Measurement and Energy Analysis of Room Heating by Various Electric Heaters and Their Potential for Load Shifting

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1 Task Description

Lucht LHZ Elektroheizung GmbH & Co. KG, based in Burgstädt, is an innovative manufacturer of electric heating systems. With their unique features, these heating systems can play a key role in Germany's efforts to transition to sustainable heating. To take advantage of flexible electricity rates for room heating in the future, the focus is also shifting to the thermal storage capabilities of these heating systems. For this reason, Lucht has designed a new heating unit, the Dynamo, which features an internal thermal storage system. This new heating system is to be analyzed and evaluated using measurement techniques in comparison to the following heating systems from Lucht:

- infrared heating and
- partial storage heating (also known as surface storage heating; the terms are used interchangeably in this study).

These investigations are to be conducted as part of the R&D project in the indoor climate room at the Combined Energy Lab at TU Dresden. The project can be broken down into the following tasks:

- Definition of a suitable experimental setup in the indoor climate room at the Combined Energy Lab at TU Dresden, as well as determination of the necessary measurement points
- Installation and commissioning of the experimental setup
- Conducting a series of measurements for the three different heating systems
    - Dynamo heating system,
    - Infrared heating system and
    - Partial storage heating system

  under various conditions for the application area of stock buildings
- Analysis of measurement data
- Comparison of the various heating systems in terms of thermal storage capacity and heat transfer to the room

2 Test room, measurement technology, and boundary conditions

2.1 General Information

The indoor climate room at TU Dresden (Combined Energy Lab [1]) will be used for the experiments. This room is characterized by the ability to fully control the temperature of all its surrounding surfaces. The range of possible surface temperatures is 5°C ≤ ϑ_W ≤ 50°C. On the air side, temperatures ranging from 10°C ≤ ϑ_{air} ≤ 35°C can be maintained. Figure 1 shows an exterior view of the test chamber. The interior dimensions are W x L x H = (4 x 5 x 2.5) m³.

Figure 1: Indoor climate room at TU Dresden

2.2 Measurement Concept, Experimental Setup and Sensors

The measurement setup was developed and implemented in consultation with the client. The electric heaters are installed in the center of the 4-meter-long side wall (see Figure 2 for the layout).

The following sensors and measuring devices will be installed in the indoor climate room for the analyses:

- Air temperature and globe temperature at three different distances from the electric heater
- NTC sensor positioned above the center of the room

- One-Wire temperature sensors in the temperature-controlled walls for regulating and controlling various load conditions
- SICAM transducers for measuring electrical quantities such as voltage, current, and power

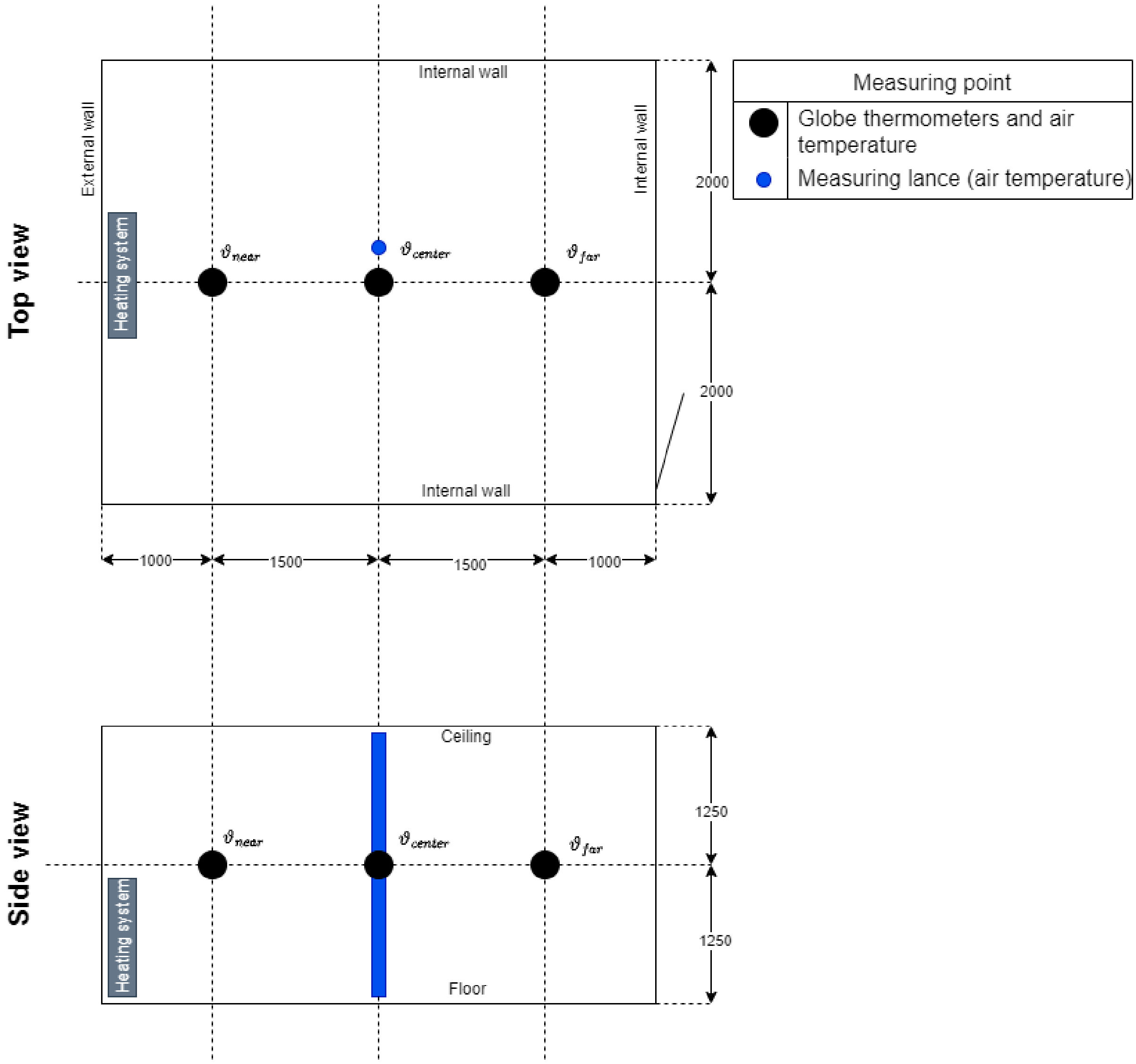

Figure 2: Schematic experimental setup

The positions of the air temperature and globe temperature sensors are shown in Figure 2. Figure 3 shows an example of the entire test setup for the Dynamo heating system. Figure 4 shows the three different heaters installed in the indoor climate room. In addition to wall mounting, the infrared heating system can also be installed on the ceiling; this was tested at three different ceiling positions in the room (see Figure 5). The terms “near,” “center,” and “far” - like the sensor designations - refer to the position relative to the exterior wall (see Figure 2).

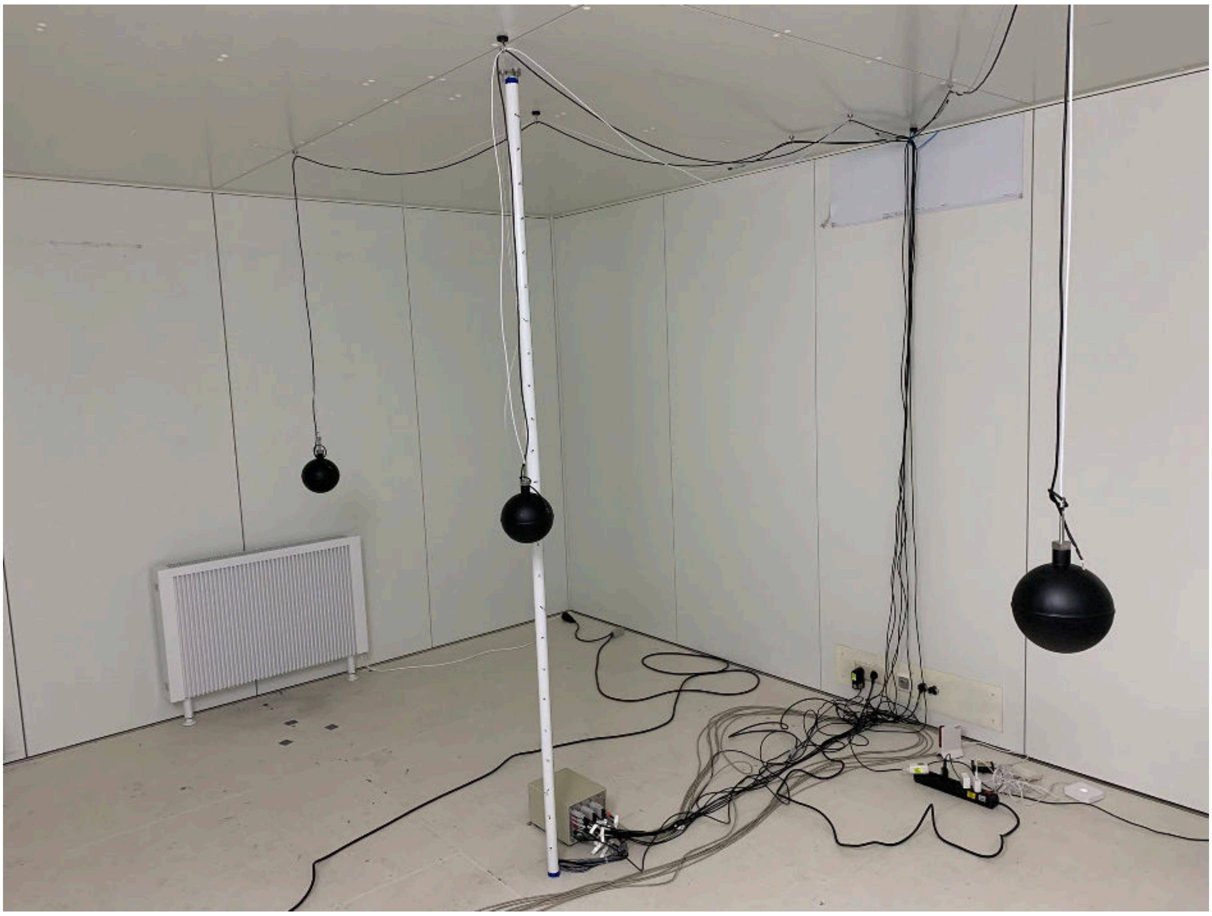

Figure 3: Overall view of the experimental setup with the Dynamo heating system

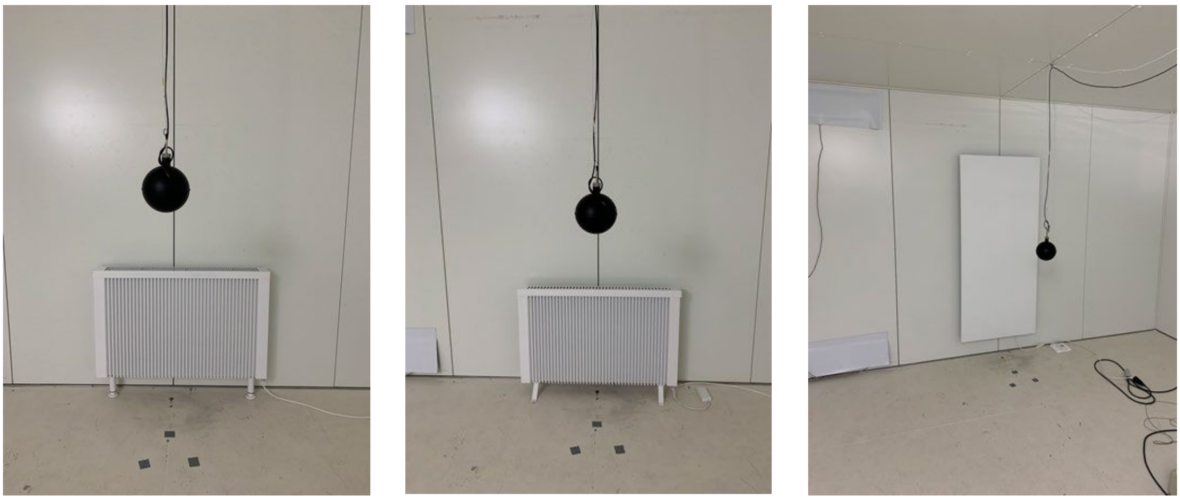

Figure 4: Heating units installed in the indoor climate room – Left: Dynamo heating system; Center: Partial storage heating system; Right: Wall-mounted infrared heating system

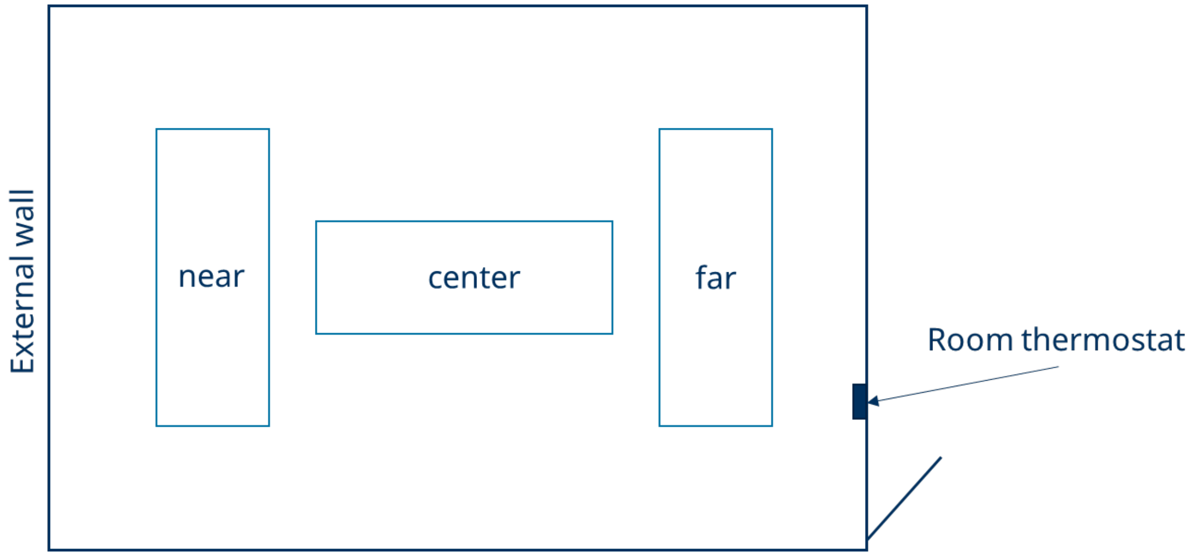

Figure 5: Schematic drawing of the three possible positions for the infrared heating system on the ceiling (top view)

Figure 6 through Figure 8 show the infrared heating system installed on the ceiling in the indoor climate chamber for the three positions.


Figure 6: Infrared heating system mounted on the ceiling – near position

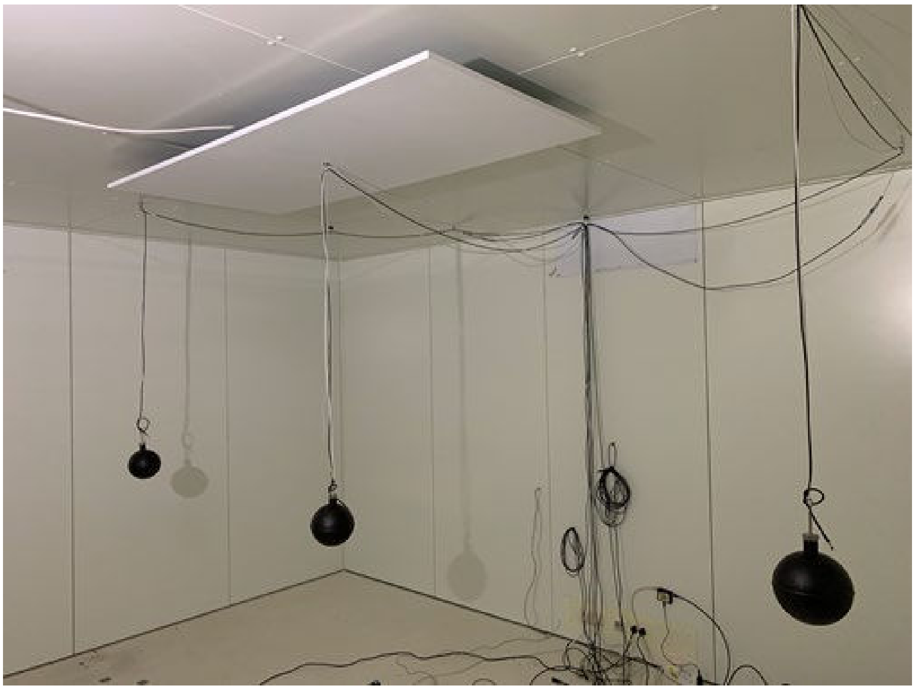

Figure 7: Infrared heating system mounted on the ceiling – center position

Figure 8: Infrared heating system mounted on the ceiling – far position

To summarize the measurement technology, the sensors used and their tolerances are listed in Table 1:

Table 1: Summary of Measurement Techniques and their Accuracy

Name / Measurement point	Type / Manufacturer	Accuracy
Temperature sensor Operating room temperature	PT100 globe thermometer	± (0,1 K + 0,17 % from the measured value)
Temperature sensor Altitude profile	NTC	± (0,2 K)
Combined humidity and temperature sensor Indoor air at medium height	capacitive digital sensor	± (2,0 % Relative humidity from the measured value) ± (0,2 K Temperature from the measured value)
Temperature sensor Wall temperature	One-Wire- Temperature sensor	± (0,5 K)
Transducer electrical power	Siemens SICAM	± (0,2 % from the measured value)

All measured values are recorded and stored at 5-second intervals using a data logger and the corresponding software from Ahlborn.

The electric heater is controlled by the accompanying room thermostat. On the Dynamo heating system, the thermostat is located directly on the heater itself. For the partial storage heating system and infrared heating system the room thermostat was installed next to the door - as is standard practice - see Figure 9. The room thermostat determines the actual temperature for the control loop. Due to its location, this measured value differs from the temperature in the occupied zone - in this study, the “center” measurement point of the globe thermometer. To determine the difference, the air temperature next to the room thermostat and the “center” globe thermometer was recorded for each heating unit in preliminary tests. Subsequently, a correction/calibration was performed via the app by entering an offset. The app was also used to control the electric heating units (turning them on/off and setting the target value) under conditions typical for existing buildings.

Figure 9: Room thermostat next to the door, including a reference measurement point

2.3 Experimental Procedure

In consultation with the client, the tests are to be conducted under boundary conditions typical of existing buildings. The required design heat load for the room is 1500W. To meet this load, the following power classes were selected for the three heating units:

- Dynamo heating system 1500 W
- partial storage heating system 1500 W
- infrared heating system 1550 W

However, the tests are not conducted under design conditions, as these reflect the rare case of very low outdoor temperatures. Instead, the tests are conducted under three different partial-load conditions that are more likely to occur during the winter and transitional seasons. To simulate these conditions, the temperatures of the interior and exterior walls (see Figure 2) are maintained at constant levels for each test variant. Table 2 summarizes the three load cases and the corresponding temperatures of the temperature-controlled walls.

Table 2: Summary of the three load cases and the corresponding temperatures of the temperature-controlled walls of the indoor climate room (percentages relative to a heating load of 1500W)

Variant	Temperature internal wall	Temperature external wall	Load
Load case 85 %	19,5 °C	16,0 °C	1275 W (85%)
Load case 60 %	20,0 °C	17,0 °C	900 W (60%)
Load case 25 %	21,0 °C	17,0 °C	375 W (25%)

Two time periods are required for the analyses. The first time period is intended for charging the heating unit's internal storage reservoir. During this period, the setpoint for the room is low, and whether it is actually reached is of secondary importance, since the room is not in use during this time. The second time period is the usage period, during which a setpoint of 21 °C must be reached to meet the room heating requirements. Figure 10 schematically illustrates the test procedure. In the investigations, a charging time of up to 3 hours and a usage time of up to 4 hours were implemented.
The setpoint change at the start of the usage period was set to 21 °C for all tests. The room temperature during the loading period was determined by the load or by the heating unit being loaded.

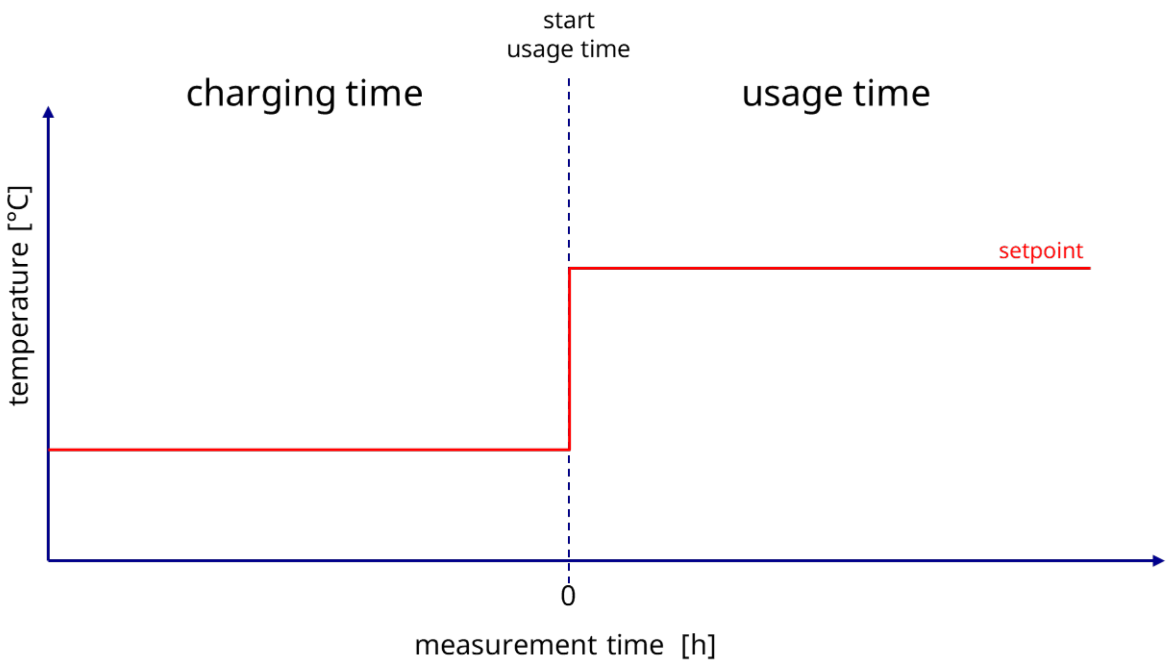

Figure 10: Schematic Overview of the Test Procedure

2.4 Analysis method

For the analysis, the time courses of the following variables

- Globe temperature – near, center, far
- Air temperature – near, center, far
- Electrical power

are analyzed.

Furthermore, the electrical power is accumulated as electrical energy separately for the two time periods: charging time and usage time.

3 Results

This section presents the results of the metrological tests. All analyses are based on a 3-hour charging period[1] and a 4-hour operating period.

3.1 Room effect

First, the room effect of the various heating devices is evaluated in detail for the 60% load case. The diagrams for the other two load cases can be found in the appendix.

3.1.1 Dynamo heating system

Figure 11 shows the time course of the globe and air temperatures, as well as the electrical power.

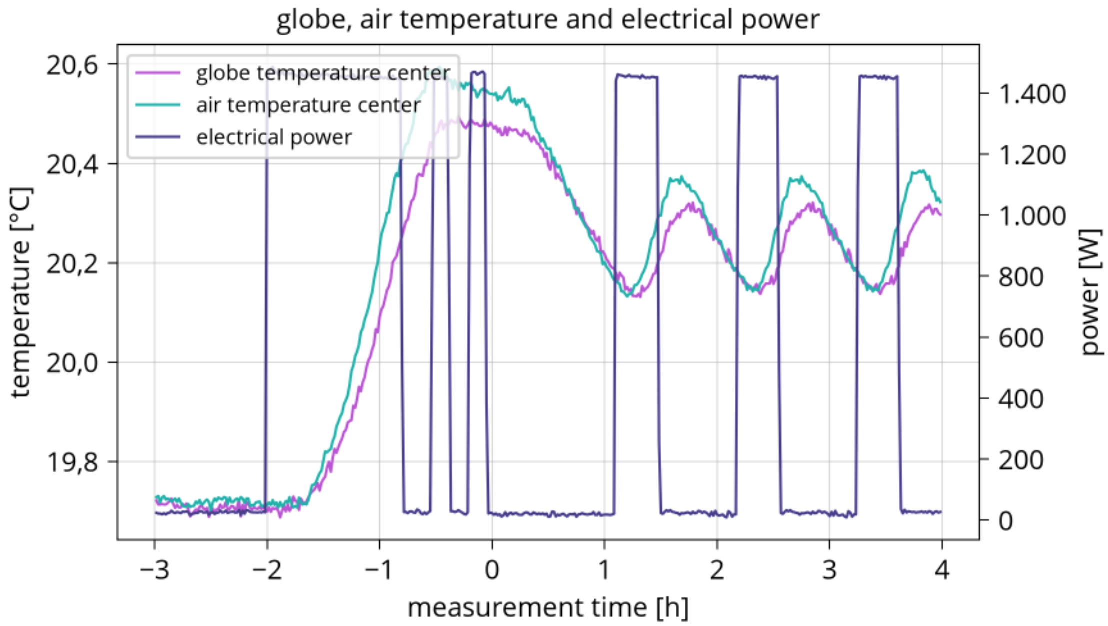

Figure 11: Globe and air temperature curves (center) and electrical power for the **Dynamo heating system** at 60% load, charging time 2 h

The Dynamo heating system has an internal thermal storage unit that is heated during the charging phase. Therefore, electricity consumption begins 2 hours before the system is to be used. Since the thermal storage unit is not isolated from the room, the room temperature begins to rise after approximately 30 minutes as a result of the charging process. After 1 hour and 15 minutes, the maximum storage temperature is reached, and the Dynamo stops charging. As a result of interaction with the room, the storage temperature drops again, triggering another charging cycle until the maximum storage

[1] The maximum period during which the heating system can be charged.

temperature is reached. This cyclical recharging pattern is observable twice before the start of the usage period. At the beginning of the usage period, the room has already reached or slightly exceeded the desired setpoint during the charging period. The internal thermal storage unit continues to release thermal energy, providing heat for the room. After approximately 1 hour and 10 minutes into the usage period, the temperature falls below the setpoint; the thermal energy in the storage unit is no longer sufficient to heat the room, and electrical power is drawn to maintain the setpoint. The system is then regulated to the setpoint by cyclically turning the Dynamo heater on and off. It can also be seen that, during operation, the air temperature in the center of the room is always higher than the globe temperature; this is due to the fact that, because of its finned design, the Dynamo heating system - similar to a partial storage heating system - has a slightly higher rate of convective heat transfer compared to radiant heat transfer.
When examining the room-wide effect of the Dynamo heating system by comparing the temperature sensors at the three positions - far, middle, and near - a small temperature difference ($\Delta\vartheta < 0.5$ K) can be observed; see Figure 12. This means that a homogeneous temperature distribution develops throughout the room.

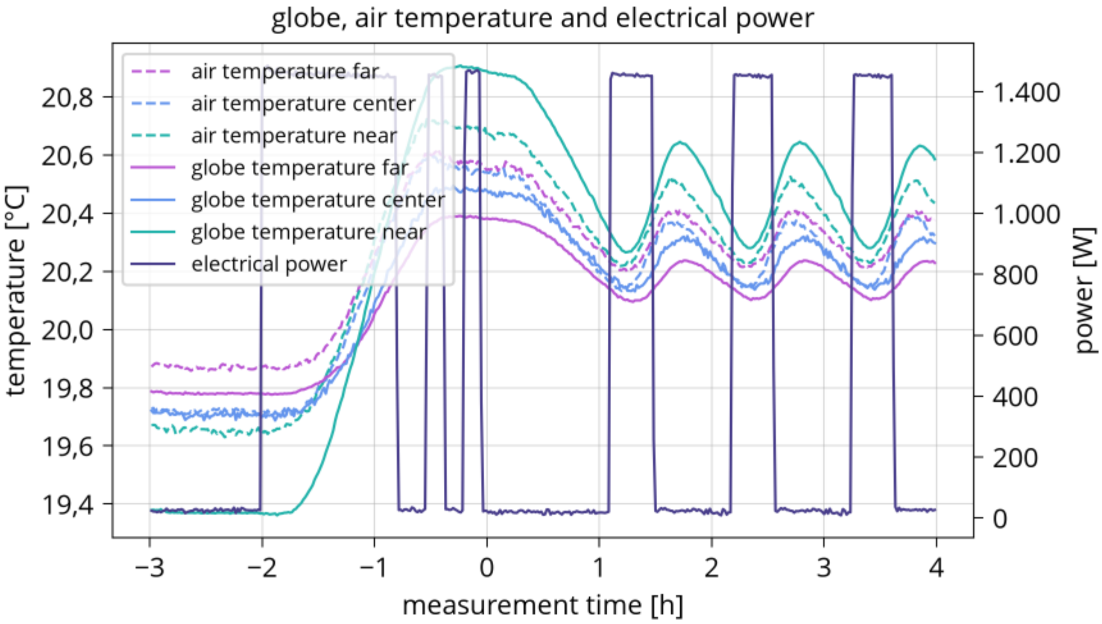

Figure 12: Globe and air temperature curve (far / center / near) as well as electrical power for the **Dynamo heating system** at 60% load, charging time 2 h

In the far field, as described above, the air temperature is always higher than the globe temperature. In the near field, the positioning of the sensors relative to the heater results in an additional radiative effect. However, this effect is considered minor compared to that of other heaters.

To evaluate the effect of the charging time, the experiment is repeated with charging times of 1 hour and 3 hours. Figure 13 shows the time-dependent curves of the globe temperature, air temperature, and electrical power for a charging time of 1 hour.

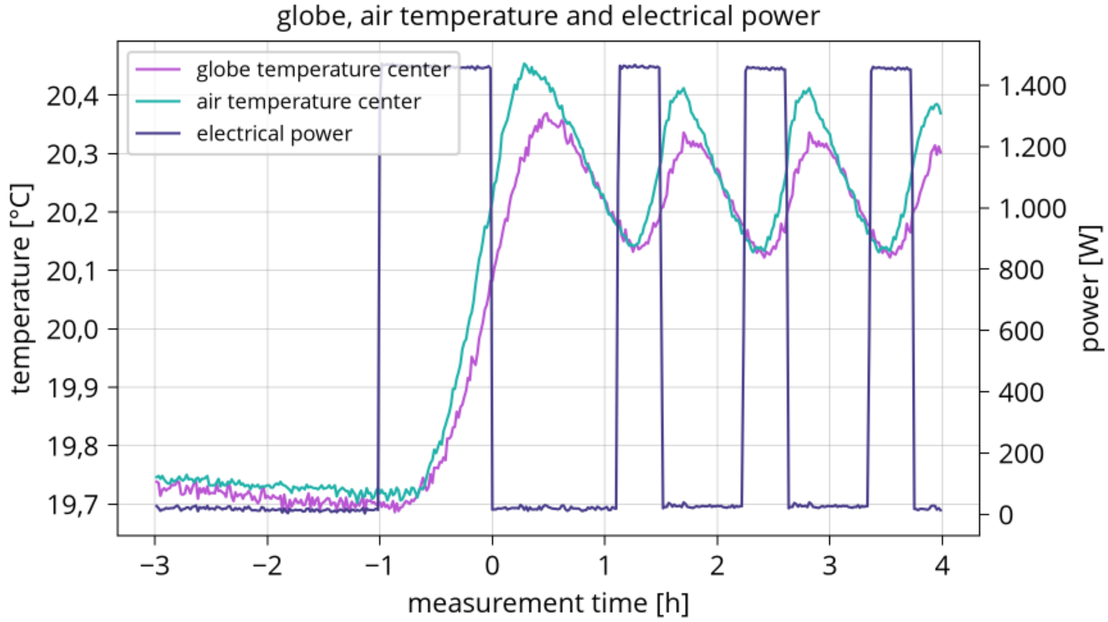

Figure 13: Globe and air temperature curves (center) and electrical power for the **Dynamo heating system** at 60% load, charging time 1 h

It can be seen that during this 1-hour period, the internal thermal storage is charged and the room temperature rises. This behavior is also evident with a charging time of 2 hours. Since the internal maximum storage temperature has not yet been reached, the system does not cycle on and off during the charging period but instead shuts off at the end of the programmed charging time after 1 hour. During the operating period, the same behavior regarding room temperature and the cyclic switching on and off can be observed as with the 2-hour charging time.

With a charging time of 3 hours, the maximum temperature of the internal thermal storage unit is reached - just as it is with a charging time of 2 hours - and cycling occurs during charging; see Figure 14. During this cycling, the room temperature remains nearly constant. During the usage period, the same trend can be observed as with the other two charging times.

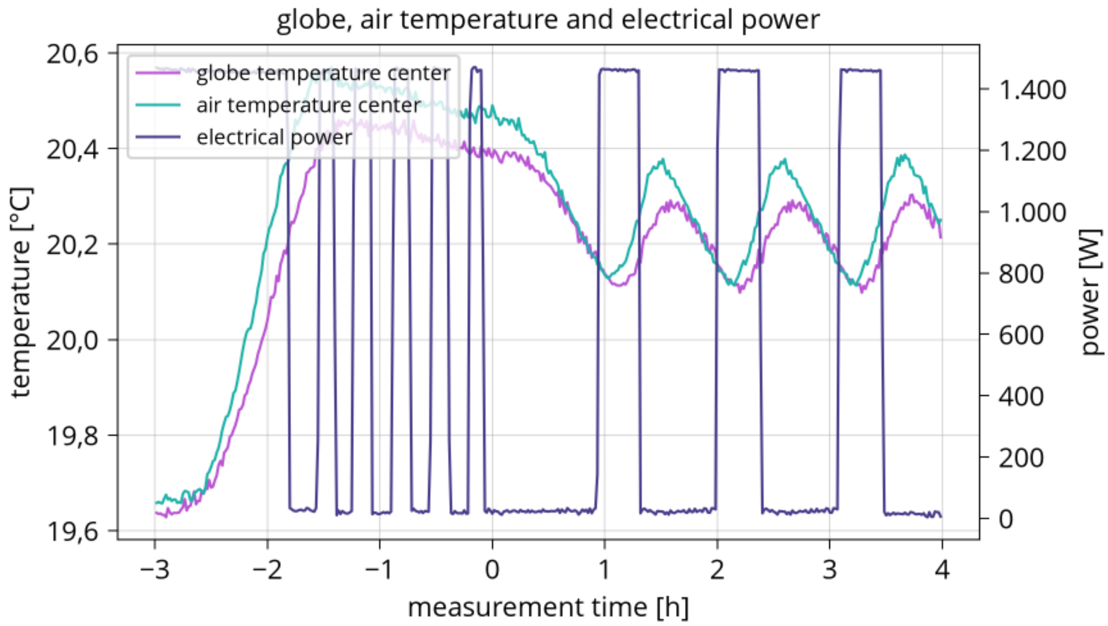

Figure 14: Globe and air temperature curves (center) and electrical power for the **Dynamo heating system** at 60% load, charging time 3 h

As an interim conclusion, it can be stated that, under the present experimental conditions, a charging time of 1 h 15 min is sufficient to fully charge the internal thermal storage system. For this reason, for the further analyses in Sections 3.2 and 3.3, only the last 1 hour of the potential 3-hour charging time will be used.
Similar relationships can be observed for the 25% and 85% load cases; see Figure 15 and Figure 16 in the appendix.

3.1.2 Partial storage heating system

Figure 15 shows the temporal course of the globe and air temperatures, as well as the electrical power.

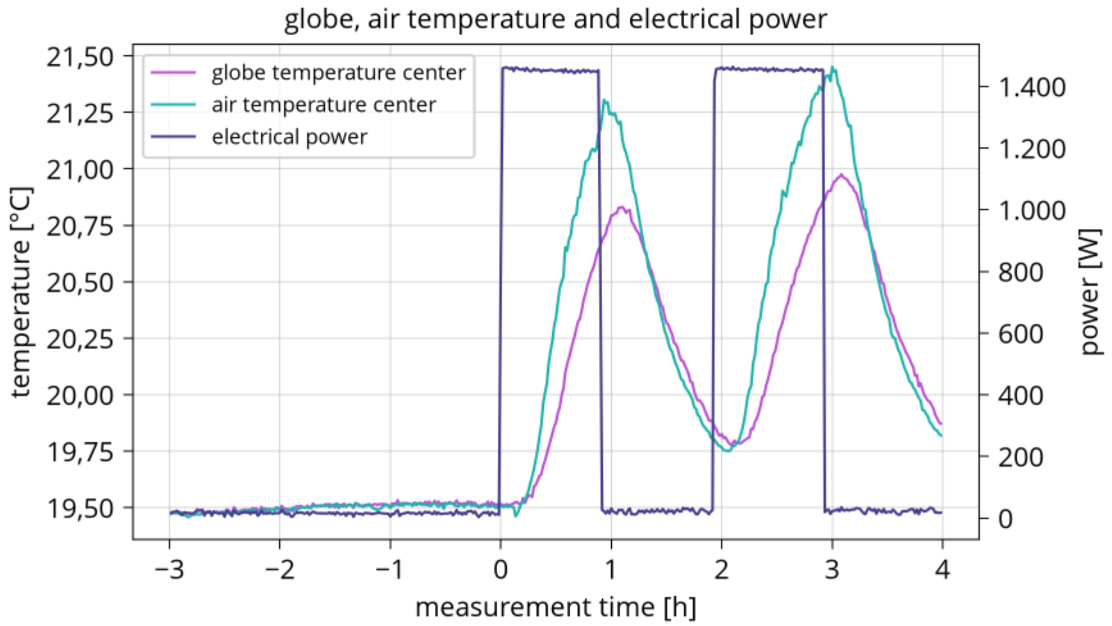

Figure 15: Globe and air temperature curves (center) and electrical power for the **Partial storage heating system** at 60% load

The partial storage heating system does not have a charging function; therefore, electrical power consumption does not begin until the start of the usage period (measurement time 0 h). The room temperature rises rapidly, and after approximately 50 minutes, the setpoint is reached for the first time, causing the partial storage heating system to shut off. The partial storage heating system has an internal thermal storage unit that is charged in parallel with the room heating. Thanks to this charging, the heat stored in the partial storage heater is sufficient to maintain the setpoint for approximately 1 hour after the heater shuts off. If the room temperature falls below the setpoint, a new cycle begins with room heating and charging of the internal thermal storage unit. It can also be seen that, during operation, the air temperature in the center of the room is always higher than the globe temperature. Thanks to its finned design, the partial storage heating system combines the heat transfer mechanisms of convection and radiation in a nearly balanced ratio; see also [2].
When examining the room effect of the partial storage heating system by comparing the temperature sensors at the three positions - far, middle, and near - a slight temperature difference ($\Delta\vartheta$ < 0.5 K) can be observed; see Figure 16. A homogeneous temperature distribution develops in the room, which is consistent with the results of the study in [3].

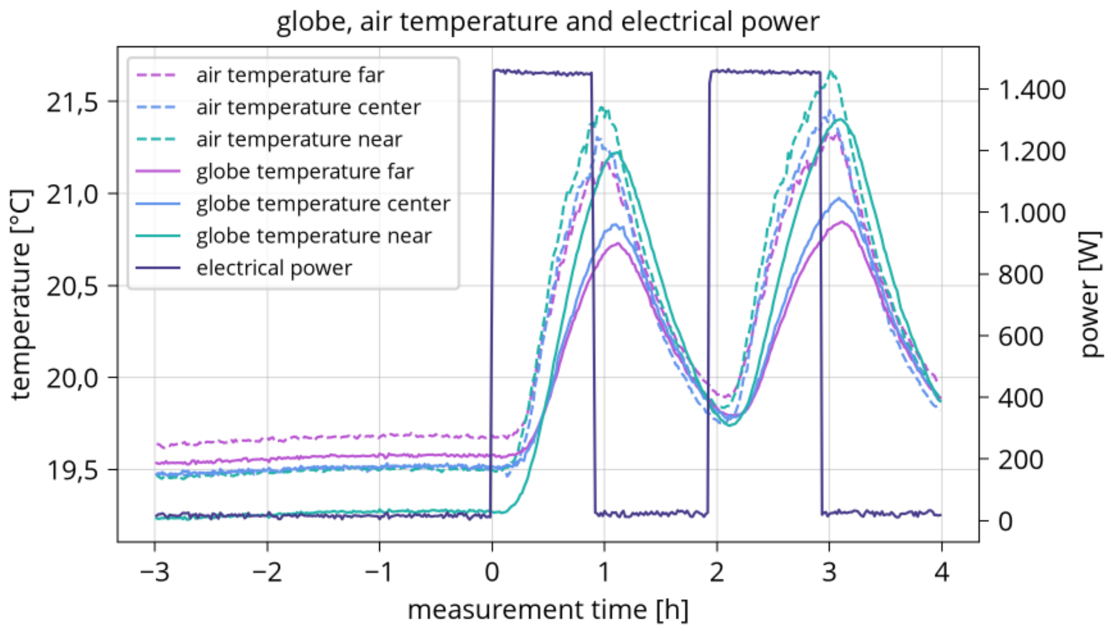

Figure 16: Globe and air temperature curve (far / center / near) as well as electrical power for the **Partial storage heating system** at 60% load

In the near zone, the positioning of the sensors relative to the heater results in an increased radiative effect. This causes the globe temperature to be approximately 0.5 K higher than at the measurement points in the middle and at a distance.

Similar relationships can be observed for the 25% and 85% load cases; see Figure 19 and Figure 20 in the appendix.

3.1.3 Infrared Heating System - wall

Figure 17 shows the course of globe temperature, air temperature, and electrical power over time.

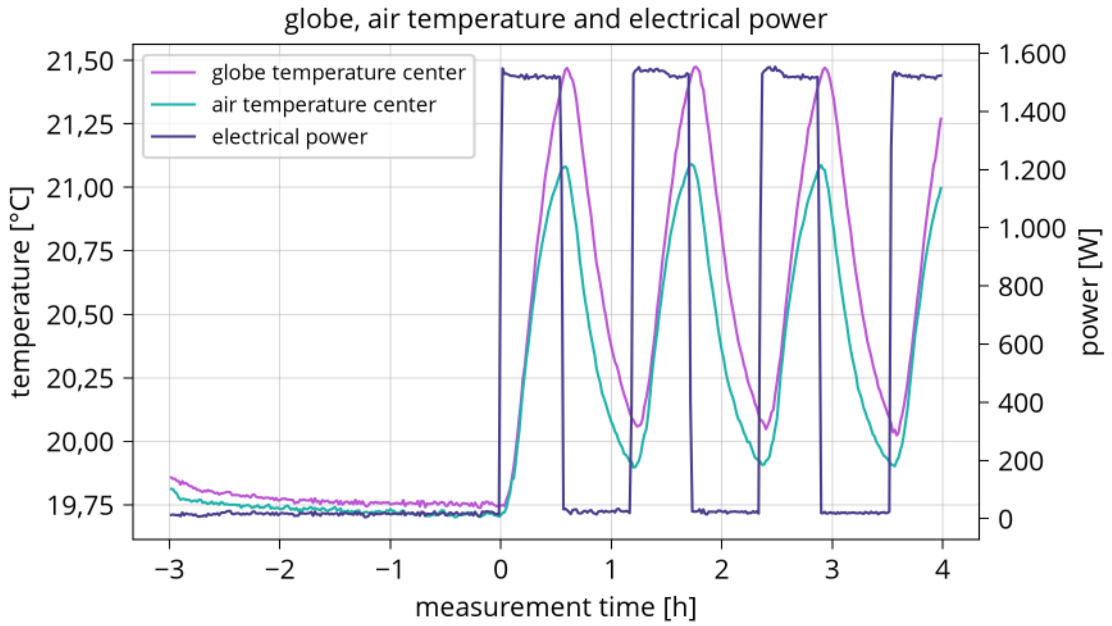

Figure 17: Globe and air temperature curves (center) and electrical power for the **infrared heating system wall** at 60% load

The infrared heating system is a fast-responding, occupancy-based heating system and therefore begins heating the room as soon as the usage period starts. Due to the system's low thermal inertia, the setpoint is reached after approximately 35 minutes, at which point the infrared heating system shuts off. The room then cools down, and depending on the switching hysteresis of the room thermostat, the system turns back on after approximately 40 minutes. The system is then turned on and off cyclically by the room thermostat control. Compared to the Dynamo heating system and partial storage heating system, the globe temperature is always higher than the air temperature. This is because, in infrared heating, radiation plays a larger role as a heat transfer mechanism. This effect also causes the globe temperature in the near field to be significantly higher than in the middle and far fields (on average, about 4 K); see Figure 18. These effects were also demonstrated in the study [3].

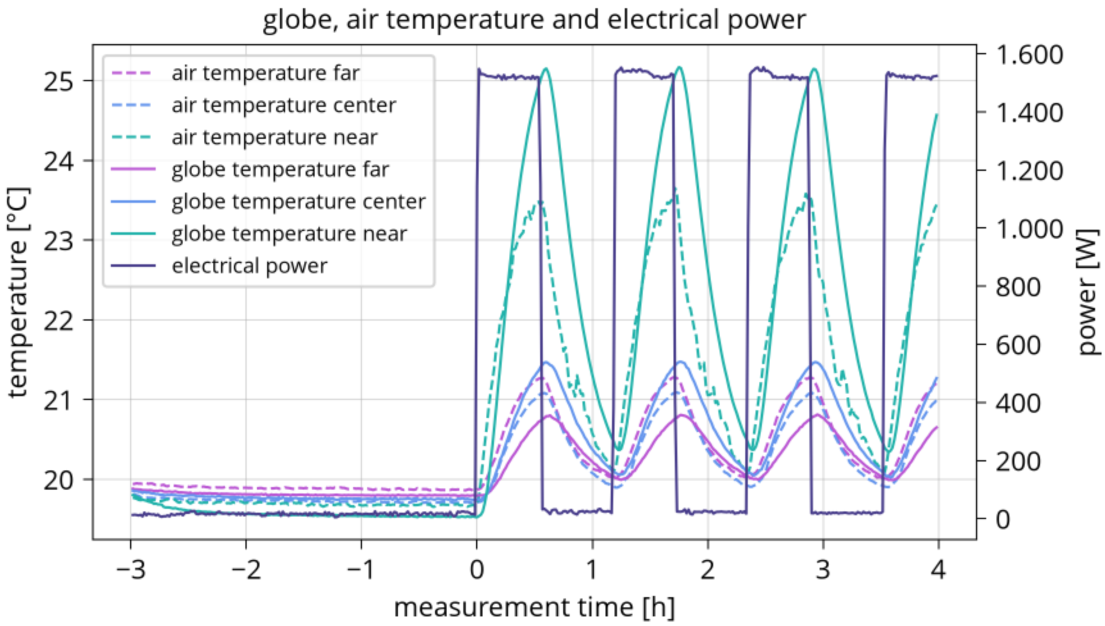

Figure 18: Globe and air temperature curve (far / center / near) as well as electrical power for the **infrared heating system wall** at 60% load

Similar relationships can be observed for the 25% and 85% load cases; see Figure 23 and Figure 24 in the appendix.

3.1.4 Infrared Heating System - ceiling

The results for the three ceiling installations examined are explained below.

3.1.4.1 Infrared Heating System – ceiling - near

Figure 19 shows the time course of the globe and air temperatures, as well as the electrical power.

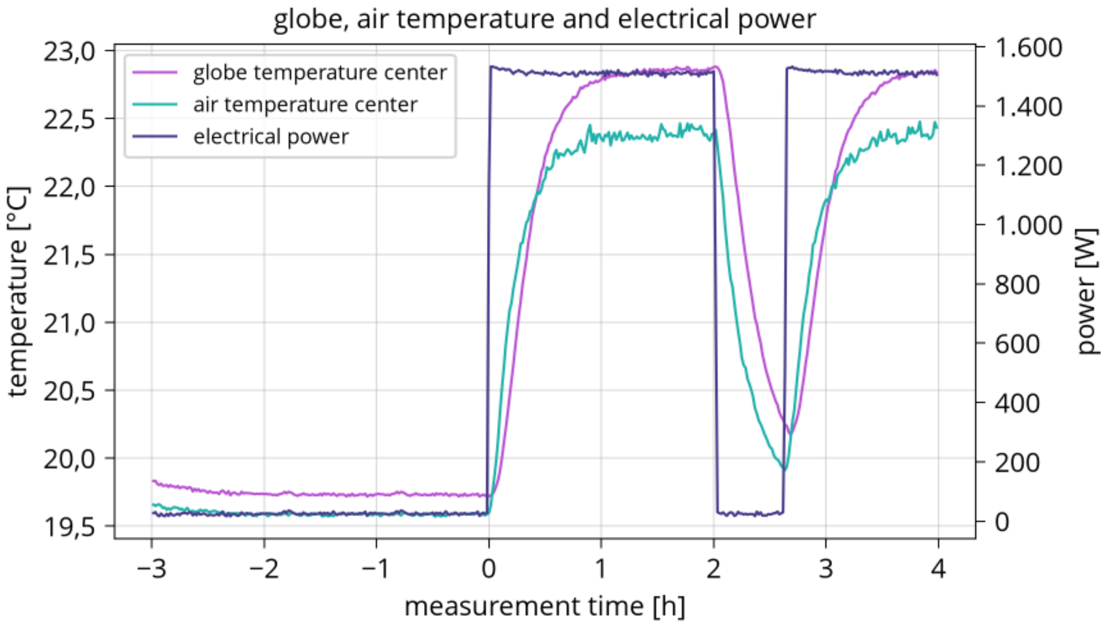

Figure 19: Globe and air temperature curves (center) and electrical power for the **infrared heating system ceiling near** at 60% load

With infrared heating, the room begins to heat up as soon as the operating period starts. It can be seen that the room temperature rises and the setpoint is also reached in the center of the room. Due to the positioning of the room thermostat, the infrared heating system is only turned off briefly. In the 85% load case, continuous operation occurs because this value is not reached despite the setpoint correction; see Figure 27. In the 25% load case, the setpoint is reached, and the described cyclic on-off operation of the infrared heater can also be observed in the ceiling-mounted configuration (see Figure 26 in the appendix).

In this case, the radiant effect of the infrared heater is clearly visible at the two Globetemperature measurements - the near and the center. Both values are significantly higher than the respective air temperatures and the far measurement points; see Figure 20. It can be seen that a temperature difference of up to 3 K develops between the near and far positions.

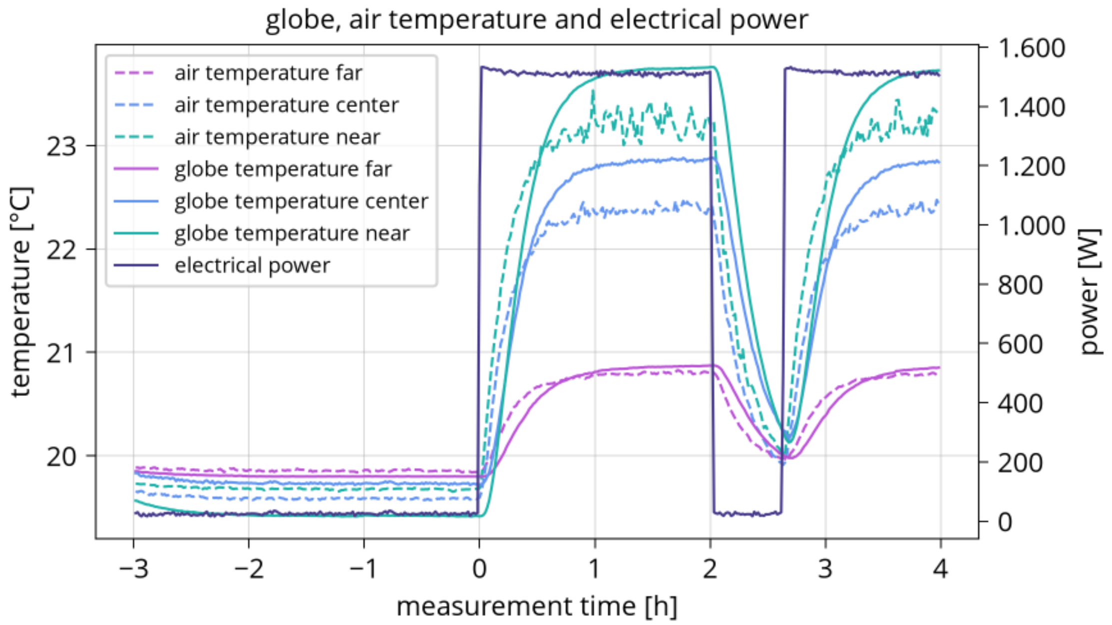

Figure 20: Globe and air temperature curve (far / center / near) as well as electrical power for the **infrared heating system ceiling near** at 60% load

Additional results are shown in Figure 27 and Figure 28 in the appendix.

3.1.4.2 Infrared Heating System – ceiling - center

Figure 21 shows the time course of the globe and air temperatures as well as the electrical power. Compared to the "near" position, it is evident that the setpoint is reached more quickly and that cyclic oscillation around this value occurs three times during the observation period. Looking at the temperatures in the room, it is evident that the center of the room is significantly warmer than the "near" and "far" areas; see Figure 22. Due to the positioning of the infrared heater, the center of the room is up to 2 K warmer than the other two areas, which maintain very similar temperature levels. In the 85% load case, continuous operation occurs - as with the "near" positioning - for the reason described above.

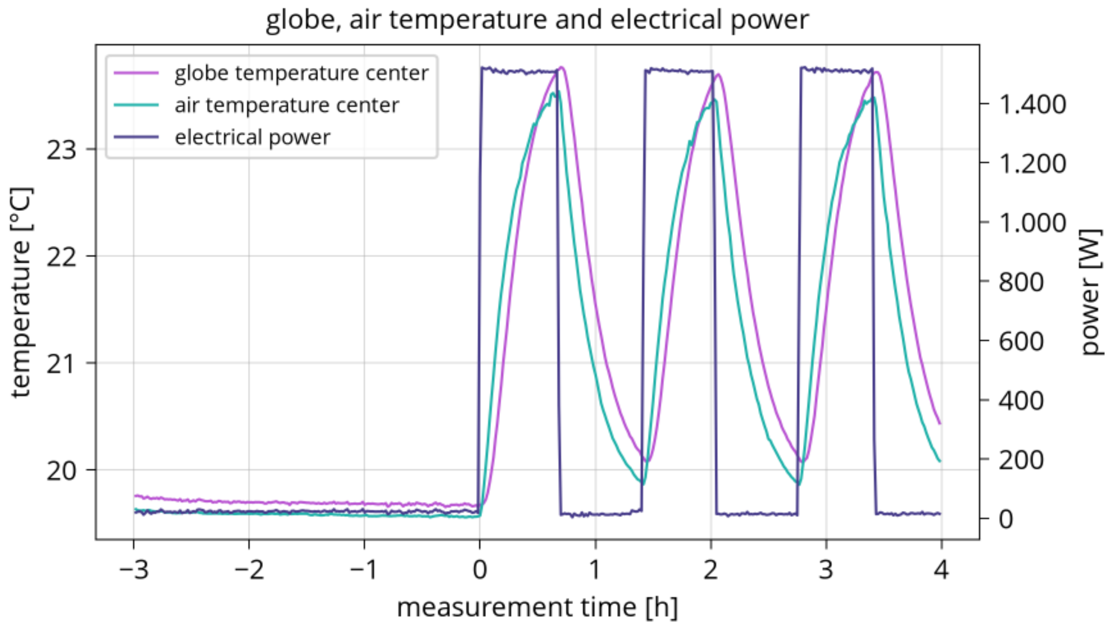

Figure 21: Globe and air temperature curves (center) and electrical power for the **infrared heating system ceiling center** at 60% load

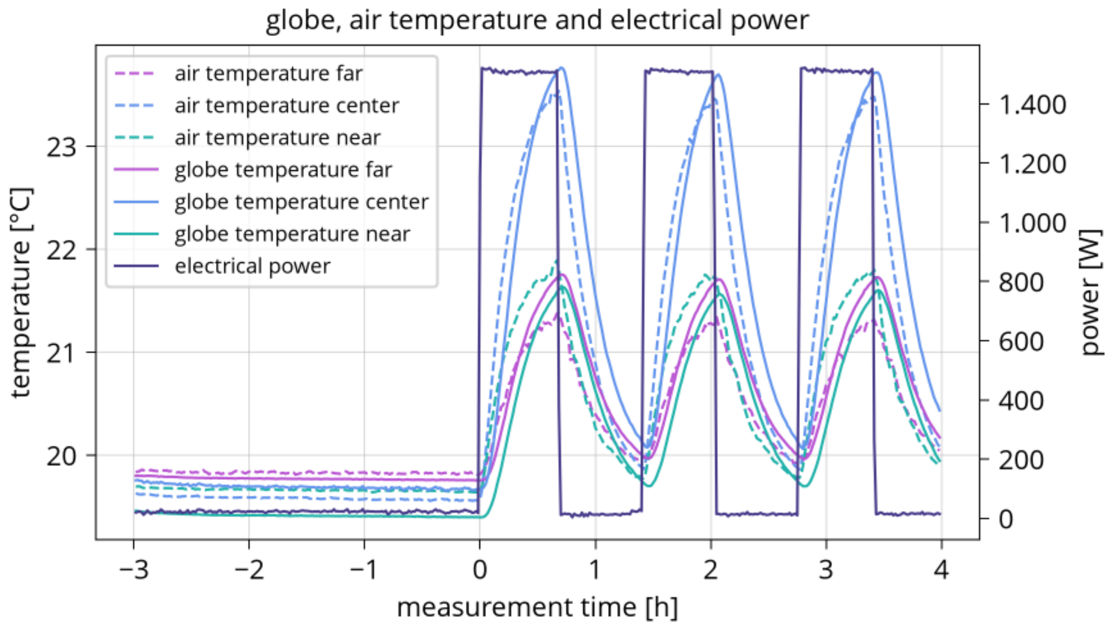

Figure 22: Globe and air temperature curve (far / center / near) as well as electrical power for the **infrared heating system ceiling center** at 60% load

Additional results are shown in Figure 31 and Figure 32 in the appendix.

3.1.4.3 Infrared Heating System - ceiling - far

Figure 23 shows the course of the globe and air temperatures as well as the electrical power over time. When the infrared heater is positioned away from the exterior wall and close to the room thermostat, it can be seen that the setpoint is reached much more quickly and that frequent, brief cycling occurs to maintain the setpoint.

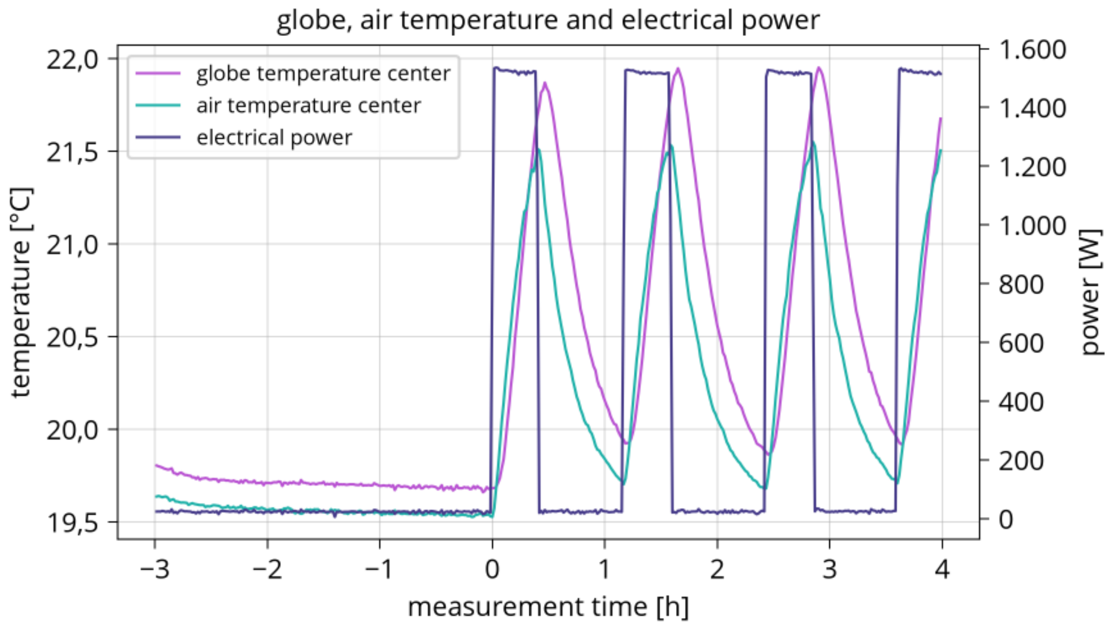

Figure 23: Globe and air temperature curves (center) and electrical power for the **infrared heating system ceiling far** at 60% load

Here, too, the positioning has a significant influence on the temperatures that develop in the room. While the highest temperatures now occur in the far field, temperatures in the near field are up to 3 K lower; see Figure 24.

Additional results are shown in the appendix in Figure 35 and Figure 36.

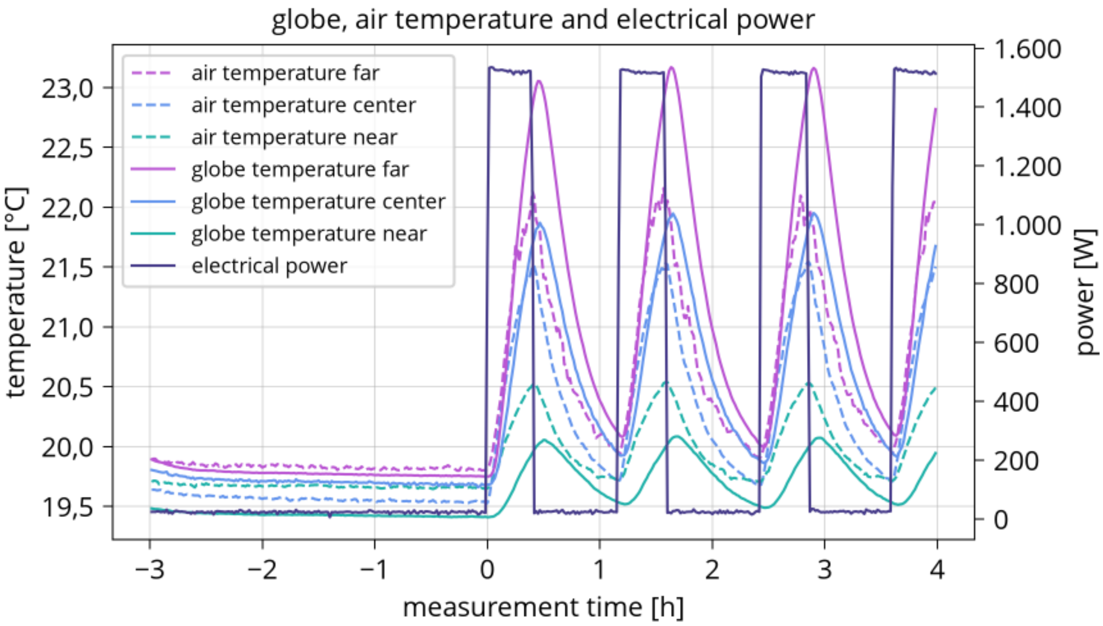

Figure 24: Globe and air temperature curve (far / center / near) as well as electrical power for the **infrared heating system ceiling far** at 60% load

To summarize the room effect of heating the room, the maximum temperature differences between the measurement points - near, center, and far - were determined. To do this, the feeling temperature (Globe temperature) was analyzed.

Table 3 summarizes the differences in feeling temperature[2] for all heating devices and load cases. It can be seen that the Dynamo and partial storage heating systems ensure a very uniform feeling temperature in the room. The infrared heating system, on the other hand, causes local variations in feeling temperature. Depending on their positioning, differences of up to 4.6 K can occur. For example, in the case of ceiling installation at a distance and a load case of 60%, this means that there is a temperature difference of 20 °C to 23.2 °C (corresponding to a difference of -3.2 K) between the near and center positions in the room.

From the perspective of thermal comfort, this difference will cause discomfort for the user. Furthermore, it can be noted that if the user is positioned directly beneath the infrared heater, local comfort criteria - such as radiation asymmetry - may no longer be met.

[2] Temperature differences between Celsius values are expressed in kelvins [K]

Table 3: Comparison of the maximum differences in feeling temperatures in the room for all heating devices and experiments

heating system	Load case	Temperature difference near-center in K	center-far in K	near-far in K	max in K
Dynamo (charging time 1 h)	25%	0,20	0,05	0,25	0,25
	60%	0,35	0,10	0,45	0,45
	85%	0,45	0,00	0,45	0,45
partial storage	25%	0,30	0,10	0,40	0,40
	60%	0,50	0,05	0,55	0,55
	85%	0,45	0,05	0,50	0,50
infrared wall	25%	3,30	0,50	3,80	3,80
	60%	3,60	0,70	4,30	4,30
	85%	3,90	0,70	4,60	4,60
infrared ceiling near	25%	0,75	1,90	2,65	2,65
	60%	0,90	1,90	2,80	2,80
	85%	1,00	1,80	2,80	2,80
infrared ceiling center	25%	-2,10	1,70	-0,40	2,10
	60%	-2,20	2,00	-0,20	2,20
	85%	-2,00	2,00	0,00	2,00
infrared ceiling far	25%	-1,55	-1,10	-2,65	2,65
	60%	-1,90	-1,30	-3,20	3,20
	85%	-2,10	-1,40	-3,50	3,50

3.2 Energy Analysis

The following section analyzes the energy consumption for room heating across the various heating systems. To do this, it is first necessary to verify the extent to which the same room temperatures were achieved in the various tests. Table 4 in the appendix summarizes the average temperature established in the room during the operating period. It can be seen that all heating systems, including their control mechanisms, are capable of achieving a nearly uniform average room temperature (average of the air temperature at the center and the globe temperature at the center) for all load cases. This allows for an energy comparison of the heating systems. Only the ceiling-mounted infrared heater results in a higher temperature in the center of the room; however, as described in Section 3.1.4, this is due to the positioning of the room thermostat.

Table 4 below summarizes the electrical energy consumption required for room heating, separately for the loading period and the operating period (4 hours), during a test for the analyzed devices as well as for the various partial-load conditions.

Table 4: Summary of the energy required during loading and operating times, the relationship to the dynamo, and the maximum temperature difference in the room for the various heating devices and the various load cases

heating system	Load case	Power charging time in Wh	Power usage time in Wh	Ratio to Dynamo	max. temp. difference in K
Dynamo (charging time 1h)	25%	1448,4	942,7	1,0	0,25
	60%	1490,7	1752,5	1,0	0,45
	85%	1399,6	2621,6	1,0	0,45
partial storage	25%	88,9	2347,8	2,5	0,40
	60%	61,4	2813,0	1,6	0,55
	85%	51,7	3299,7	1,3	0,50
infrared wall	25%	46,5	2047,0	2,2	3,80
	60%	67,8	3236,1	1,8	4,30
	85%	62,3	4051,8	1,5	4,60
infrared ceiling near	25%	76,4	2857,3	3,0	2,65
	60%	67,5	5143,3	2,9	2,80
	85%	67,0	6053,9	2,3	2,80
infrared ceiling center	25%	49,7	1524,2	1,6	2,10
	60%	87,5	2973,2	1,7	2,20
	85%	58,7	6054,8	2,3	2,00
infrared ceiling far	25%	76,3	1501,7	1,6	2,65
	60%	85,0	2564,9	1,5	3,20
	85%	85,5	3366,1	1,3	3,50

The low values during the charging period for the partial storage heating system and infrared heating system are due to standby power consumption.

It can be seen that the Dynamo heating system shows almost identical values during the charging period, regardless of the load. This is due to the 1-hour charging period, during which the internal storage unit is charged almost completely; its thermal capacity is approximately independent of the load in the room. Because of this internal thermal storage, the Dynamo heating system requires the least amount of energy during the operating period in every load scenario. All other heating systems require more energy during the operating period. As a result, the ratio relative to the Dynamo heating system is always greater than 1.0.

When comparing the other heating systems with one another, it becomes apparent that, at the lowest partial load (25% load case), the wall-mounted infrared heating system requires slightly less energy than the partial storage heating system to reach and maintain the room temperature. In the other two load cases, however, the partial storage heater requires less energy than the infrared heating system. At the same time, the partial storage heater ensures a uniform temperature distribution throughout the room (< 0.5 K)

across all load cases, whereas the wall-mounted infrared heating system exhibits a significant inhomogeneity in temperature distribution.
If we consider only the effect of the infrared heating system's position on the ceiling, we can summarize for all load conditions that the closer the infrared heating system is installed to the room thermostat, the lower the energy required to reach and maintain the setpoint. However, this is also associated with an uneven temperature distribution in the room.

Figure 25 shows a graphical comparison of energy consumption relative to that of a Dynamo heating system.

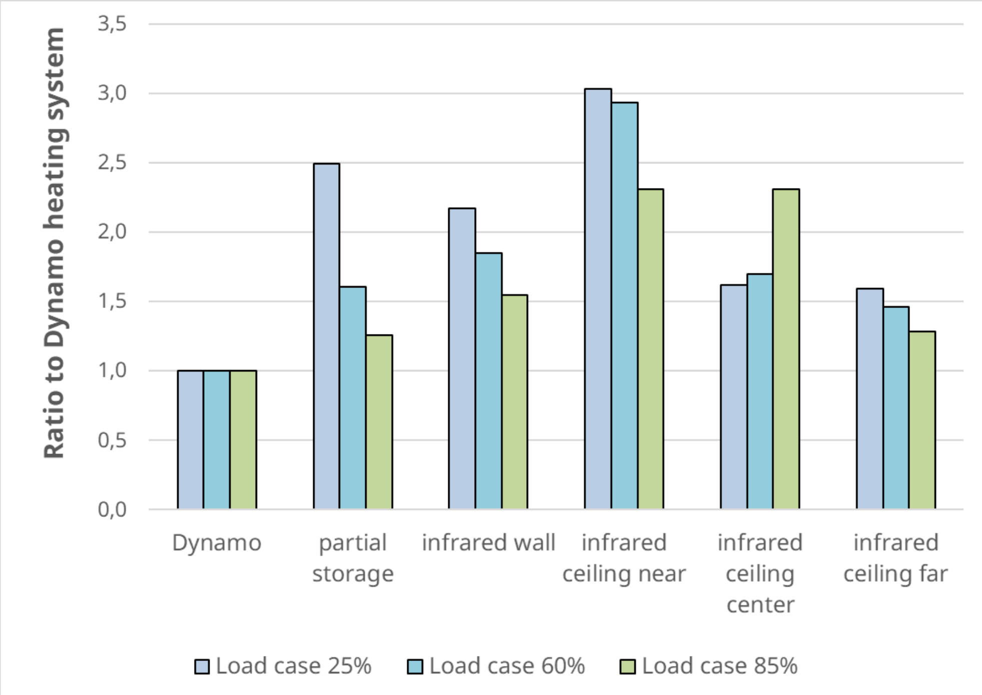

Figure 25: The energy consumption of the heating devices studied compared to that of a Dynamo heating system

When considering the effect of charging time on the Dynamo heating system, it can be observed that the amount of electrical energy required increases as the charging time increases. For a charging time of 1 hour under the 60% load case, for example, this amounts to 1490,7 Wh (see Table 4); for 2 hours, it is 2236,9 Wh; and for 3 hours, it is 2843,6 Wh. For the operating time, however, the energy consumption is approximately the same for all three charging times (≈1750 Wh for 1 hour and ≈1700 Wh for 2 and 3 hours).

3.3 Economic Analysis of Energy Consumption

The operation of the various heating devices is evaluated in monetary terms by considering different pricing scenarios. Three different electricity pricing scenarios are used for this analysis; see Table 5. Only the variable rate is taken into account; other cost factors, such as the base rate or investment costs, are not considered.

Table 5: Overview of Pricing Scenarios

Scenario	Description	Price Loading	Price for Use
1	Fixed electricity rate	0,30 €/kWh	0,30 €/kWh
2	Dynamic electricity rate	0,15 €/kWh	0,40 €/kWh
3	Combining PV electricity with a fixed electricity rate	0,08 €/kWh	0,30 €/kWh

Scenario 1 assumes a fixed electricity price for all operating periods. There is no price differentiation between charging and usage periods.
A dynamic electricity rate is assumed in Scenario 2. Under this scenario, the low rate applies during the loading period and the high rate applies during the usage period. For the purposes of the analysis, it is assumed that the switch between the low and high rates occurs at the start of the usage period.
Scenario 3 assumes that surplus PV electricity is available during the loading period, for which feed-in tariffs could have been earned as an alternative to using the electricity in the heating system. A fixed electricity price is assumed during the period of use.
These three scenarios are applied to and compared for all heating systems. The basis for this is the energy required (see Table 4) by the various heating systems for the different load cases. Table 6 summarizes the resulting costs. It can be seen that, regardless of the heating system, energy demand increases with rising load during the charging and operating periods - and thus costs also rise - for all cases considered.
Price Scenario 1 ensures that all energy consumed costs the same amount per load case. Since the Dynamo heating system, in most cases, consumed slightly more energy in total during its operating and usage periods than the partial storage heating system and infrared heating system, costs are sometimes higher depending on the load case.
If a dynamic electricity rate is used, the energy consumed during charging and usage periods is priced differently. As a result, the operating costs for the Dynamo heating system are, in most cases, lower than those for partial storage heating system and infrared heating system. This effect is further amplified in Scenario 3, as the use of self-generated PV electricity during the charging period reduces costs even more significantly.

Table 6: Comparison of operating costs for the heating Systems for various load cases and price scenarios

heating system	Load case	costs		
		Scenario 1 in €	Scenario 2 in €	Scenario 3 in €
Dynamo (charging time 1h)	25%	0,72	0,59	0,40
	60%	0,97	0,92	0,64
	85%	1,21	1,26	0,90
partial storage	25%	0,73	0,95	0,71
	60%	0,86	1,13	0,85
	85%	1,01	1,33	0,99
infrared wall	25%	0,63	0,83	0,62
	60%	0,99	1,30	0,98
	85%	1,23	1,63	1,22
infrared ceiling near	25%	0,88	1,15	0,86
	60%	1,56	2,07	1,55
	85%	1,84	2,43	1,82
infrared ceiling center	25%	0,47	0,62	0,46
	60%	0,92	1,20	0,90
	85%	1,83	2,43	1,82
infrared ceiling far	25%	0,47	0,61	0,46
	60%	0,79	1,04	0,78
	85%	1,04	1,36	1,02

In summary, it can be concluded that Price Scenario 1 is appropriate for the partial storage heating system and infrared heating system, as these are not equipped to interact with dynamic electricity rates. The dynamic electricity rate (Scenarios 2 and 3) should be used for the Dynamo heating system, as its internal thermal storage and electrical circuitry allow it to take advantage of the potential for shifting energy consumption to the lower-cost rate.

4 Summary and Conclusion

As part of the study, various heating devices were examined for heating a room in an existing building (room heating load of 1500 W) under different partial-load conditions for an assumed operating time of 4 hours. The focus was on the energy shifting potential of heating devices with integrated thermal storage units and the associated potential reductions in consumption-based costs under dynamic electricity rates. To this end, extensive measurement analyses were designed and carried out in the indoor climate chamber of the Combined Energy Lab at TU Dresden, the measurement data were then analyzed and evaluated with regard to the effects of room heating and the potential for energy shifting.

The studies highlight the following key aspects:

- The Dynamo heating system and partial storage heating system perform very similarly when it comes to room heating. A uniform temperature distribution is achieved throughout the room.
- Due to the radiation effect of the infrared heating system, its placement is important for effective room heating. The studies considered here show that a uniform temperature distribution does not develop within the room. When there are large local differences (between near and far), noticeable temperature differences of up to 4,6 K can occur.
- The use of the room – determining the occupied zone – is the key factor in selecting the heating system
    - Full-room use: Dynamo heating system or partial storage heating system
    - Partial use of a room or multiple occupancy zones: Infrared heating system
- Integrated thermal storage systems can be used to shift the heating energy required during the usage period to an earlier loading period. This can increase total electricity consumption over the loading and usage periods. However, by using a suitable electricity rate plan or PV power, this can still be more cost-effective compared to other heating systems.
- At the highest thermal load tested, the Dynamo heating system and partial storage heating system require less energy for room heating during operating hours than the wall- and ceiling-mounted infrared heating system.
- By utilizing dynamic electricity rates (low rates during loading and high rates during usage), it is possible to reduce costs through the use of storage-integrated systems such as the Dynamo heating system.
- For systems without an integrated thermal storage unit, fixed electricity rates may be a good option.
- The goal for all electrically powered heating systems, if available, should be a high level of self-consumption of PV electricity.

The studies show that the Dynamo heating system with the integrated thermal storage unit offers practical applications. Load the storage unit during periods of non-use without taking a target room temperature into account to ensure moderate room heating. Under certain circumstances, this may result in a slight increase in room temperature. During the following period of use, room heating is initially provided by the energy stored in the internal thermal storage unit. Only afterward is additional heating necessary, if at all. Since existing buildings typically have higher heating loads compared to new construction and exhibit lower room thermal stability, the use of the Dynamo heating system is particularly effective in these situations.

5 Bibliography

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[2] L. Schinke, M. Beyer und J. Seifert, „Ermittlung der Wärmeströme an einer elektrischen Teilspeicherheizung," Technische Universität Dresden, Dresden, 2024.

[3] L. Schinke, M. Beyer und J. Seifert, „Messtechnischer Vergleich der Raumbeheizung mit einer elektrischen Teilspeicherheizung und einer Infrarotheizung," Technische Universität Dresden, Dresden, 2024.

6 List of Symbols

Symbol	Beschreibung	Einheit
W	width	m
H	height	m
L	length	m
P	power	W
ϑ	Celsius temperature	°C
Δϑ	temperature difference	K

Index	Beschreibung
1	Index 1
2	Index 2
near	position near
center	position center
far	position fear
L	air
Str	radiation
emp	sensation
w	wall
air	air

7 Appendix

Additional Results Charts for the Dynamo Heating System

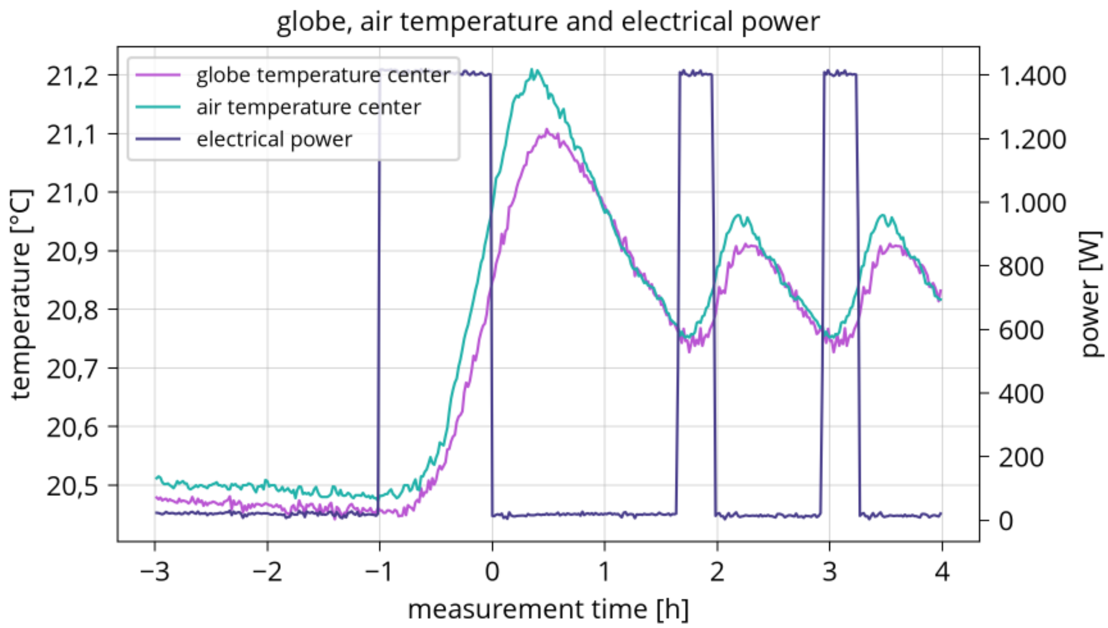

Figure 26: Globe and air temperature curves (center) and electrical power for the **Dynamo heating system** at 25% load, charging time 1 h

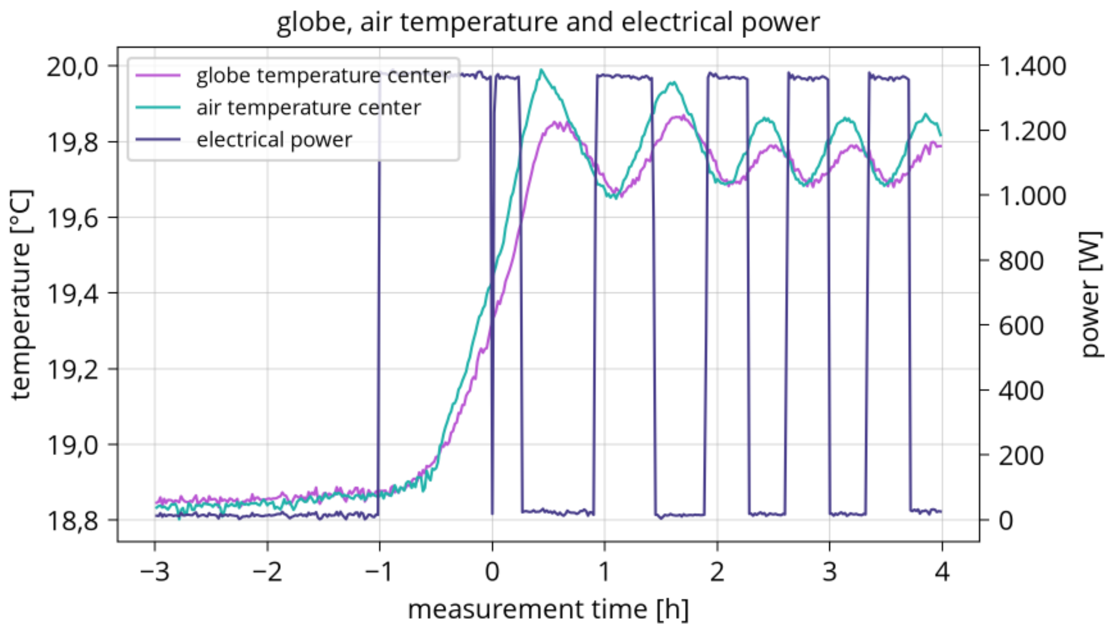

Figure 27: Globe and air temperature curves (center) and electrical power for the **Dynamo heating system** at 85% load, charging time 1 h

Additional Results Charts for the Partial storage heating system

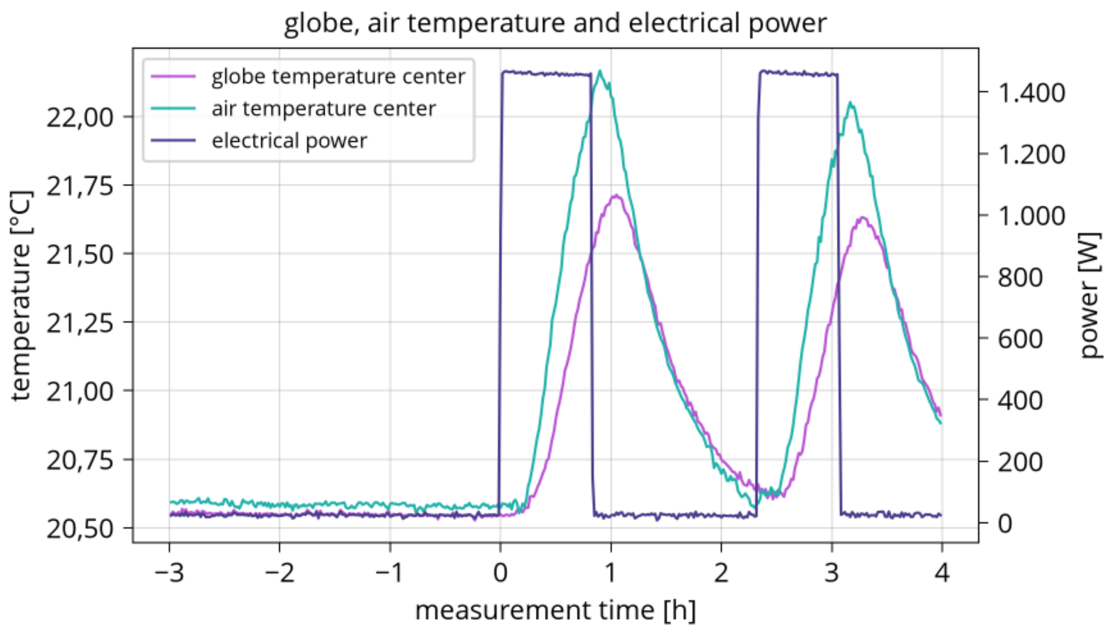

Figure 28: Globe and air temperature curves (center) and electrical power for the **Partial storage heating system** at 25% load

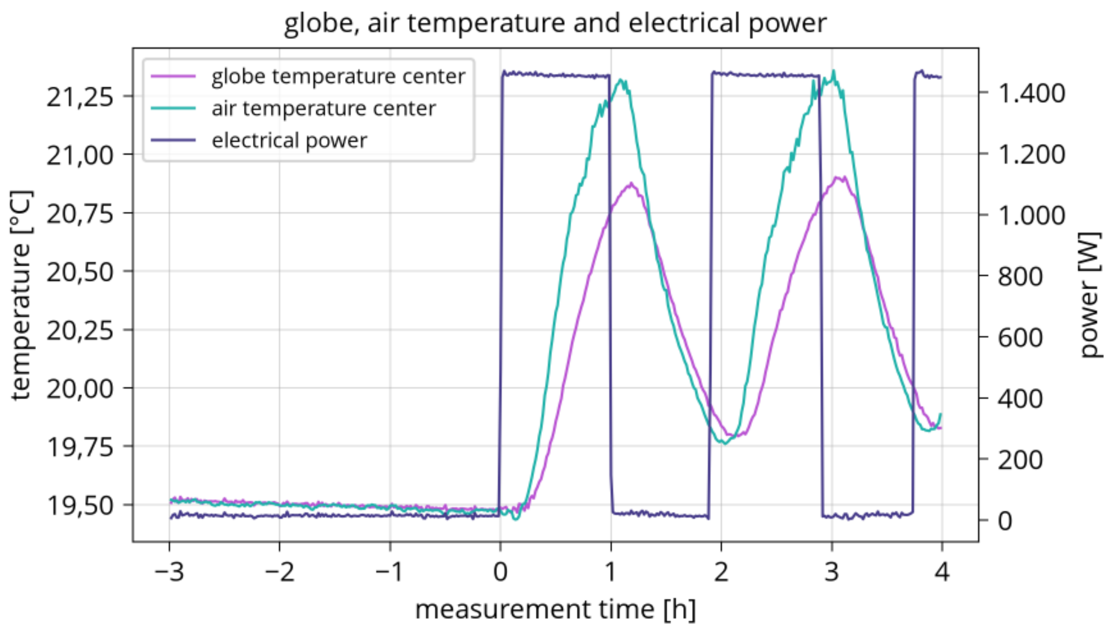

Figure 29: Globe and air temperature curves (center) and electrical power for the **Partial storage heating system** at 85% load

Additional Results Charts for the infrared heating system wall

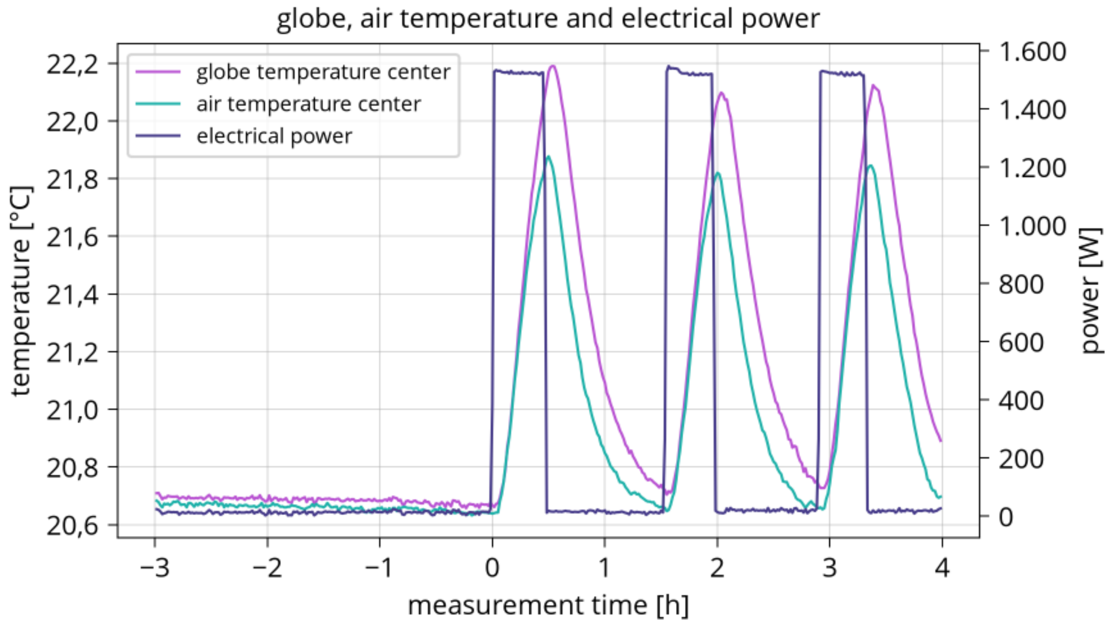

Figure 30: Globe and air temperature curves (center) and electrical power for the **infrared heating system wall** at 25% load

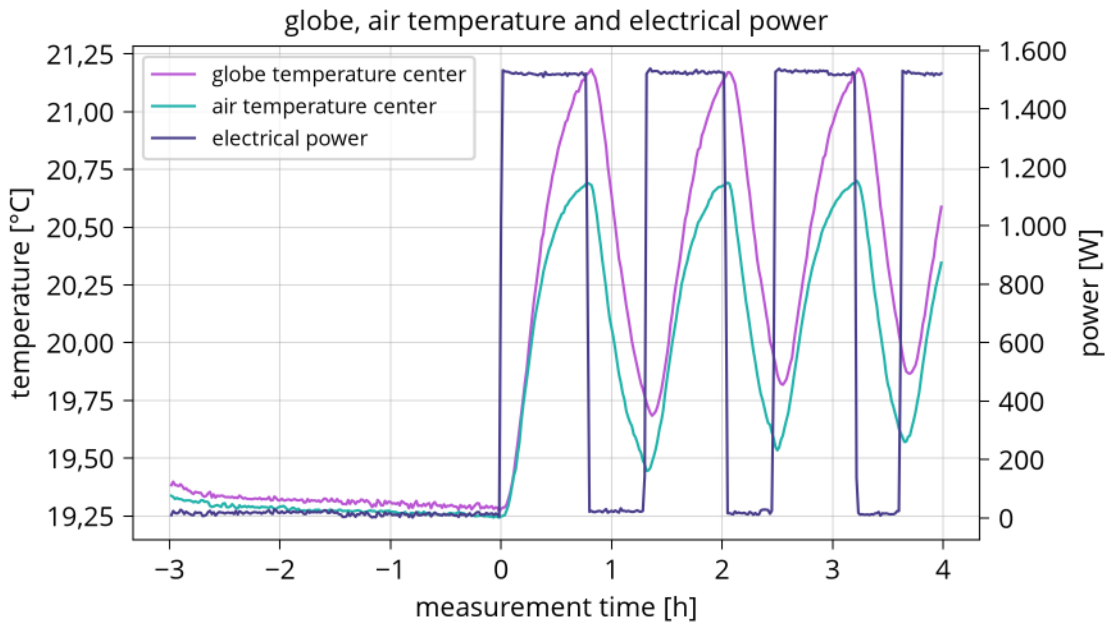

Figure 31: Globe and air temperature curves (center) and electrical power for the **infrared heating system wall** at 85% load

Additional Results Charts for the infrared heating system ceiling near

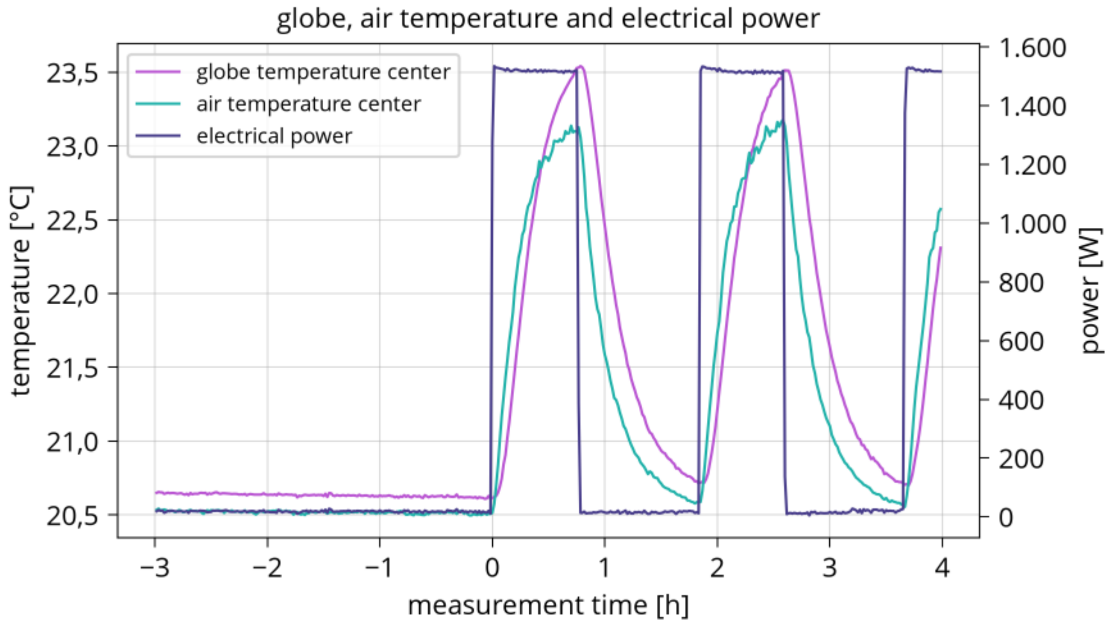

Figure 32: Globe and air temperature curves (center) and electrical power for the **infrared heating system ceiling near** at 25% load

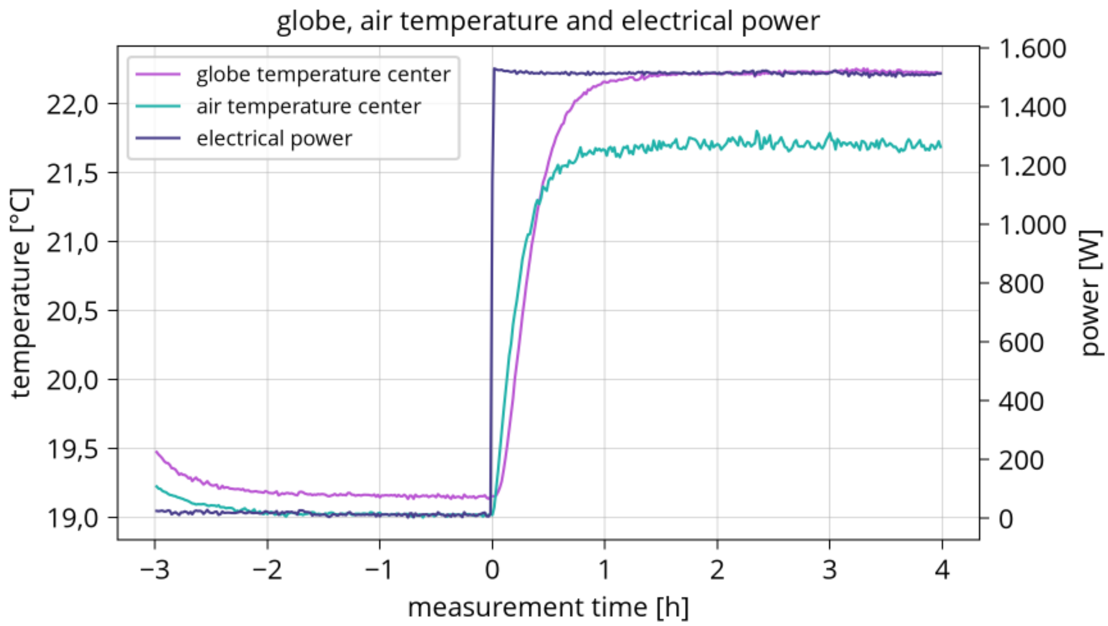

Figure 33: Globe and air temperature curves (center) and electrical power for the **infrared heating system ceiling near** at 85% load

Additional Results Charts for the infrared heating system ceiling center

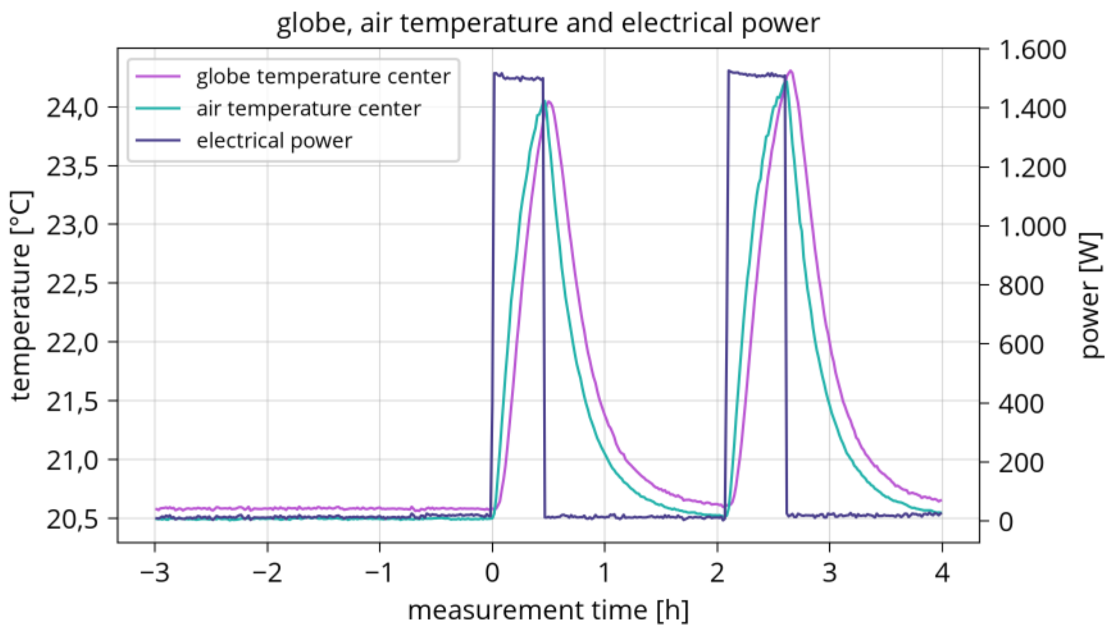

Figure 34: Globe and air temperature curves (center) and electrical power for the **infrared heating system ceiling center** at 25% load

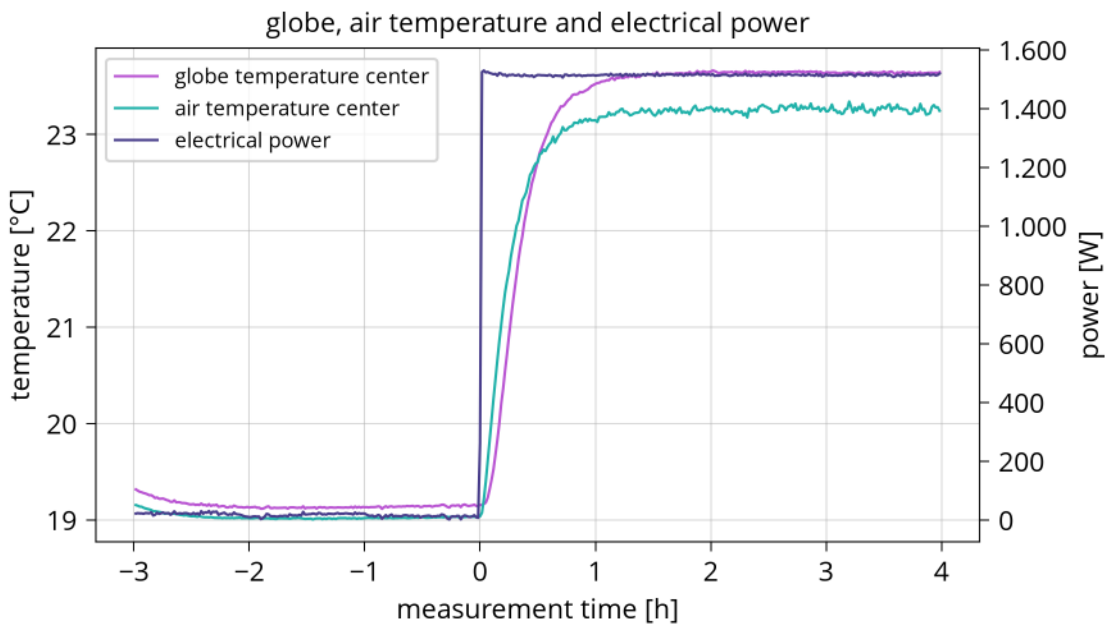

Figure 35: Globe and air temperature curves (center) and electrical power for the **infrared heating system ceiling center** at 85% load

Additional Results Charts for the infrared heating system ceiling far

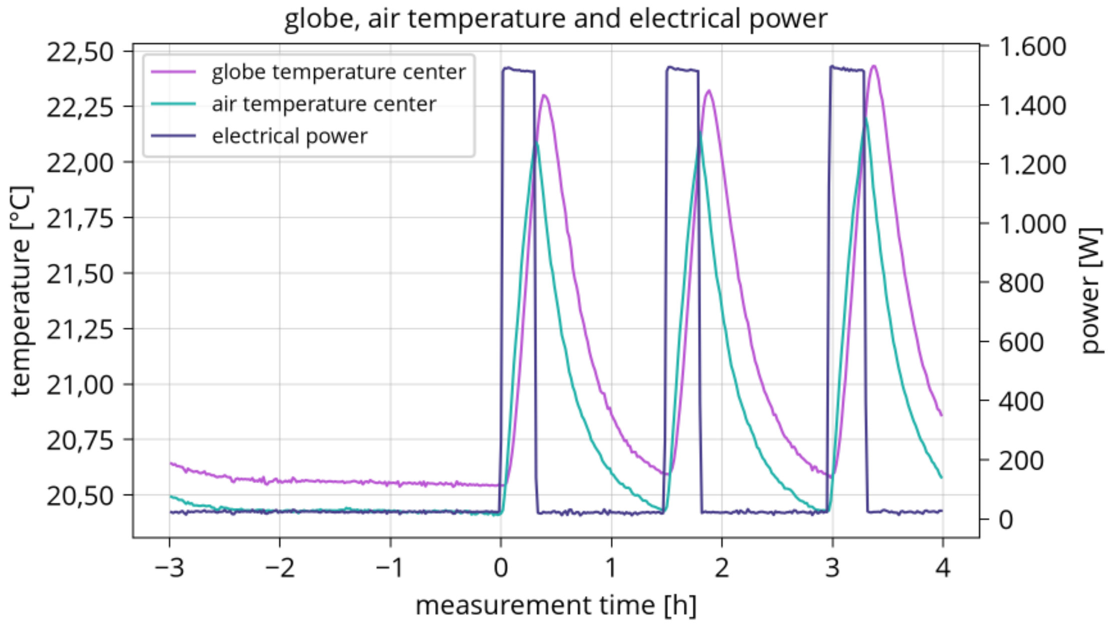

Figure 36: Globe and air temperature curves (center) and electrical power for the **infrared heating system ceiling far** at 25% load

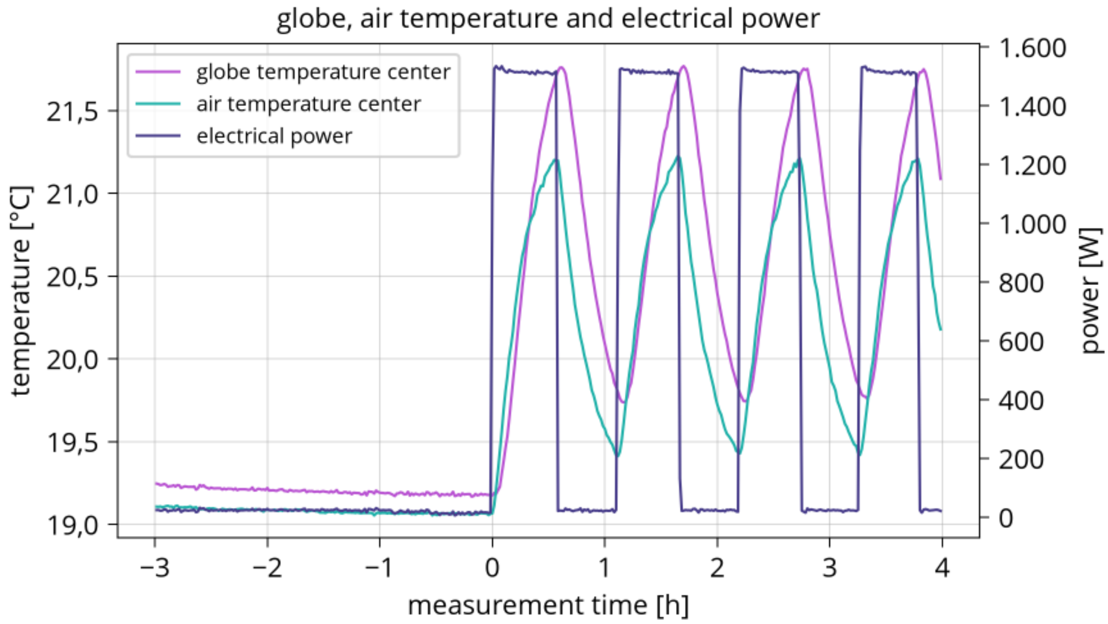

Figure 37: Globe and air temperature curves (center) and electrical power for the **infrared heating system ceiling far** at 85% load

Average room temperatures during the tests

Table 7: Summary of the average room temperature during operating hours for the various heating devices and the various load cases

heating system	Load case	average temperature during the time of use in °C
Dynamo (charging time 1h)	25%	20,9
	60%	20,3
	85%	20,0
partial storage	25%	21,1
	60%	20,3
	85%	20,3
infrared wall	25%	21,2
	60%	20,6
	85%	20,3
infrared ceiling near	25%	22,0
	60%	21,8
	85%	21,7
infrared ceiling center	25%	21,9
	60%	21,6
	85%	23,0
infrared ceiling far	25%	21,1
	60%	20,6
	85%	20,5