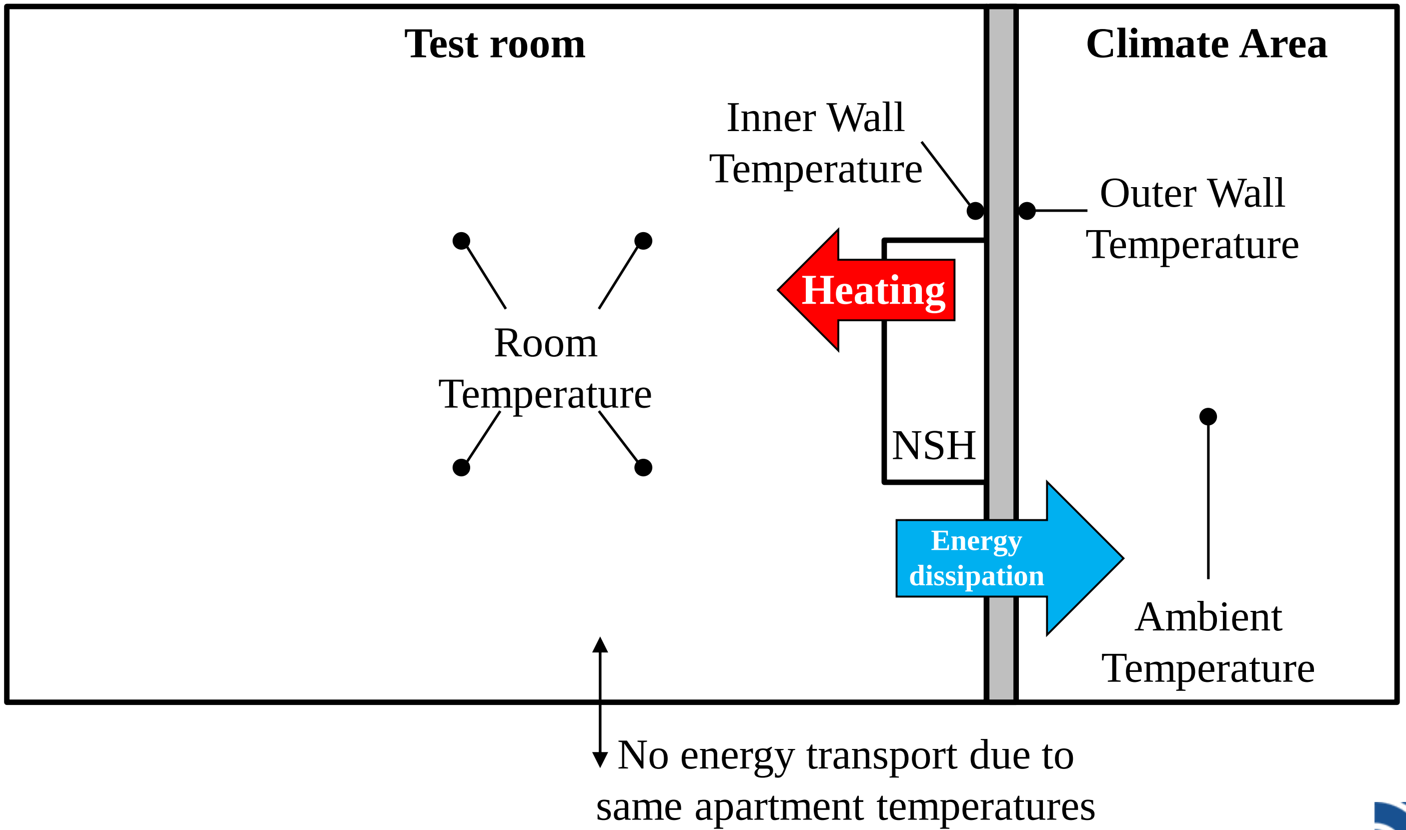
# Test Room Setup



# Test Setup


Test room
Climate Area
Inner Wall
Temperature
Outer Wall
Temperature
Resistant Sensors measuring
Room Temperature
Night storage heater
Ambient
Temperature
AC
Unit

# Test Setup



Test room
Climate Area
Inner Wall Temperature
Outer Wall Temperature
Heating
Room Temperature
NSH
Energy dissipation
Ambient Temperature
No energy transport due to same apartment temperatures

# Energy Transport

## Fourier's heat conduction law

$$\frac{\partial T}{\partial t} = a \cdot \nabla^2 T = a \cdot \mathrm{div}(\mathrm{grad}\, T)$$

## Thermal conductivity equation

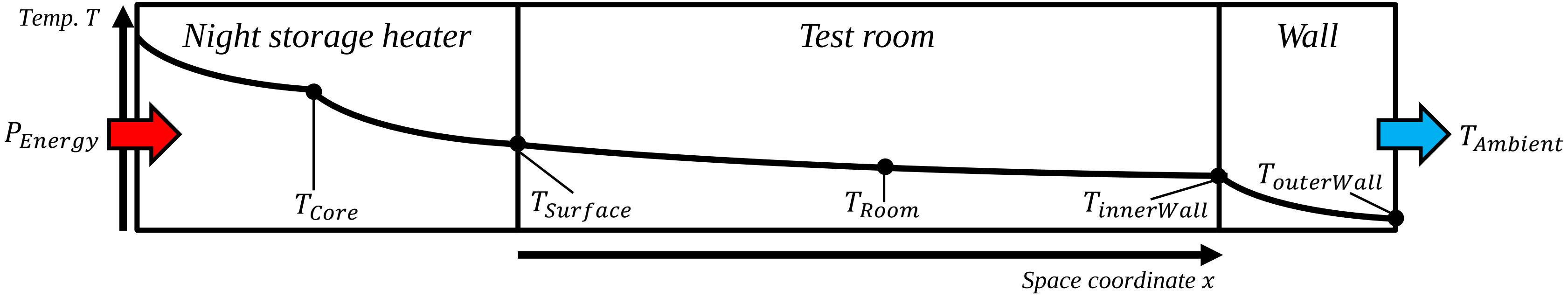
$$\dot{q} = -k\, \nabla T = -k\,(T_1 - T_2) \textbf{ with } T_1 > T_2,$$

$$m\,c\,\frac{dq}{dt} = U_1 A_1 T_1 - U_2 A_2 T_2.$$

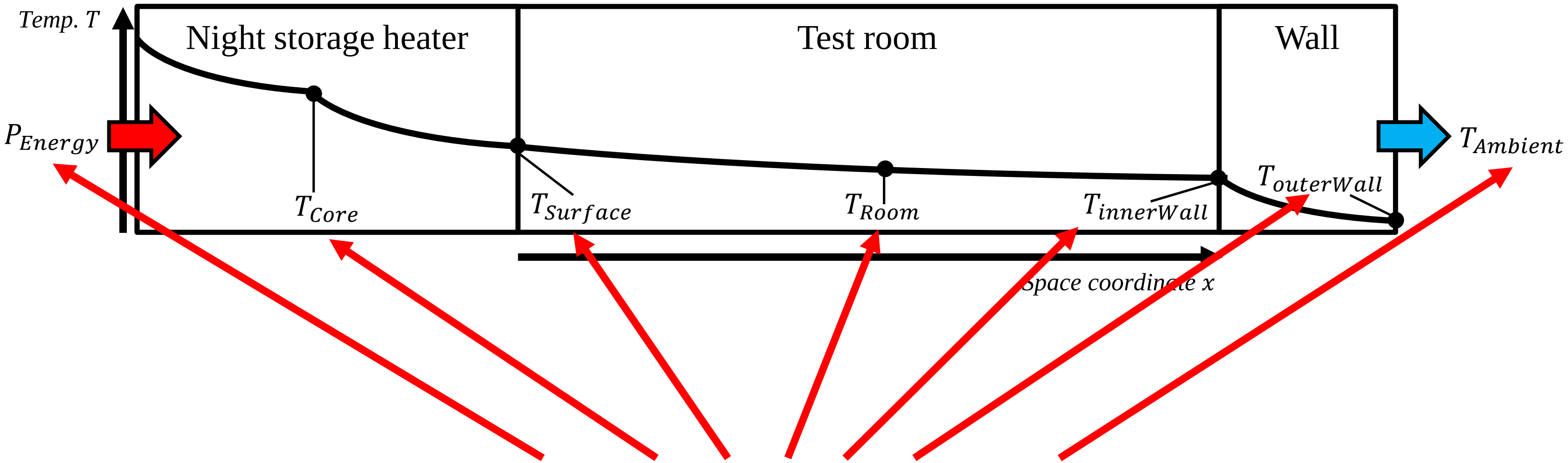
## Relaxation leads to a parametrized equation

$$\frac{dT}{dt} = \frac{U_1 A_1}{m\,c\,\Delta S} T_1 - \frac{U_2 A_2}{m\,c\,\Delta S} T_2 \Leftrightarrow \frac{dT}{dt} = p_1 \cdot T_1 - p_2 \cdot T_2 \textbf{ with } T_1 > T > T_2,$$

# Energy Transport

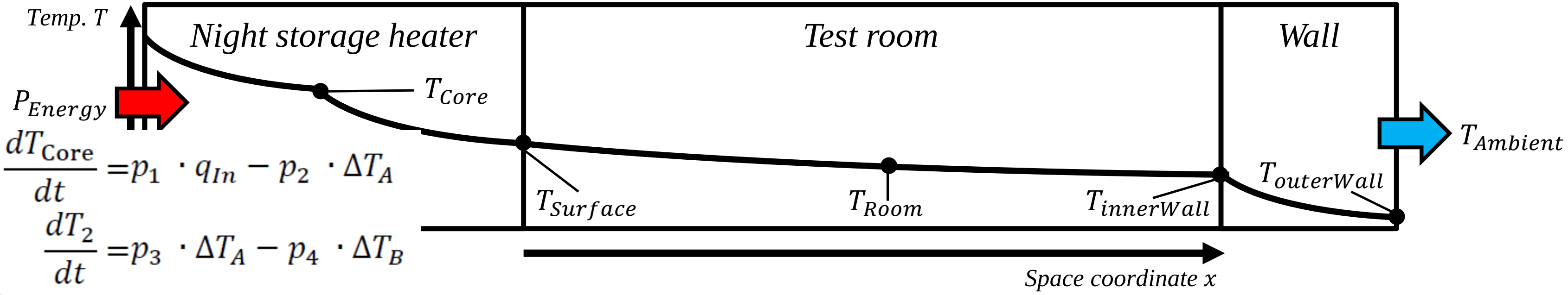


# Energy Transport




Measurable and known temperatures and input parameters for parameter estimation

# Energy Transport




$$\frac{dT_{\text{Core}}}{dt} = p_1 \cdot q_{In} - p_2 \cdot \Delta T_A$$

$$\frac{dT_2}{dt} = p_3 \cdot \Delta T_A - p_4 \cdot \Delta T_B$$

$$\frac{dT_{Surface}}{dt} = p_5 \cdot \Delta T_B - p_6 \cdot \Delta T_C$$

$$\frac{dT_{\text{Room}}}{dt} = p_7 \cdot \Delta T_C - p_8 \cdot \Delta T_D$$

$$\frac{dT_5}{dt} = p_9 \cdot \Delta T_D - p_{10} \cdot \Delta T_E$$

$$\frac{dT_{innerWall}}{dt} = p_{11} \cdot \Delta T_E - p_{12} \cdot \Delta T_F$$

$$\frac{dT_7}{dt} = p_{13} \cdot \Delta T_F - p_{14} \cdot \Delta T_G$$

$$\frac{dT_{outerWall}}{dt} = p_{15} \cdot \Delta T_G - p_{16} \cdot \Delta T_H$$

- **Each layer can be modelled using thermal conductivity equation**

**This leads to**

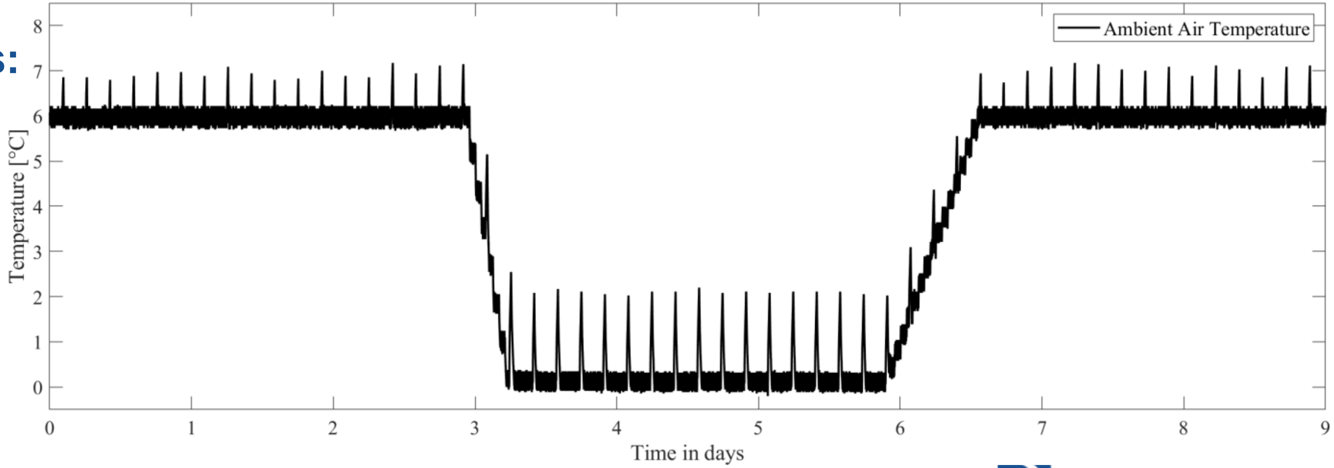
- **16 unknown parameters**
- **8 ODEs**
- **With 5 *inner state* temperatures, and**
- **two input parameter vectors (electric energy and ambient temp.)**

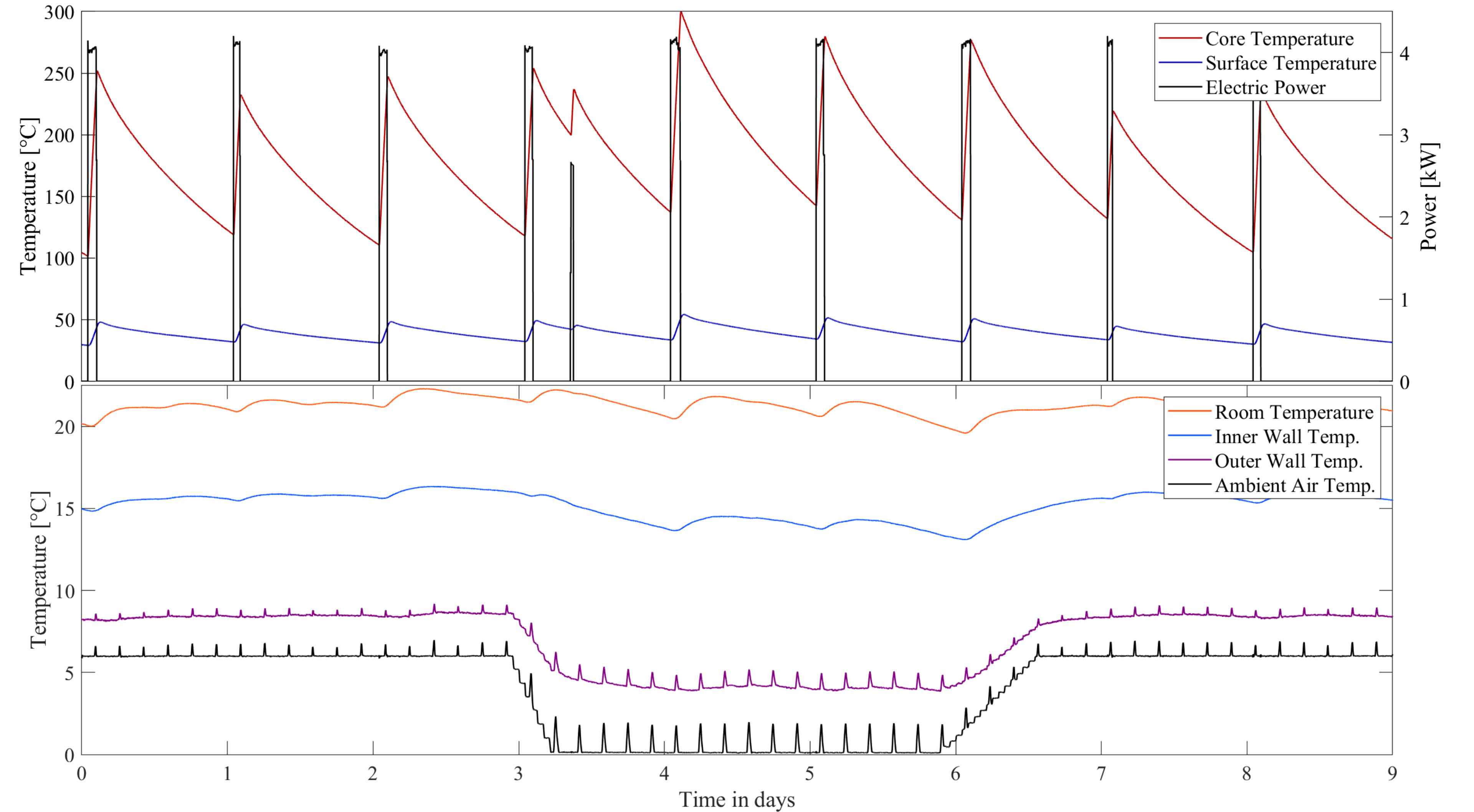
# Reference Scenario for Parameter Estimation

- Nine day test run
- Ambient temperature was predefined
- Standard heating program was applied:
  Electric Heating was allowed during night times

**Measured temperatures:**

- Core
- Surface
- Room
- Inner Wall
- Outer Wall





Core Temperature
Surface Temperature
Electric Power
Temperature [°C]
Power [kW]
Room Temperature
Inner Wall Temp.
Outer Wall Temp.
Ambient Air Temp.
Temperature [°C]
Time in days

# Parameter Estimation

## State space representation

$$\underline{\dot{x}}(t) = \underline{A}\,\underline{x}(t) + \underline{B}\,\underline{u}(t), \underline{x}(0) = \underline{x}_0, \underline{x} \in \mathbb{R}^8, \underline{A} \in \mathbb{R}^{8\times8}, \underline{B} \in \mathbb{R}^{8\times2}, \underline{u} \in \mathbb{R}^2.$$

## Algebraic solution

$$\underline{x}(t) = e^{\underline{A}t}\underline{x}_0 + e^{\underline{A}t}\int_0^t e^{-\underline{A}\tau}\,\underline{B}\,\underline{u}(\tau)d\tau$$

**Expression size was not computable, thus, Matlab’s ODE45 solvers were used.**

# Parameter Estimation

## ODEs to be solved

$$\dot{x}_1(t) = p_1 \cdot P_{Enery}(\mathrm{t}) - p_2(x_{Core}(t) - x_2(t))$$

$$\dot{x}_2(t) = p_3(x_{Core}(t) - x_2(t)) - p_4\left(x_2(t) - T_{Surface}(\mathrm{t})\right)$$

$$\dot{x}_{Surface}(t) = \dot{x}_3(t) = p_5\left(x_2(t) - x_{Surface}(t)\right) - p_6\left(x_{Surface}(t) - T_{Room}(\mathrm{t})\right)$$

$$\dot{x}_{Room}(t) = \dot{x}_4(t) = p_7\left(T_{Surface}(\mathrm{t}) - x_{Room}(t)\right) - p_8(x_{Room}(t) - x_5(t))$$

$$\dot{x}_5(t) = p_9(x_{Room}(t) - x_5(t)) - p_{10}(x_5(t) - T_{innerWall}(\mathrm{t}))$$

$$\dot{x}_{innerWall}(t) = \dot{x}_6(t) = p_{11}(x_5(t) - x_{innerWall}(t)) - p_{12}(x_{innerWall}(t) - x_7(t))$$

$$\dot{x}_7(t) = p_{13}\ (x_{innerWall}(t) - x_7(t)) - p_{14}(x_7(t) - T_{outerWall}(\mathrm{t}))$$

$$\dot{x}_{outerWall}(t) = \dot{x}_8(t) = p_{15}(x_7(t) - x_{outerWall}(t)) - p_{16}(x_{outerWall}(t) - T_{Ambient}(\mathrm{t}))$$

# Parameter Estimation

**Unknown parameter vector $\underline{p}^*$ is computable by least squares estimation**

$$\underline{p}^* = \underset{\underline{p}}{\operatorname{argmin}} \sum_{k=1}^{k_{max}} \left( x_{Measure}(k) - x_{Model}\left(k; \underline{p}\right) \right)^2 ,$$

**whereby**

**$x_{Measure}(k)$ represents temperature measurements of five metering points, and $x_{Model}\left(k; \underline{p}\right)$ is computed by solving the above mentioned ODEs. $k$ counts the second wise timestamp over nine days from 1 to 777,600.**

**In general, nonlinear programming does not provide the global minimum, thus, the given result represents a local minimum.**



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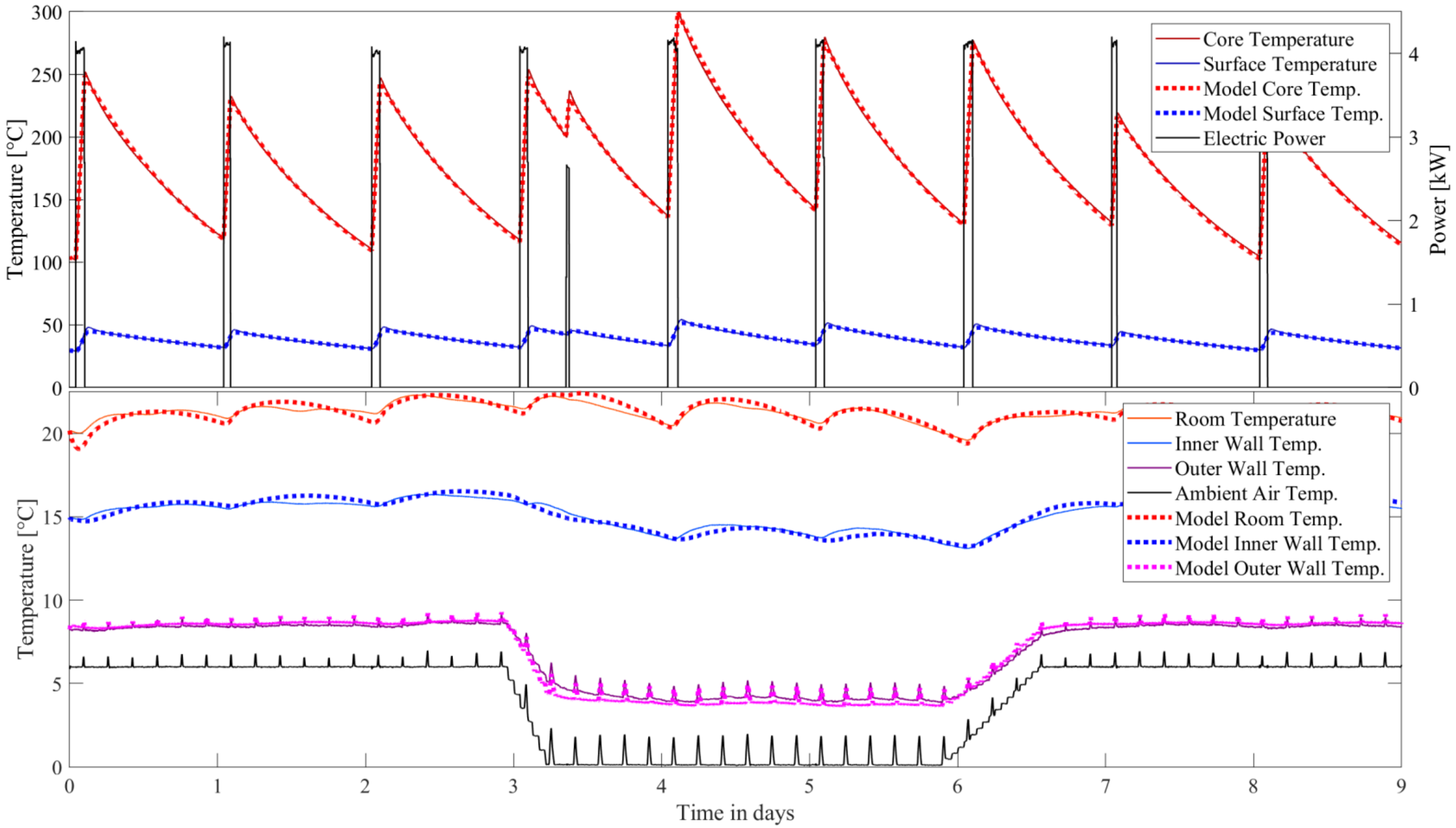
# Parameter Estimation

$$\underline{p}^* = \underset{p}{\operatorname{argmin}} \sum_{k=1}^{k_{max}} \left( x_{Measure,Core}(t_k) - x_{Core}\left(t_k; \underline{p}, P_{Energy}, T_{Ambient}\right)\right)^2$$
$$+ \sum_{k=1}^{k_{max}} \left( x_{Measure,Surface}(t_k) - x_{Surface}\left(t_k; \underline{p}, P_{Energy}, T_{Ambient}\right)\right)^2$$
$$+2 \cdot \sum_{k=1}^{k_{max}} \left( x_{Measure,Room}(t_k) - x_{Room}\left(t_k; \underline{p}, P_{Energy}, T_{Ambient}\right)\right)^2$$
$$+ \sum_{k=1}^{k_{max}} \left( x_{Measure,innerWall}(t_k) - x_{innerWall}\left(t_k; \underline{p}, P_{Energy}, T_{Ambient}\right)\right)^2$$
$$+ \sum_{k=1}^{k_{max}} \left( x_{Measure,outerWall}(t_k) - x_{outerWall}\left(t_k; \underline{p}, P_{Energy}, T_{Ambient}\right)\right)^2$$

# Results

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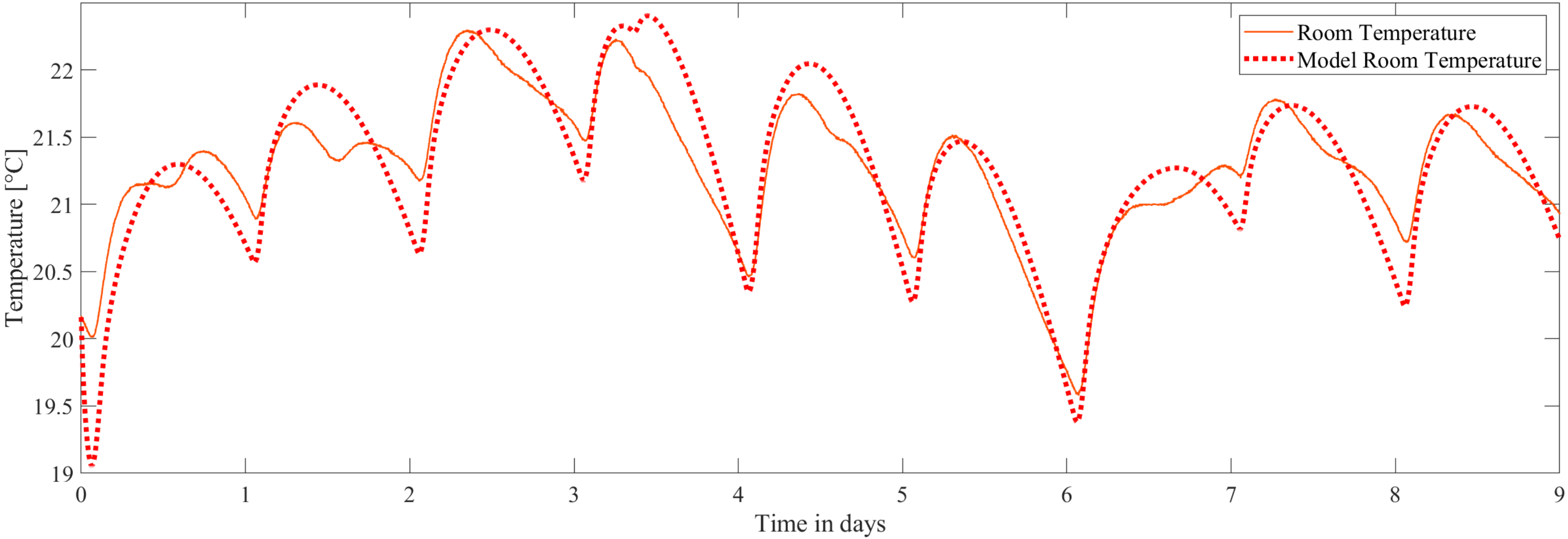
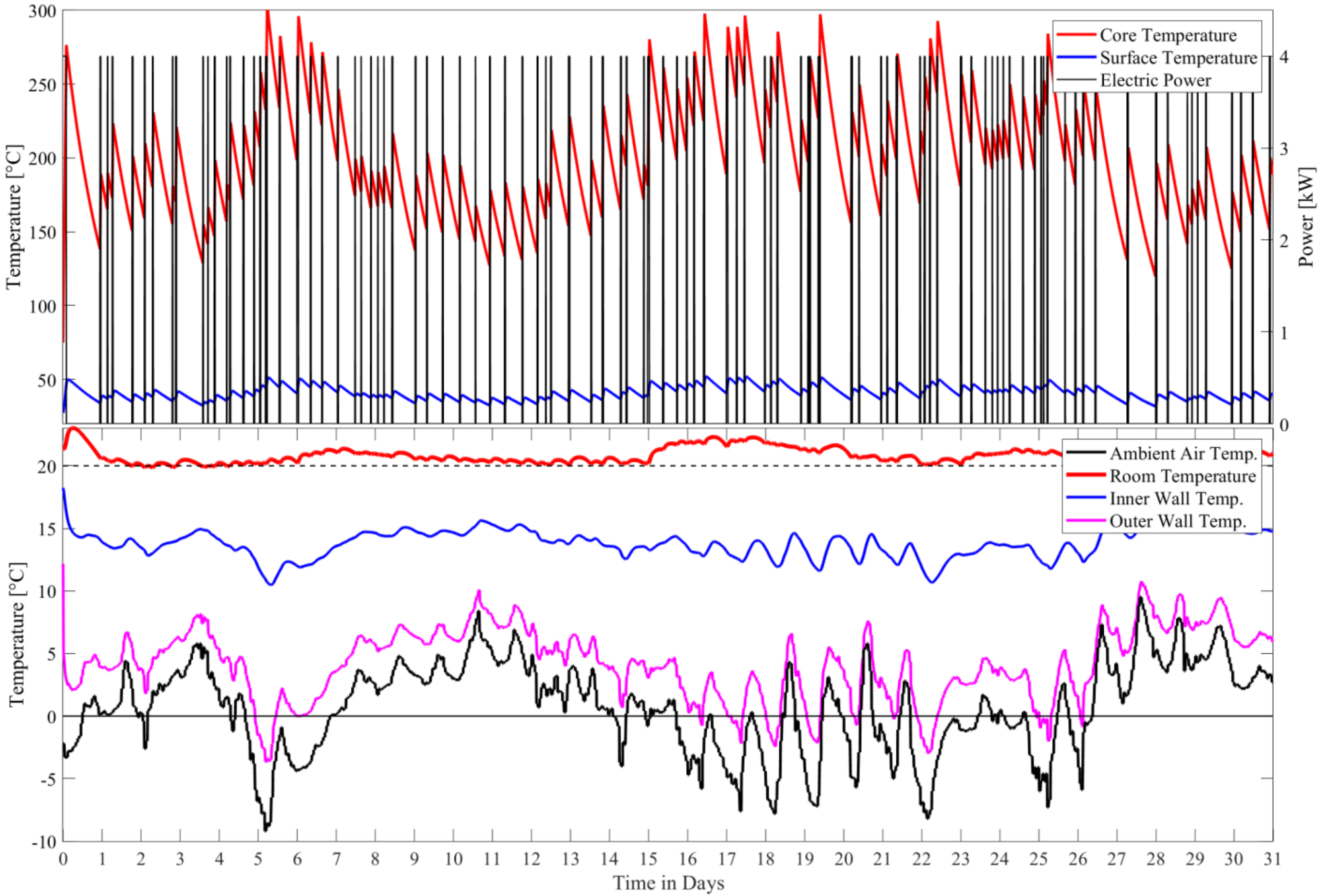
# Results




**Maximum temperature deviation** **0.96 Kelvin**

**Average temperature deviation** **0.21 Kelvin**

# Results - January Ambient Temperature Test Simulation

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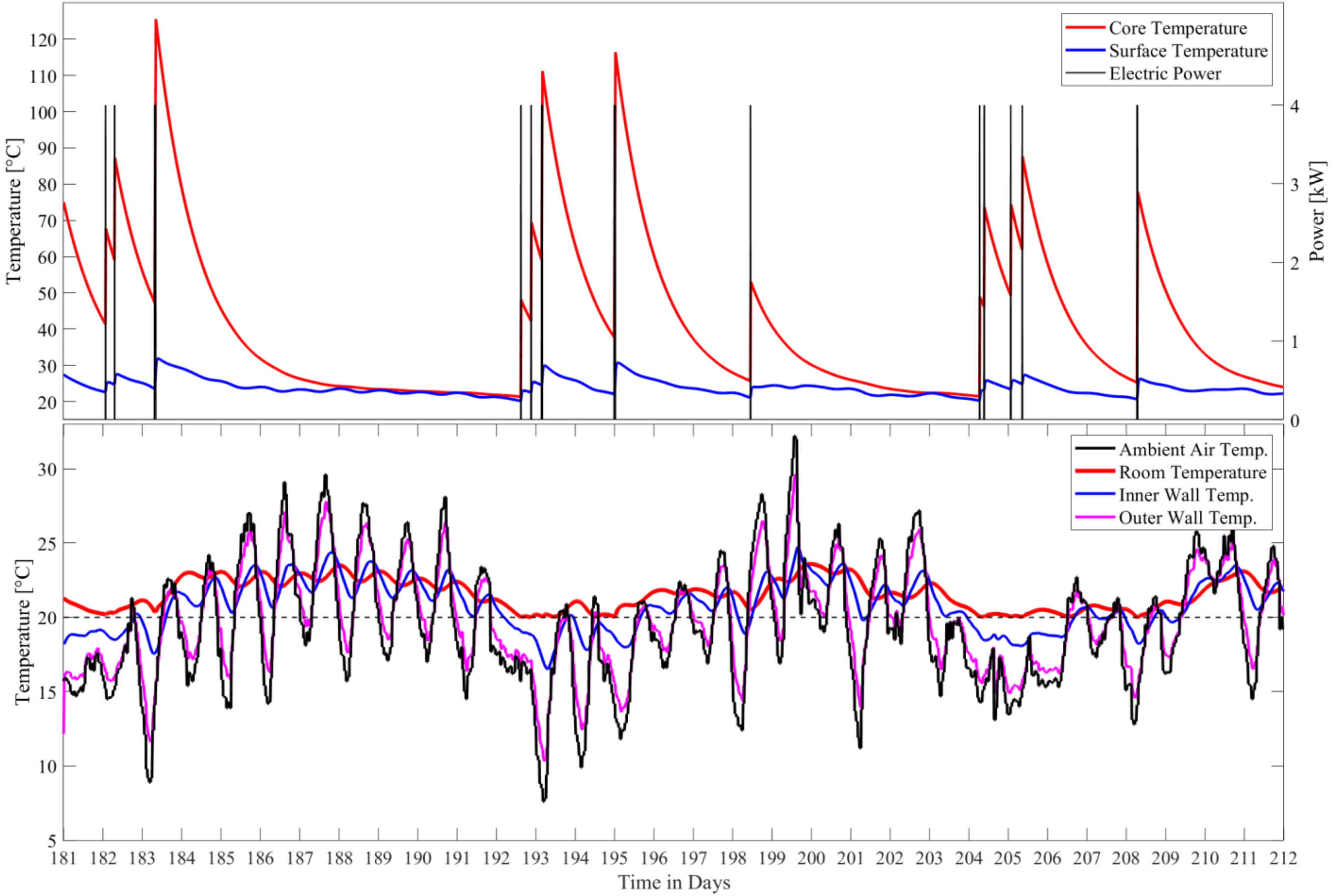
# Results - July Ambient Temperature Test Simulation

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# Outlook

- Apartment comfort temperature is within 20 to 22ºC
- It is controllable with an reliable temperature model

- Energy expenses could be minimized using fluctuating market prices
- Moreover, net-grid-stability could be improved

- Modeling real apartment’s energy dissipation has to be done to apply this method to real world applications

# Thank you for your attention!

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