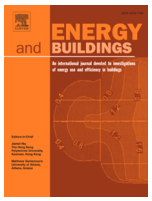
Energy & Buildings 367 (2026) 117714

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild



Evaluation of energy saving potential of IR reflective walls combined with IR heaters using EnergyPlus

Lukas Anselm Wille [a,b,*], Vasimraza Kaji [a], Björn Schiricke [a], Kai Gehrke [c], Bernhard Hoffschmidt [a,b]

[a] Institute of Solar Research, German Aerospace Center (DLR), Linder Höhe, Cologne, 51147, Germany
[b] Chair of Solar Components, RWTH Aachen University, Aachen, 52062, Germany
[c] Institute of Networked Energy Systems, German Aerospace Center (DLR), Carl-von-Ossietzky-Straße 15, Oldenburg, 26129, Germany

ARTICLE INFO

Keywords:
Thermal comfort
IR heater
PMV
EnergyPlus
Low-ϵ surface
Energy efficiency

ABSTRACT

Previous work showed potential to reduce air temperature in buildings when radiant temperature is increased by using infrared (IR) heaters combined with IR reflective walls. In this study we compare the energy demand of a building equipped with a conventional gas heating system and one retrofitted with additional IR heaters and reduced interior IR emittance. For the latter, the setpoint air temperature is decreased from 21 °C to 18 °C. Once a person enters the room, the IR heater is activated to ensure thermal comfort by quickly raising radiant temperature. EnergyPlus was used for modelling the heating energy demand. The four parameters occupancy type, climate, building type and building age class were modified and for each combination the energy savings were evaluated. The results confirm the energy saving potential of this novel technology. Heating energy demand decreases when combining IR heaters with conventional heating. However, the reduction strongly depends on the occupancy pattern as well as building age class and climate. Absolute energy savings are largest for buildings with high heating energy demand and intermittent occupancy. Here, the savings through IR heaters and reflective walls even exceeded the savings achieved by a refurbished building envelope. Relative heating energy savings are larger in new buildings with low overall heating energy demand because internal gains already cover most heating demand for the lowered temperature setpoint. Cost savings are possible for scenarios of short intermittent occupancy.

1. Introduction

Buildings are meant to protect occupants from harsh weather conditions, providing safety and comfort. They are essential for our lives. In almost all climatic zones, heating and cooling systems keep the indoor temperature and humidity at levels, that provide thermal comfort. Mostly this is associated with a substantial energy demand in form of electricity, natural gas or oil. Looking not just at the few most promising but at all possible solutions to make buildings more sustainable, environmentally friendly and more affordable remains an important research topic.

1.1. Motivation

In two previous studies we presented the energy saving potential of infrared (IR) reflective walls in combination with electric IR heaters [1,2]. The principal idea is to decrease air temperature in the room and, hence, reduce thermal losses through the building envelope. To make up for low air temperatures, the IR heater, combined with IR reflective interior walls, increases radiant temperature and ensures good thermal comfort during occupancy times. This concept was investigated first in a simulation study [1] and then in an experimental setup [2]. The results show that the air temperature can be reduced while maintaining constant thermal comfort, but our previous studies only considered the general concept and its influence on thermal comfort. They did not look into actual energy saving potential of a building equipped with IR heaters and IR reflective walls over the course of a whole year. In this work we attempt to close that gap and present numbers on energy savings for selected scenarios. We take the regression formula for thermal comfort from the experimental study [2] and use it in our model to control the IR heater power in the test rooms to achieve optimal thermal comfort. Thereby, we take the next step at evaluating the energy saving potential of the novel heating approach. With the results for the energy demand, we calculate heating costs for one selected scenario.

* Corresponding author.
E-mail address: lukas.wille@dlr.de (L.A. Wille).

https://doi.org/10.1016/j.enbuild.2026.117714
Received 19 February 2026; Received in revised form 21 April 2026; Accepted 26 May 2026
Available online 29 May 2026
0378-7788/© 2026 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

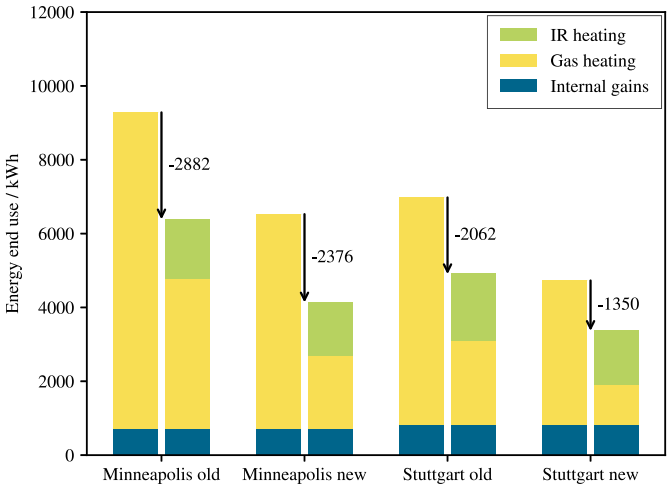


Fig. 2. Heating demand for the cabin model with the living room occupancy pattern.

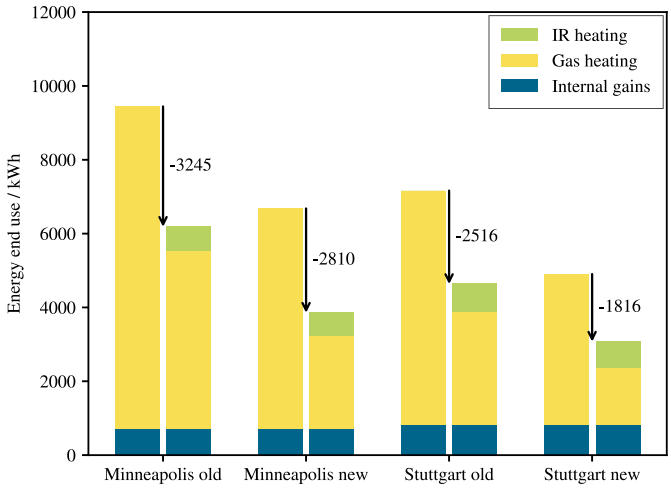


Fig. 3. Heating demand for the cabin model with the dining room occupancy pattern.

they still contribute to the thermal energy in the room. Only the energy that is being used during the heating period where the heating system is available (see Section 2.2) is included into the graphs.
- "Gas heating" is the amount of gas heating energy provided by the conventional heating system.
- "IR heating" is the electric energy that is needed for the IR heating system in the new occupancy-based heating approach.

Combined, these three sections account for all thermal energy that enters the simulation model, however, only gas heating and IR heating are counted as dedicated heating energy. Internal gains have a different primary use. Results are shown pairwise in column charts: the first column for the conventional heating without IR heaters and without reflective walls, the second for the novel heating technology with IR heaters and IR reflective walls. The results show the heating demand for a whole year.

3.1. Cabin

The cabin has only one heated thermal zone and little volume relative to its outside surface area. Therefore, we expect to see high heating energy demand per square meter.

Living room

Results for the living room occupancy pattern are shown in Fig. 2. The first column shows an energy demand of 9 282 kWh (371 kWh/m^2) for the old insulation cabin in Minneapolis. As expected, the energy demand is very high but still reasonable when considering poor insulation, small volume per outside surface area and harsh winter conditions in Minneapolis. In the second column, the conventional gas heating is combined with the IR heater, IR reflective walls and its occupancy-based heating control. The energy demand is 2 882 kWh less than for the conventional heating case. Gas consumption is reduced by over 50% from 8 596 kWh to only 4 096 kWh while an extra 1 646 kWh of electric energy is needed for the operation of the IR heater. The seen effect by the IR heater and the new heating control is larger than the reduction we see from an improved building envelope in the third column. This means that the use of the novel heating approach with IR heaters and IR reflective walls has a similar impact to the building's energy demand as improving the building envelope from pre 1980 to 2004 standard. In the last column pair, new insulation for Stuttgart climate, we see the lowest energy demand, because the insulation is better and the winter in Stuttgart is milder than in Minneapolis. The internal gains as baseline remain constant while, the relative reduction of heating energy demand (purely heating, without internal gains) is as high as 34%. The absolute energy savings are smaller than for the other column pairs.

Dining room

Fig. 3 shows the simulation results of the cabin model with the dining room occupancy pattern. This pattern is characterized by short, intermittent occupancy where the benefits of IR heaters are most prominent. Data show the same trend as for the living room but with larger energy saving potential for the IR heater. While the largest decrease in energy demand for the living room pattern in Fig. 2 was 2 882 kWh, the saving potential for the dining room is 3 245 kWh. The share of IR heating is significantly lower compared to the living room case, due to the shorter total occupancy duration and the resulting reduction in IR operating hours. Again, the use of the novel heating approach has a higher impact than the refurbishment of the building envelope and the smallest absolute energy savings are seen at the last pair with the new insulation in the Stuttgart climate.

3.2. Hotel

The hotel is a much larger building compared to the cabin with a larger and, therefore, energetically more favorable volume to outside surface ratio. All walls, apart from one, of the investigated room are inside walls, whereas the cabin model has only outside walls. We therefore expect to see a much lower energy demand in the hotel room. The graphs show results for one guest room (Fig. A.8).

Living room

Fig. 4 shows the heating energy demand for the hotel model with the living room occupancy pattern. Again, the results show clear energy saving potential for the IR heating approach. For all four pairs, energy demand decreases. The difference to the cabin model is, that the overall heating energy demand per square meter is lower due to a higher volume to outside wall ratio. That means the internal gains become a major factor in the heating of the building. Especially for the last column pair, new insulation in Stuttgart, nearly all heating energy demand is covered by the internal gains only. This results in absolute heating energy savings of only 122 kWh, while the relative savings are as high as 76% (only including heating energy, not internal gains) (Fig. A.9).

Dining room

Finally, Fig. 5 shows the results of the hotel model with dining room occupancy. The IR heaters work less hours than for the living room occupancy, therefore the savings are larger and the IR heater proportion is

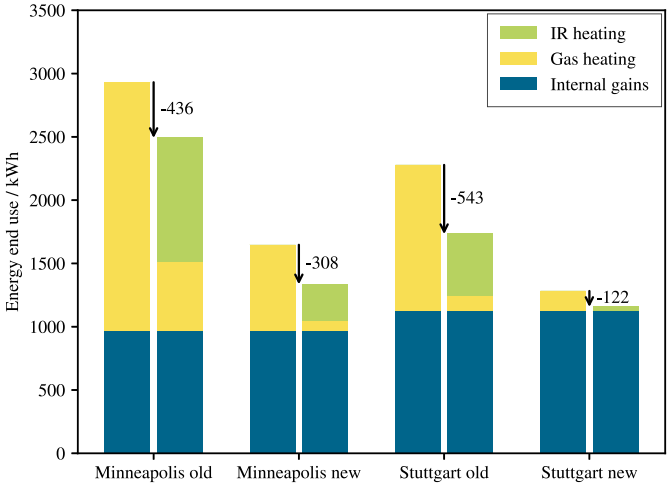


Fig. 4. Heating demand for the hotel room model with the living room occupancy pattern.

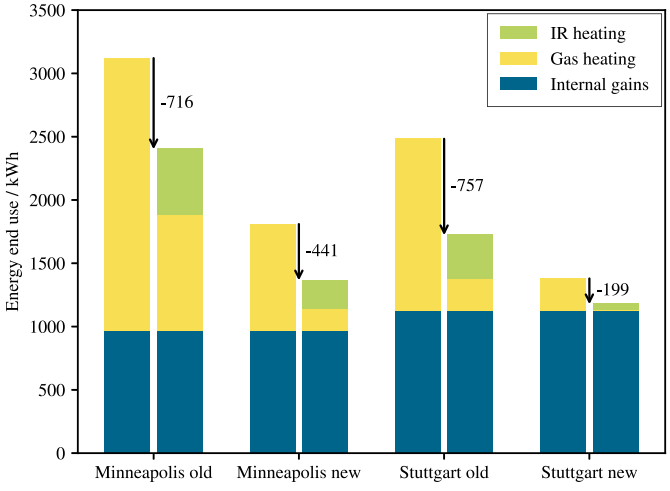


Fig. 5. Heating demand for the hotel room model with the dining room occupancy pattern.

smaller. This is favored because IR heaters have high operational costs (Fig. A.10).

All simulation results confirm the energy saving potential of IR heaters combined with IR reflective walls. For the buildings with high heating energy demand, high absolute savings of up to 3245 kWh in the cabin and 757 kWh in the hotel room are possible. For buildings with a lower initial heating energy demand, internal gains become more prominent, so that absolute savings are less while relative savings increase up to 44% for the cabin and 77% for the hotel. Most heat demand is covered by the internal gains. Factors that cause a high energy demand, like large outside surfaces, bad insulation and cold winters, therefore increase the absolute saving potential for IR heaters. The two occupancy patterns show that for short intermittent dining room pattern, energy savings are larger and also the energy share of the IR heater is smaller. This reduces the costs compared to the living room pattern, because electricity prices are higher than gas prices. In buildings like the hotel with new insulation, the heating energy demand becomes small so that it is questionable whether a conventional heating with a hydraulic system is necessary or if all heating demand could be covered by the IR heaters. Heider et al. performed a cost analysis with a field study house [7] supporting this idea. However, the concept of reflective walls or automated IR heater controls was not implemented in the study. Instead, they tried to compensate high energy costs with large photovoltaic systems (Table A.2).

3.3. Cost estimation

Energy savings are an important indicator for the performance of heating systems. However, in practice, decisions are usually driven by economic considerations. In the following, we therefore estimate the total expenditure (TOTEX) for the case in which the IR heater is implemented as an additional heating option to an existing gas heating system. The gas heating system is thus assumed to be already installed and available. Consequently, its investment and maintenance costs are not considered in the economic assessment, as they are equal in both cases. The cost analysis focuses on the additional investment required for the IR system and on the resulting annual energy costs for gas and electric energy. The annual energy cost is calculated from the simulated gas- and electricity-related energy demand. The gas heating system is assumed to operate with a fuel conversion factor from gas to heat of $\eta_{\mathrm{gas}} = 0.8$. The conversion factor for the IR heater is $\eta_{\mathrm{IR}} = 1$. The annual energy cost is then given by

$$C_{\mathrm{energy}} = c_{\mathrm{gas}} \frac{Q_{\mathrm{gas}}}{\eta_{\mathrm{gas}}} + c_{\mathrm{el}} \frac{Q_{\mathrm{el}}}{\eta_{\mathrm{el}}}, \tag{1}$$

where Q_{gas} is the annual heat provided by the gas heating system, Q_{el} is the annual heat provided by IR heater, c_{gas} is the specific gas price, and c_{el} is the specific electricity price. Prices of $c_{\mathrm{gas}} = 0.11\,\mathrm{EUR\,kWh^{-1}}$ and $c_{\mathrm{el}} = 0.28\,\mathrm{EUR\,kWh^{-1}}$ are used [15,18]. As the gas heating system is treated as given, only the investment cost of the additional IR system is considered. The corresponding investment cost is estimated from the required installed IR heating power as

$$C_{\mathrm{inv,IR}} = c_{\mathrm{inv,IR}}\, P_{\mathrm{IR}}, \tag{2}$$

where P_{IR} is the maximum IR heating power obtained from the simulations and $c_{\mathrm{inv,IR}}$ is the specific investment cost of the IR system. In the present analysis, $c_{\mathrm{inv,IR}} = (375 + 1200)/2\,\mathrm{EUR\,kW^{-1}} = 788\,\mathrm{EUR\,kW^{-1}}$ is assumed (see Table 1). To allow for a more meaningful comparison between annual operating costs and one-time investment costs, the annualized TOTEX is calculated. The annualized share of the IR investment is determined using the capital recovery factor

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1}, \tag{3}$$

where $i = 0.05$ is the discount rate and $n = 25$ is the observation period and assumed lifetime of the IR heater in years. The annualized TOTEX is then calculated as

$$\mathrm{TOTEX_{ann}} = C_{\mathrm{energy}} + C_{\mathrm{inv,IR}}\,\mathrm{CRF}. \tag{4}$$

This cost assessment is deliberately kept simple and should be interpreted as a rough guideline rather than as a detailed techno-economic analysis. In particular, costs for reflective paint are not considered, because there is no applicable product on the market. In addition, the resulting values are associated with considerable uncertainty, since energy prices have fluctuated strongly in recent years, which were affected by political and military conflicts. Therefore, the calculated TOTEX values should not be understood as exact economic predictions, but rather as indicative values for comparing the investigated heating concepts (Table A.3).

In Fig. 6 the costs for the hotel guest room with living room occupancy is presented. Annualized TOTEX is the sum of the annual energy costs in green and the investment costs for the IR heater in blue. The comparison shows that in all cases TOTEX is higher for the novel IR approach than it is for the base case with gas heating. Especially for the first column pair, Minneapolis old, the most extra costs of $148\,\mathrm{EUR\,a^{-1}}$ arise. While energy savings were observed with this setting, economically it is the worst performing, because of its large share of electric heating energy during long occupancy times of the living room occupancy pattern (Table A.4).

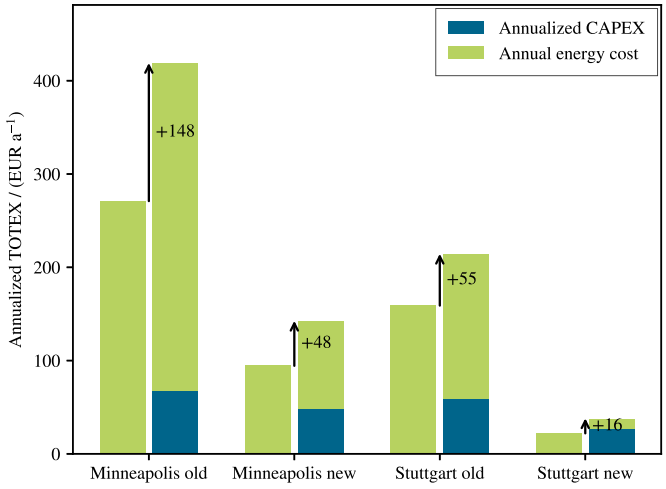


Fig. 6. Annualized TOTEX for the hotel model with the living room occupancy pattern.

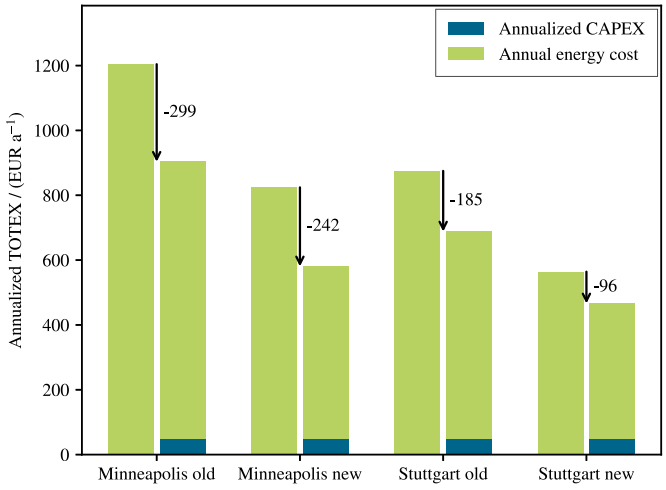


Fig. 7. Annualized TOTEX for the cabin model with the dining room occupancy pattern.

In contrast to that, in Fig. 7 results for the house with dining room pattern are presented with more favorable values for annualized TOTEX: all column pairs show cost reductions between 96 EUR a^{-1} and 299 EUR a^{-1}. Cost savings are possible, because of short intermittent heating phases that result in a low share of electric energy demand. The two remaining cases, hotel with dining room pattern and cabin with living room pattern, can be found in Appendix A.4.

The cost analysis confirms that it is crucial for the technology to not just reduce overall energy demand but also to keep the share of electric energy as small as possible so that it can compete economically. If the IR heater would be considered not as an addition to the existing heating but as an alternative, especially buildings with low overall heat demand and/or high internal gains should be considered, because investment and maintenance costs of heat pumps and gas heatings might exceed the higher electric energy costs of the operation of IR heater. If in the future the price ratio of gas and electric energy shifts towards cheaper electric energy, IR heaters would become the cheaper option also for scenarios with extended IR operation times.

4. Conclusion

In this paper, the energy-saving potential of combining IR heaters with IR reflective walls was quantified by means of whole-year building energy simulations. By coupling our previous experimental results with EnergyPlus simulations, the performance of this novel heating approach could be assessed for different buildings and occupancy scenarios. The results show significant overall energy saving potential for all IR heater scenarios, with heating energy savings ranging from 22–77%, depending on the case considered. The technology is most effective in rooms with short intermittent occupancy, as the key advantage of IR heaters is their swift response time and rapid increase in radiant temperature, whereas their main disadvantage is the comparatively high energy cost. For the cabin model, the energy savings achieved with the novel IR heating approach even exceeded those obtained from the newer insulation standard. The results further indicate that, with a growing share of renewables in the electricity supply, IR heaters combined with IR reflective walls could contribute to reducing CO_2 emissions and costs in the building sector. At the same time, the simulations show that the concept is particularly suitable for buildings or rooms with low overall heating demand, short operating periods, and favorable geometric conditions, such as a large volume-to-outside-surface ratio. In contrast, a complete replacement of gas heating by IR heaters alone appears questionable, as their energy cost is much higher than that of gas heating systems or heat pumps. A viable all-IR scenario therefore seems limited to well-insulated buildings with low overall heating demand and a large volume-to-outside-surface ratio. Overall, IR heaters represent a promising option especially for applications with short operating times or low heating demand and may play an increasingly important role in the transition away from CO_2-intensive technologies toward sustainable and renewable heating systems. Further research on IR reflective paints, the influence of non-reflective surfaces such as furniture, and the risk of mold is required to evaluate the full potential of the concept more thoroughly.

CRediT authorship contribution statement

Lukas Anselm Wille: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization; **Vasimraza Kaji:** Writing – review & editing, Methodology, Investigation; **Björn Schiricke:** Writing – review & editing, Supervision, Methodology, Conceptualization; **Kai Gehrke:** Writing – review & editing, Supervision, Methodology, Conceptualization; **Bernhard Hoffschmidt:** Writing – review & editing, Supervision, Conceptualization.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

Research was funded by the Institute of Solar Research at the German Aerospace Center (DLR).

Appendix A. Appendices

A.1. Occupancy patterns

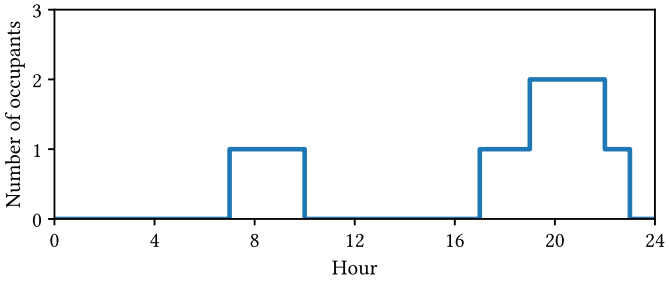


Fig. A.8. Living room pattern with long uninterrupted occupancy.

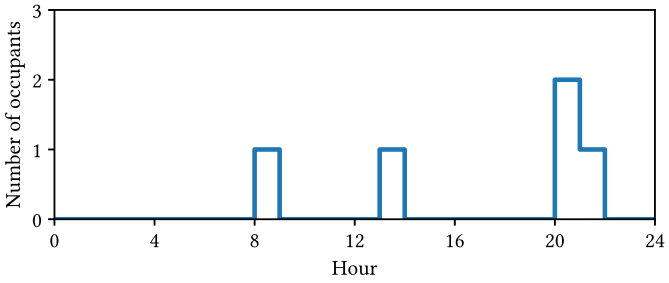


Fig. A.9. Dining room pattern with short intermittent occupancy.

A.2. Parameter combinations

Table A.2
Full factorial simulation plan with five different parameters and 32 parameter combinations.

No.	Building	Age	Climate	occupancy	Heating
1	cabin	pre 1980	Minneapolis	dining room	gas
2	cabin	pre 1980	Minneapolis	dining room	gas + IR
3	cabin	pre 1980	Minneapolis	living room	gas
4	cabin	pre 1980	Minneapolis	living room	gas + IR
5	cabin	pre 1980	Stuttgart	dining room	gas
6	cabin	pre 1980	Stuttgart	dining room	gas + IR
7	cabin	pre 1980	Stuttgart	living room	gas
8	cabin	pre 1980	Stuttgart	living room	gas + IR
9	cabin	2004	Minneapolis	dining room	gas
10	cabin	2004	Minneapolis	dining room	gas + IR
11	cabin	2004	Minneapolis	living room	gas
12	cabin	2004	Minneapolis	living room	gas + IR
13	cabin	2004	Stuttgart	dining room	gas
14	cabin	2004	Stuttgart	dining room	gas + IR
15	cabin	2004	Stuttgart	living room	gas
16	cabin	2004	Stuttgart	living room	gas + IR
17	hotel	pre 1980	Minneapolis	dining room	gas
18	hotel	pre 1980	Minneapolis	dining room	gas + IR
19	hotel	pre 1980	Minneapolis	living room	gas
20	hotel	pre 1980	Minneapolis	living room	gas + IR
21	hotel	pre 1980	Stuttgart	dining room	gas
22	hotel	pre 1980	Stuttgart	dining room	gas + IR
23	hotel	pre 1980	Stuttgart	living room	gas
24	hotel	pre 1980	Stuttgart	living room	gas + IR
25	hotel	2004	Minneapolis	dining room	gas
26	hotel	2004	Minneapolis	dining room	gas + IR
27	hotel	2004	Minneapolis	living room	gas
28	hotel	2004	Minneapolis	living room	gas + IR
29	hotel	2004	Stuttgart	dining room	gas
30	hotel	2004	Stuttgart	dining room	gas + IR
31	hotel	2004	Stuttgart	living room	gas
32	hotel	2004	Stuttgart	living room	gas + IR

A.3. U-values and internal gains

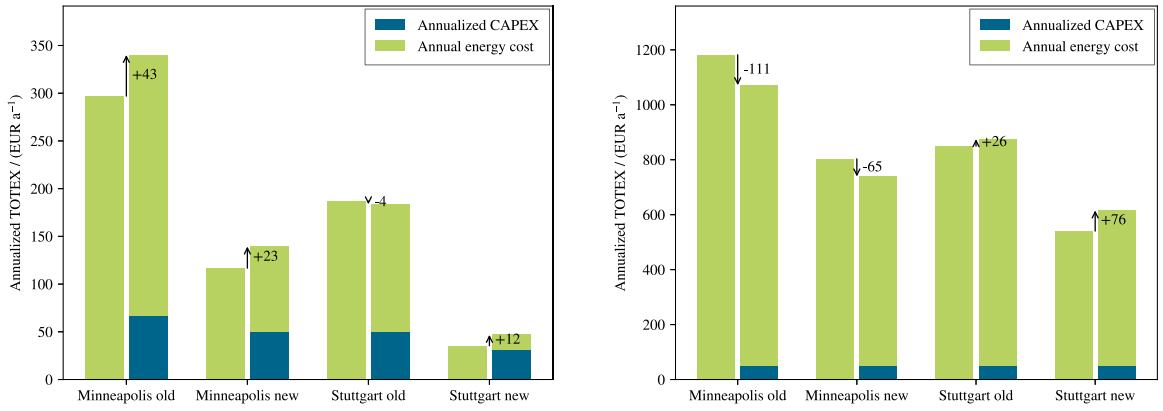
Table A.3
Thermal properties of building envelope components for old (pre-1980) and new (2004) standard models.

Construction	Old W m^{-2} K^{-1}	New W m^{-2} K^{-1}
External wall	0.82	0.36
Roof	0.33	0.35
Floor	1.85	1.85
Window	3.53 / 0.41 (SHGC)	3.24 / 0.39 (SHGC)

Table A.4
Internal gains for the used building models. Values for lighting and equipment are from ASHRAE 90.1 - 2019 for small hotel guest rooms, accessed via Bemcyclopedia [42]. The value for heat gain from occupants is taken from the experimental study for the IR heater control [2].

Internal gains	W m^{-2}
Lighting	4.40
Equipment	11.84
Occupants	144 W person^{-1}

A.4. Costs



(a) Hotel room model with the dining room occupancy pattern.

(b) Cabin model with the living room occupancy pattern.

Fig. A.10. Annualized TOTEX.

References

[1] L.A. Wille, B. Schiricke, K. Gehrke, B. Hoffschmidt, Reduction of heating energy demand by combining infrared heaters and infrared reflective walls, Buildings 14 (7) (2024). https://doi.org/10.3390/buildings14072183

[2] L.A. Wille, B. Schiricke, K. Gehrke, T. Dehne, B. Hoffschmidt, Reduction of heating energy demand by combining IR heaters and IR reflective walls: an experimental study, Energy Build. 357 (2026) 117112. https://doi.org/10.1016/j.enbuild.2026.117112

[3] Umwelt Bundesamt, Indikator: energieverbrauch für Gebäude, accessed on 2025-11-14, https://www.umweltbundesamt.de/daten/umweltindikatoren/indikator-energieverbrauch-fuer-gebaeude#die-wichtigsten-fakten.

[4] Bundesverband energieeffiziente Gebäudehülle e.V., Sanierungsquote 2024: Weiter auf geringem Niveau, accessed on 2025-12-04, https://buveg.de/pressemeldungen/sanierungsquote-2024-weiter-auf-geringem-niveau/.

[5] R. Lazzarin, Dual source heat pump systems: operation and performance, Energy Build. 52 (2012) 77–85. https://doi.org/10.1016/j.enbuild.2012.05.026

[6] G. Alarnaot Alarnaout, J. Navarro-Esbrí, A. Mota-Babiloni, Operational, economic, and carbon footprint feasibility of a moderately-high-temperature heat pump as an alternative to conventional boilers in various scenarios, Energy Convers. Manage. 309 (2024) 118424. https://doi.org/10.1016/j.enconman.2024.118424

[7] J. Heider, N. Conrad, T. Stark, A. Abdulganiev, P. Kosack, A.-K. Wagner, Forschungsprojekt IR Bau, HTWG Konstanz (2020). https://www.htwg-konstanz.de/fileadmin/pub/ou/energie/Forschung/IR-Bau/Abschluss-bericht_Forschungsprojekt_IR-Bau.pdf.

[8] Arbeitskammer, Wärmewende droht an sozialer Realität zu scheitern, accessed on 2025-12-29, https://www.arbeitskammer.de/aktuelles/pressedienste/pressemeldung/arbeitskammer-waermewende-droht-an-sozialer-realitaet-zu-scheitern/.

[9] J. Thomä, A. Weiß, M. Wesling, Zwischen Klimazielen und Fachkräftemangel, Göttingen Research Online, Göttingen, 2025. https://doi.org/10.47952/gro-publ-317

[10] J. Sitarz, M. Pahle, S. Osorio, G. Luderer, R. Pietzcker, EU carbon prices signal high policy credibility and farsighted actors, Nat. Energy 9 (6) (2024) 691–702. https://doi.org/10.1038/s41560-024-01505-x

[11] Umwelt Bundesamt, Der Europäische emissionshandel, accessed on 2025-12-04, https://www.umweltbundesamt.de/daten/klima/der-europaeische-emissionshandel#teilnehmer-prinzip-und-umsetzung-des-europaischen-emissionshandels.

[12] Deutsche Emissionshandelsstelle (DEHSt), Verschiebung des starts der regelphase des EU-ETS 2, accessed: 2026-02-10, https://www.dehst.de/SharedDocs/news/DE/euets2-verschiebung.HTML.

[13] C. Frings, B. Helgeson, Developing a Model for Consumer Management of Decentralized Options, Technical Report ISSN: 1862–3808, Institute of Energy Economics at the University of Cologne (EWI), 2022. https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2022/12/EWI_WP_22-05_Developing_a_model_for_consumer_management_of_decentralized_options_Frings_Helgeson.pdf.

[14] NDR Info, Gaspreis aktuell: so viel kostet die Kilowattstunde, accessed: 2026-02-10, https://www.ndr.de/nachrichten/info/Gaspreis-aktuell-wie-viel-kostet-Kilowattstunde,gaspreis142.HTML.

[15] Verivox, Gaspreisentwicklung 2026 – Infos zu Gaspreisen inkl. vergleich, Accessed: 2026-04-12, https://www.verivox.de/gas/gaspreisentwicklung/.

[16] D. Cutler, B. Shen, N. Fumo, J. Griggs, Condensing Boilers Evaluation: Retrofit and New Construction Applications, Technical Report NREL/TP-5500-56402, National Renewable Energy Laboratory, 2013. https://docs.nrel.gov/docs/fy14osti/56402.pdf.

[17] H. Satyavada, S. Baldi, Monitoring energy efficiency of condensing boilers via hybrid first-principle modelling and estimation, Energy 142 (2018) 121–129. https://doi.org/10.1016/j.energy.2017.09.124

[18] Verivox, Strompreisentwicklung 2026 in Deutschland, Accessed: 2026-04-12, https://www.verivox.de/strom/strompreisentwicklung/.

[19] Heatness, Infrared heating costs: prices for purchase and operation, accessed: 2026-02-10, https://www.heatness.de/infrarotheizung/kosten/.

[20] M. Kersken, H. Sinnesbichler, C. Wörle, Messtechnischer Vergleich des Heizungsenergieverbrauchs Eines Konventionell Beheizten Einfamilienhauses Mit Einem Gebäude Mit Infrarotheizung, IBP-Bericht EER-013/2024/720, Fraunhofer-Institut für Bauphysik IBP, Holzkirchen, 2024. https://ig-infrarot.de/wp-content/uploads/Bericht_IBP_IG-Infrarot_20240812.pdf.

[21] A. Joudi, H. Svedung, C. Bales, M. Rönnelid, Highly reflective coatings for interior and exterior steel cladding and the energy efficiency of buildings, Appl. Energy 88 (12) (2011) 4655–4666. https://doi.org/10.1016/j.apenergy.2011.06.002

[22] P. Kosack, Beispielhafte Vergleichsmessung zwischen Infrarotstrahlungsheizung und Gasheizung im Altbaubereich, TU Kaiserslautern Arbeitkreis Ökologisches Bauen (2009). https://www-user.rhrk.uni-kl.de/~kosack/menu1/ForschungsberichtIR.pdf.

[23] H.J. Gläser, Improved insulating glass with low emissivity coatings based on gold, silver, or copper films embedded in interference layers, Glass Technol. 21 (1980) 254–261.

[24] L. Noč, I. Jerman, Review of the spectrally selective (CSP) absorber coatings, suitable for use in SHIP, Sol. Energy Mater. Sol. Cells 238 (2022) 111625. https://doi.org/10.1016/j.solmat.2022.111625

[25] M. Zinzi, S. Agnoli, G. Ulpiani, B. Mattoni, On the potential of switching cool roofs to optimize the thermal response of residential buildings in the Mediterranean region, Energy Build. 233 (2021) 110698. https://doi.org/10.1016/j.enbuild.2020.110698

[26] C. Fabiani, A.L. Pisello, E. Bou-Zeid, J. Yang, F. Cotana, Adaptive measures for mitigating urban heat islands: the potential of thermochromic materials to control roofing energy balance, Appl. Energy 247 (2019) 155–170. https://doi.org/10.1016/j.apenergy.2019.04.020

[27] G.A. Niklasson, C.G. Granqvist, Electrochromics for smart windows: thin films of tungsten oxide and nickel oxide, and devices based on these, J. Mater. Chem. 17 (2007) 127–156. https://doi.org/10.1039/B612174H

[28] A. Ganji Kheybari, M. Alwalidi, C. Hepf, T. Auer, S. Hoffmann, A multi-objective evaluation for envelope refurbishments with electrochromic glazing, Results Eng. 14 (2022) 100417. https://doi.org/10.1016/j.rineng.2022.100417

[29] E. Wäckelgård, H. Svedung, Optical characterization and modelling of paint top-coatings for low-emittance applications, Infrared Phys. Technol. 78 (2016) 275–281. https://doi.org/10.1016/j.infrared.2016.08.011

[30] Y. Peng, J.-C. Lai, X. Xiao, W. Jin, J. Zhou, Y. Yang, X. Gao, J. Tang, L. Fan, S. Fan, Z. Bao, Y. Cui, Colorful low-emissivity paints for space heating and cooling energy savings, Proc. Natl. Acad. Sci. U.S.A. 120 (34) (2023) e2300856120. https://doi.org/10.1073/pnas.2300856120

[31] J. Xu, A.P. Raman, Controlling radiative heat flows in interior spaces to improve heating and cooling efficiency, iScience 24 (8) (2021) 102825. https://doi.org/10.1016/j.isci.2021.102825

[32] S. Malz, W. Krenkel, O. Steffens, Infrared reflective wall paint in buildings: energy saving potentials and thermal comfort, Energy Build. 224 (2020) 110212. https://doi.org/10.1016/j.enbuild.2020.110212

[33] J.K. Tong, X. Huang, S.V. Boriskina, J. Loomis, Y. Xu, G. Chen, Infrared-transparent visible-opaque fabrics for wearable personal thermal management, ACS Photonics 2 (6) (2015) 769–778. https://doi.org/10.1021/acsphotonics.5b00140

[34] F. Tartarini, S. Schiavon, pythermalcomfort: a Python package for thermal comfort research, SoftwareX 12 (2020) 100578. https://doi.org/10.1016/j.softx.2020.100578

[35] International Organization for Standardization, ISO 7730:2005. Ergonomics of the thermal environment – analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, International Organization for Standardization, Geneva, Switzerland, 2005, International Standard.

[36] P.O. Fanger, Thermal Comfort: Analysis and Applications in Environmental Engineering, McGraw-Hill, New York, 1970–1972.

[37] Institut für Wohnen und Umwelt, “TABULA” - EU-project, accessed on 2025-12-30, https://www.iwu.de/1/research/gebaeudebestand/tabula-en/.

[38] M. Deru, K. Field, D. Studer, K. Benne, B. Griffith, P. Torcellini, B. Liu, M. Halverson, D. Winiarski, M. Rosenberg, M. Yazdanian, J. Huang, D. Crawley, U.S. Department of Energy Commercial Reference Building Models of the National Building Stock, Technical Report NREL/TP-5500-46861, National Renewable Energy Laboratory, 2011. https://doi.org/10.2172/1009264

[39] EnergyPlus Documentation, Validation and testing, Accessed: 2026-04-13, https://bigladdersoftware.com/epx/docs/9-2/tips-and-tricks-using-energyplus/validation-and-testing.HTML.

[40] EnSimS, IDF example files: airflownetwork_simple_house, EnergyPlus example model page, accessed 2026-04-08, https://app.ensims.com/idf/examples.HTML.

[41] U. S. Department of Energy, Reference buildings by building type: small hotel, 2010, accessed 2026-04-08, https://www.energy.gov/cmei/articles/reference-buildings-building-type-small-hotel-1.

[42] BEMcyclopedia, Internal gains, 2026, accessed: 2026-04-14, https://apps.bemcyclopedia.com/lookups/gains.