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Validation of the smart readiness indicator on real test buildings - energy efficiency of heat generators

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ABSTRACT

Smart technologies have the potential to combat rising energy prices, climate change, and political dependencies. The Smart Readiness Indicator (SRI) assesses the intelligence of a building via evaluating the implemented smart technologies. Previous studies of the SRI and its effects on energy efficiency have been conducted through simulations. This paper validates the SRI through experiments on two identical real buildings, equipped with district heating (H-2a) and heat pump (H-2b). The aim of this paper is to quantify the energy savings achieved by increasing SRI functionality levels for heat generator control. The results show that higher functionality levels lead to higher energy savings: up to 16.8 % for H-2a and 51.3 % for H-2b. However, the measured values deviate significantly from the SRI-predicted efficiencies and the forecast factors from EN ISO 52120. Moreover, the two services - while equally weighted in the SRI - differ notably in their actual energy-saving potential. This discrepancy highlights that the SRI does not reliably reflect real energy performance and that functionality levels alone are insufficient to estimate actual efficiency gains. The findings suggest that the SRI, in its current form, is limited as a framework for predicting the effect of smart technologies, especially when compared across services. This paper contributes the first empirical evidence of this kind and supports the need for a performance-oriented refinement of the SRI.

1. Introduction

In Germany, occupants face rising energy costs. The consumer price of heating gas has more than doubled since the beginning of 2015 until November 2022 [1], while the consumer price of electricity has increased by almost 50 % [1] in the same time. Political dependencies regarding the supply of energy sources, especially gas [2], and climate change necessitate the use of renewable energy and more energy-efficient building operation. Buildings account for approximately 35 % of final energy consumption and 30 % of carbon dioxide emissions in Germany [3].

One potential solution to achieve a cost-efficient balance between reducing a building's energy consumption and decarbonizing the use of energy systems is using intelligent technologies in buildings [4]. The Smart Readiness Indicator (SRI), developed in the European Union (EU) and published by the European Commission (EC), evaluates a building's smart readiness [5]. The indicator proposes various smart technologies and categorizes them based on energy efficiency, the adaption to occupants' needs and energy flexibility. The SRI was developed based on studies and independent experts [6,7]. Therefore the effects of smart technologies are merely assumed. Previous publications have mostly investigated this effect using simulations and calculations [8–12].

The aim of this paper is to quantify the correlation between the implementation of smart technologies and resulting energy savings, with focus on improving the smartness of heat generator control in real buildings. Additionally, it aims to compare the energy savings of specific heat generators in terms of their valued contribution to the SRI. The paper focuses on two out of the ten SRI services in the heating domain: heat generator control of combustion or district heating (DH) and heat pump (HP).

2. Theoretical background and literature overview of the SRI

2.1. Origin

In 2018, the revised Energy Performance of Buildings Directive (2018/844/EU), the EU's buildings directive, referred to the SRI for

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Table 1
Definition of functionality levels of service H-2a and related impact scores of Energy Efficiency (EE), Energy Flexibility (EF) and Comfort (Co).

	Impact Scores				
Level	EE	EF	Co	SRI Definition	Further Explanation
0	0	0	0	Constant temperature control.	A predefined temperature is maintained.
1	1	0	1	Variable temperature control depending on outdoor temperature.	The setpoint for the generator temperature varies according to the outdoor temperature.
2	2	0	2	Variable temperature control depending on the load.	The required load is determined by heat meters or temperature sensors in the supply and return circuits. Generator temperature is managed according to the actual temperature demand of the occupant.

Table 2
Definition of functionality levels of service H-2b and related impact scores of Energy Efficiency (EE), Energy Flexibility (EF) and Comfort (Co).

	Impact scores				
Level	EE	EF	Co	SRI Definition	Further Explanation
0	0	0	0	On-/off-control of the heat generator.	A predefined temperature is maintained.
1	1	1	1	Multi-stage control of heat generator capacity depending on the load or demand.	The setpoint for the generator temperature varies according to the outdoor temperature.
2	2	1	2	Variable control of heat generator capacity depending on the load or demand.	The required load is determined by heat meters or temperature sensors in the supply and return circuits. Generator temperature is managed according to the actual temperature demand of the occupant.
3	2	3	2	Variable control of heat generator capacity depending on the load and external signals from grid.	-

the first time. The SRI concept was then developed in cooperation with EU member states and relevant stakeholders in the construction industry [6,13,14]. The SRI aims to reduce carbon emissions in the building sector and energy systems, while at the same time creating healthier, more efficient, and more comfortable living conditions by implementing smart technologies and interacting with a smart grid [6].

In 2020, a second study was conducted to substantiate the SRI and coordinate the associated calculation methodology [15]. The SRI is currently in the test phase, i. e. the EU countries can implement and adapt the scheme to their regional characteristics and standards as well as provide feedback on how it can be further improved [16].

2.2. Assessment scheme

The latest version of the SRI contains a total of 54 smart ready services, that are divided into the following nine technical domains: (1) heating, (2) domestic hot water, (3) cooling, (4) ventilation, (5) lighting, (6) dynamic building envelope, (7) electricity, (8) electric vehicle charging and (9) monitoring and control. Within the domain, each service is given the same weight. Each domain contributes to the total score with a different weighting. The services are evaluated on seven impact categories: (1) energy efficiency, (2) energy flexibility and storage, (3) comfort, (4) convenience, (5) health, well-being and accessibility, (6) maintenance and fault prediction and (7) information to occupants [5,7,17]. Most of the services are defined in standards and can be assessed on the basis of up to five functionality levels. Level 0 is equivalent to a non-smart technology, while a high level indicates a smart technology or service [5,7,17]. The functionality levels in the heating domain are assigned an impact score from 0 to 3 concerning the energy efficiency, based on EN 15232 / EN ISO 52120, which is relevant for the subsequent calculation of the total SRI score [17]. The higher the impact score, the smarter the technology and the higher the impact on the total SRI score. The total score is then given as a percentage of the maximum possible smartness.

Tables 1 and 2 show the relationship between the functionality levels and their impact scores. The levels of two services are also defined as examples, based on [17–20]: Table 1 details service H-2a, which is the heat generator control of combustion or district heating (DH). Table 2 elaborates on service H-2b, which contains the heat generator control of a heat pump (HP).

2.3. Findings of previous research

Recent publications focus on the applicability of the SRI assessment. Researchers analyze scenarios to enhance a building's energy performance and highlight challenges in achieving the maximum SRI score [7,8,10,11,16,21–23].

Several studies have examined the relationship between a building's energy performance and the level of Building Automation and Control Systems (BACS) installed, which also influences the SRI score [7,9,22,24–27]. The researchers have found that there are discrepancies while comparing the weighting factors of the SRI to the actual energy performance, as well as when comparing them to the estimated factors of energy savings, outlined in EN ISO 52120-1. Morkunaite et al. [9] calculated the forecasted energy savings in the heating domain by increasing BACS, in accordance with EN ISO 52120-1. The highest possible calculated energy savings are 26 % when optimizing from the lowest (0) to the highest functionality level (2 or 3) [9]. Vandenbogaerde et al. [26] state that the energy savings from implementing BACS cannot be estimated using the factors outlined in EN ISO 52120-1, which is supported by Thillo et al. [27] and their findings.

While using a Building Information Modeling based assessment tool, Plienaitis et al. [8] were able to simulate up to 10 % savings in the building's heating energy consumption during winter months by improving the installed BACS. They suggest that minor modifications concerning the heating system were responsible for the improvement. On the other hand, they argue that a lower energy consumption of heating systems does not always result in a higher SRI score. In analyzing how to cost-effectively enhance a building's SRI score, Emich et al. [28] state that one way is to improve the management of the heating, ventilation and air conditioning systems. According to Varsami and Burman [22], the heating domain has the biggest impact on achieving a higher SRI score.

In the heating domain, regarding the specific heat generators used in this paper, Janhunen et al. [29] argue that the SRI lacks recognizing advanced DH networks. The other considered heat generator is examined by Huchtemann et al. [30]. They identified an improvement of a HP's efficiency as they implemented a supply temperature control based on heat load. The researchers indicate that the reduction of the heat generator's temperature is to be aimed for, which is intended to be achieved in this paper through the two considered SRI services (presented in Section 2.2) [19].

The publications examined indicate a partial correlation between a higher SRI score and energy efficiency, as demonstrated by Plienaitis et al. [8]. Nevertheless, energy consumption is mostly simulated or calculated throughout the different functionality levels or BACS equipment and are not measured in real buildings, which is why it is further validated by real tests on buildings in the present paper.

3. Materials and methods

3.1. Energy efficiency

To assess the improvement of the energy performance depending on different functionality levels, the impact scores of individual levels are set in relation to each other. The actual improvement of the energy performance is measured in a reduction of energy consumption [31].

3.2. Control of heating services on the supply side

In German households, more than 2/3 of the final energy consumption is used for space heating [32]. Therefore, the focus is on this sector to maximize the contribution to the environment and minimize costs for occupants.

The focus is on the two services H-2a and H-2b, as they can be applied to the existing building stock (see Section 3.3) and at the same time fulfill the following new legal regulation: Since the Amendment to the German Building Energy Act ('Gebäudeenergiegesetz') requires that heating systems in new buildings be powered by at least 65 % renewable energy, alternatives to the commonly used oil and gas heating systems will be needed. It must therefore be determined at the municipal level whether a centralized supply via a DH network or a decentralized supply, such as an HP, will cover the heating demand in the coming years [33,34].

3.3. Experimental buildings and heat generators

As single-family homes make up about 86 % of the German housing stock [35], they are considered in this work. The real experimental buildings, located at the Karlsruhe Institute of Technology (KIT) Campus North in Karlsruhe, Germany, are part of the Living Lab Energy Campus and Energy Lab Project. Three two-story buildings of identical construction are part of the lab [36]. The building envelope is identical, but they are equipped with different heating systems [37]. Sensors for thermal, electrical, and hydraulic measurements are provided [36]. Further building specifics are given in Table 3.

Table 3
Features of the Experimental Buildings [38].

Feature	Value/status
Building type	Residential / single-family home
Building standard	EnEV 2016[a]
Building state	Original/unrenovated
A/V-ratio	0.66 $\frac{1}{m}$
Window-glazing	Triple-glazing
Window percentage on surface area	35 %
Total useful floor area	100 m^2
SRI climate zone	West Europe
Location	49°06'01.4"N 8°26'11.6"E

[a] German energy saving ordinance ('Energieeinsparverordnung').

The heat generation concerning the two buildings is shown in Fig. 1. Investigating service H-2a, there is one building using DH (a). This building represents existing buildings as they can be easily converted from combustion heating to DH. This is cost-saving because the radiators (b) can be retained due to the supply temperature in the range of 50 °C to 90 °C [39,40]. Additionally, these buildings are an example of a densely populated urban area where noise emissions may be too high for an air-to-water heat pump (AWHP) [41] and drilling for a brine-to-water heat pump (BWHP) is prohibited.

The other building is used to examine service H-2b and is therefore equipped with an HP (c). As in the year 2021 more than 50 % of buildings were equipped with HPs, this represents new buildings [42]. HPs are combined with panel heating systems, such as underfloor heating (d), because of the supply temperature of under 50 °C [40,43]. In this experiment, a BWHP is used. This reduces the influence of the outdoor temperature on the energy required for heat generation, since the obtained geothermal energy through the soil remains nearly constant throughout the year. In the case of an AWHP, a higher dependence of energy demand on outdoor temperature is expected [44].

3.4. Variables of the experiment

The variables of the experiment are categorized according to the structure of Albers et al. [45]: independent variable, dependent variable and confounding variable. The independent variable is the functionality level, which can be adjusted by changes in heat generation control. The dependent variable is the energy consumption of the heat generator. The confounding variables are presented in Table 4. Concerning the meteorological parameters, Liu et al. [46] indicate that the relative humidity has no impact on the heating energy consumption, while the outdoor temperature has the biggest effect. According to them, the influence of wind is also of minor importance, although this varies depending on the location. [47–53] outline a linear correlation between the outdoor temperature and the energy consumption and therefore perform a linear regression.

Plienaitis et al. [8] state that the energy performance of a building is related to the level of smartness depending on BACS. Therefore, the

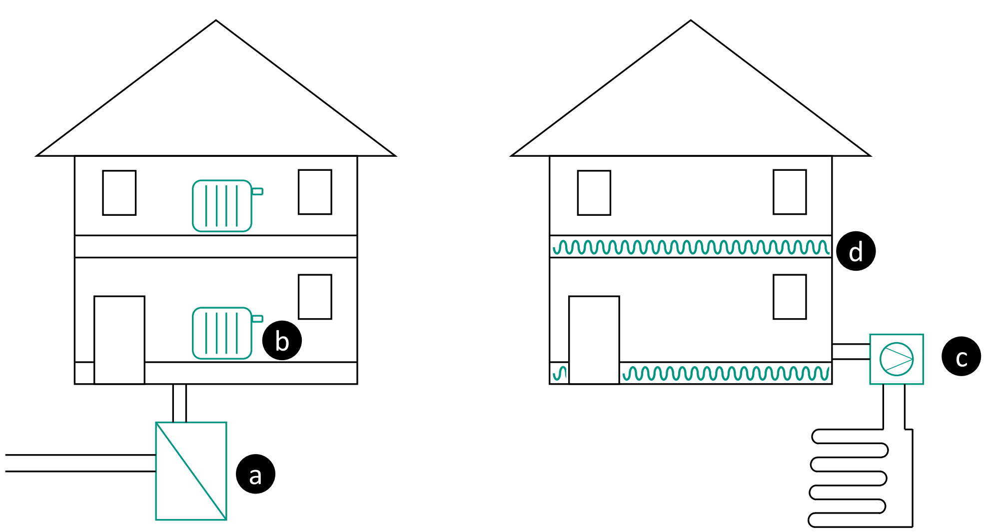

Fig. 1. Heat generators and heat emitters of the buildings: (a) District Heating, (b) Radiator, (c) Brine-to-Water Heat Pump, (d) Underfloor Heating.

Table 4
Confounding variables and respective consideration in the experiments.

Confounding variable	Minimization or control of the variable
Meteorological parameters (outdoor temperature, relative humidity, wind) [46]	Energy consumption standardized to the climatic conditions, if relevant (see Section 4.1)
Solar input	Considered in the usage scenarios (see Section 3.5)
Usage: internal heat gains (occupant, equipment and lighting) considering EN ISO 52016-1 [54] and ventilation losses due to manual ventilation	Considered in the usage scenarios (see Section 3.5)
Heat losses from supply and waste water	No domestic hot water available in the building

hypothesis to be investigated in the experiment is that the higher the impact score according to the SRI functionality level, the higher the energy savings of the considered heat generator.

3.5. Usage scenarios

As stated by Ramezani et al. [7], the occupant's interference must be reduced to achieve maximum energy efficiency, as it mainly influences the energy performance. Consequently, the usage in each building will be restricted in the majority of the scenarios. The building is technically designed and furnished as a single-family home, intended for a four-person household. To simulate defined usage scenarios, the building is used by the research staff. The rooms are assigned to typical residential room classes (e.g. living room, children's room) and equipped with representative setpoint temperatures. During working hours, staff occupancy mimics occupant-side disturbance variables such as internal gains, window ventilation, and lighting use, but without the ability to manually alter heating setpoints. At night, no people are present in the building, allowing for occupant-independent experiments to assess the intrinsic energy efficiency of each control strategy. This dual approach enables a comparative evaluation: daytime operation reflects typical household behavior, while night periods provide baseline measurements free from occupant interaction and solar influence. Table 5 provides a concise overview of the usage components concerning the following scenarios. Fig. 2 illustrates when each scenario occurs in the heating period from 13.12.2023 to 18.03.2024.

3.5.1. Night

The *Night* scenario will take place from 6 p.m. to 6 a.m. throughout the week. To highlight the actual increase in energy efficiency, it is important to minimize any confounding variables [47]. During this scenario, no persons are present in the building. There is also no solar input as the sun sets around 6 p.m. and rises around 8 a.m. This allows for occupant-neutral and solar-neutral evaluation of heating system performance. The lights are turned off automatically to prevent internal heat gains and to produce an approach that is similar to the typical use during the night. A decision was made against night set-back of the heating system because it could result in a higher total energy demand in the morning, as the building needs to be heated up quickly. This would also make a comparison to the following scenarios more difficult. A higher energy demand resulting from the absence of night set-back is accepted.

Table 5
Information on the usage scenarios.

Scenario	Night	Weekday	Weekend Daytime
Usage	None	Free	None
Utilization of devices	None	Depending on occupant	None
Solar input	None	Depending on occupant	Roller shutters opened

The absence of occupant influence and solar input makes this scenario particularly suitable for assessing the isolated energy performance of each functionality level, with minimal confounding variables [47]. On this basis, the influence of other confounding variables represented in the following two scenarios can be assessed.

3.5.2. Weekday

The building is used as an office during a typical workday from 6 a.m. to 6 p.m. During this time, four staff members are present and exhibit typical occupant behavior, such as opening windows, using electrical devices, and manually adjusting roller shutters. Importantly, occupants cannot alter heating setpoints or override the predefined heating control system. This scenario introduces internal heat gains, manual ventilation losses, and varying solar input, representing real-life disturbance variables in household settings. It serves as a contrast to the controlled *Night* scenario and is used to evaluate the impact of occupant behavior on the overall heating demand.

3.5.3. Weekend daytime

The building remains unused on weekends, comparable to the *Night* scenario. The roller shutters are open, the lights are off, and there is no automated ventilation. The building is inspected from 6 a.m. to 6 p.m. but the impact of heating losses due to manual ventilation and heating gains from intern waste heat is absent, compared to the *Weekday* scenario.

This scenario allows comparison with both *Night* and *Weekday* scenarios: it isolates the effect of solar input while excluding human activity. It represents cases where residents are temporarily absent during the day.

3.6. Experimental setup

Varsami and Burman [22] state that the services are not clearly defined, which was also apparent in the experimental setup design of this work. Thus, the technical adaptions utilized in the experiment, to fulfill the specifications of the services, will be presented in Table 6 for H-2a and Table 7 for H-2b.

To obtain more accurate heat generation results and view the two services in isolation, both buildings will operate without a heat storage tank. A representative situation and comfortable living conditions are created by defining different setpoint temperatures for each room class using norm temperatures (Fig. 3) [55,63]. The temperature in each room is regulated by wall sensors that automatically close the thermostatic valves when the set temperature is reached. Room doors should therefore remain closed.

Each test run lasts approximately two weeks, after that the system is switched over. Table 8 shows that functionality level 0 is considered first

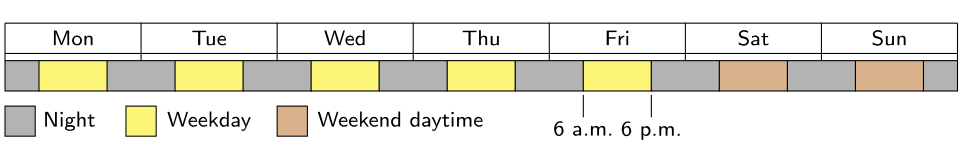

Fig. 2. Time of the scenarios during the week.

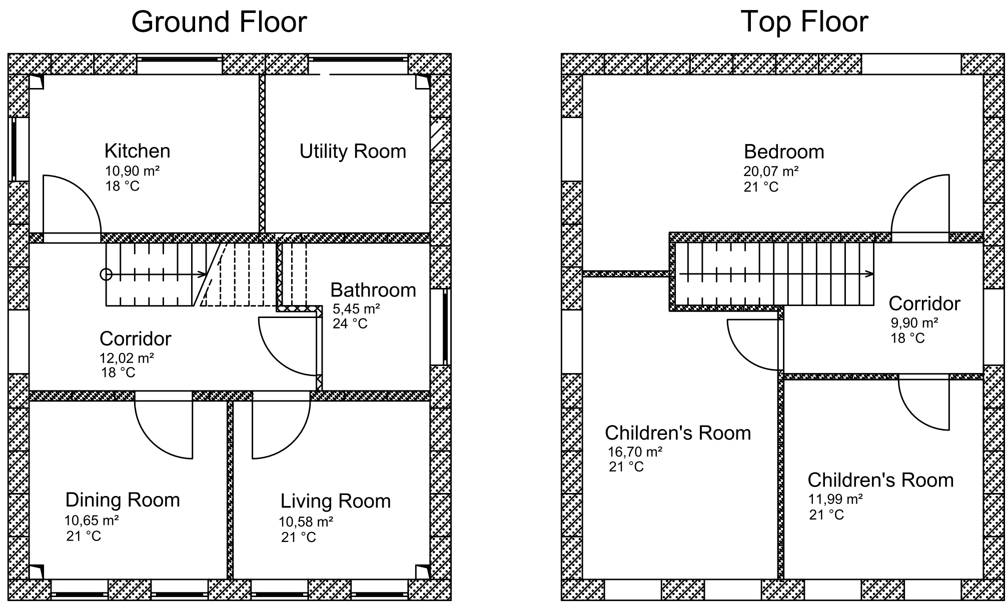

Fig. 3. Floor plan of the buildings with room area and setpoint temperature.

Table 6
Technical adaptions on the functionality levels of service H-2a.

Level	Definition
0	The heat transfer station of DH continuously provides a supply temperature of 60 °C, calculated using the standard heating load [55].
1	A suitable heating curve is implemented to adjust the supply temperature depending on the outdoor temperature. The curve for a supply temperature of 60 °C at −10 °C outdoor temperature is selected [56].
2	The load is determined by the temperature spread between the supply and return circuit, which is 10 K for a radiator [57]. The necessary adjustment of the supply to ensure the spread was determined for a representative outdoor temperature and statically defined.

Table 7
Technical adaptions on the functionality levels of service H-2b.

Level	Definition
0	The HP continuously provides a supply temperature of 45 °C, calculated using the standard heating load [55].
1	A suitable heating curve is implemented to adjust the supply temperature depending on the outdoor temperature. The curve for a supply temperature of 45 °C at −10 °C outdoor temperature is selected [56].
2	The load is determined by the temperature spread between the supply and return circuit, which is 7 K for panel heating [57]. The necessary adjustment of the supply to ensure the spread was determined for a representative outdoor temperature and statically defined.
3	The electricity spot market price of a representative week one year before the experiment is taken from [58]. The price signals to activate the different existing Smart Grid (SG) Ready modes of the HP [59] are calculated using the approach of [60]. Depending on the SG Ready mode, the indoor setpoint temperature is either increased by 1 K or 2 K or it remains the same [61]. The modified version 'level 3_{ad}' is also tested, which lowers the SG Ready modes by 1 K [62]. No data is predicted by the HP.

and then gradually increased until level 3 is reached. To compare H-2a with the H-2b, the energy savings from level to level are considered.

3.7. Preparation and evaluation of measured data

As shown in Section 3.5, the *Night* scenario has the least confounding variables. Thus, the energy consumption during the night is used to determine the comparison of the different functionality levels and services omitting the solar input and usage. The energy consumption data is compared to the data of the measurable confounding variables mentioned in Section 3.4 at the same time. The full experimental dataset, including all measured variables, sensor locations, and temporal resolutions for both buildings under various heating scenarios, is openly available on Zenodo [64].

In addition to the outdoor temperature, the influence of wind and relative humidity is reviewed. To consider varying weather conditions in the individual tests, a standardization to the average ambient conditions is carried out. This will enable the comparison of different levels. For this purpose, a multiple linear regression is performed with energy consumption as the dependent variable and the outdoor temperature, wind and relative humidity as independent variables. The analysis of the standardized coefficients allows a direct comparison of the relative significance of each independent variable in the model. These are used to decide whether a variable is relevant. The significance of these variables is determined in Section 4.1 and a suitable standardization is carried out based on their relevance.

The linear regression is validated by averaging the energy consumption at the same temperature over a 1 K outdoor temperature range. This can then be compared to the linear regression function. To calculate the measured energy savings (ES), divide the standardized energy consumption (EC) of a higher level to that of level 0 and subtract the result from 1, as shown in Eq. 1:

$$ES_{\text{measured}} = 1 - \frac{EC_{\text{Level } i}}{EC_{\text{Level } 0}}, \quad i > 0 \tag{1}$$

3.8. Calculation of the SRI scores

To calculate the SRI score, the respective service under consideration is isolated and evaluated. All other SRI services are classified as 'not applicable', except for those that have an impact on the total score, even if they are not taken into account. These are each assigned level 0. This assessment is performed using the latest version of the SRI calculation sheet (4.5) [17] and validated utilizing the KIT SRI calculator [65]. The

Table 8
Time of the Test Runs.

Level 0	Level 1	Level 2	Level 3	Level 3_{ad}
13.12.23 – 03.01.24	22.01.24 – 05.02.24	12.02.24 – 26.02.24	01.03.24 – 11.03.24	11.03.24 – 18.03.24

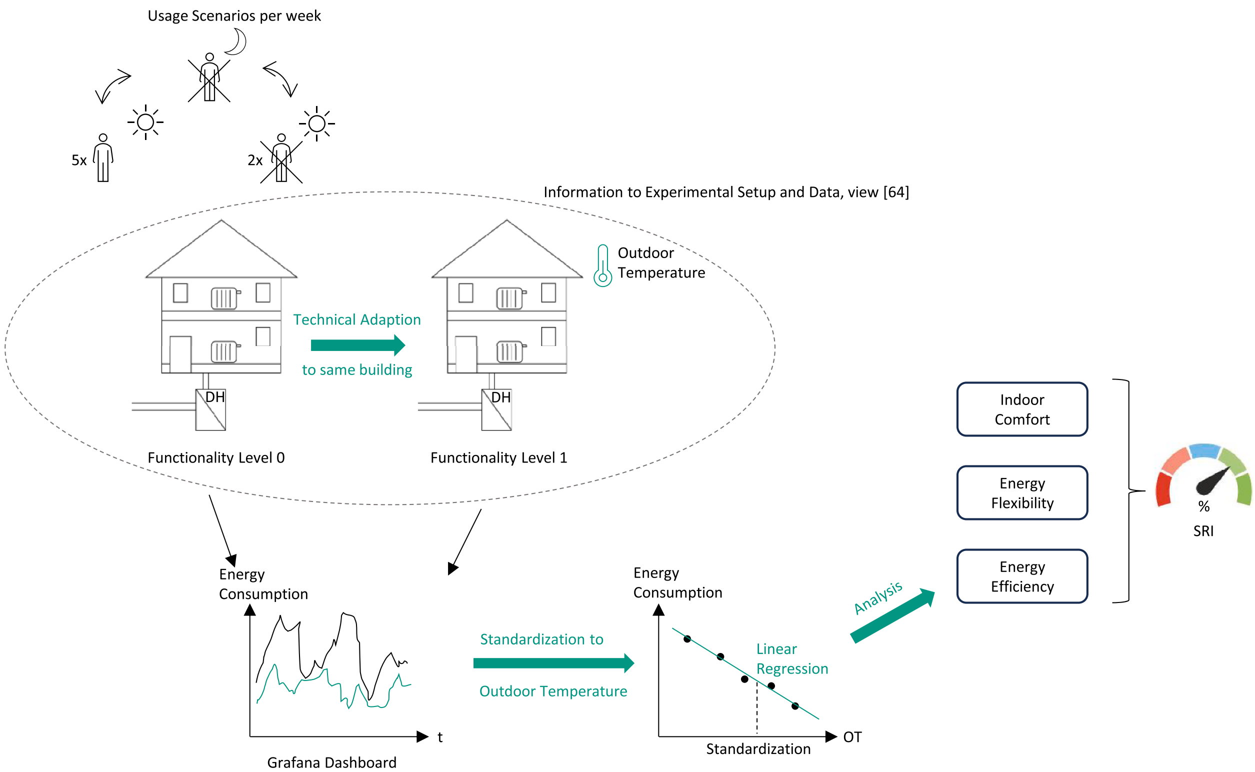

Fig. 4. Summarized methodology of this paper.

SRI only calculates the contribution of energy efficiency to the overall score and does not make any statement regarding the actual energy savings. Therefore, the Building Automation and Control (BAC) factors ($f_{\text{BAC,th}}$) specified in EN ISO 52120 [19], to which the SRI refers, are utilized (see Tables 11 and 12). To calculate the energy savings referenced to functionality level 0, divide the factor of the higher level by that of level 0 and subtract the result from 1. Eq. 2 shows this calculation that was similarly performed by [9]:

$$ES_{\text{calculated}} = 1 - \frac{f_{\text{BAC,th, Level } i}}{f_{\text{BAC,th, Level 0}}}, \quad i > 0 \tag{2}$$

3.9. Methodological workflow

To provide a clear overview of the experimental process and the subsequent evaluation steps, Fig. 4 summarizes the key stages of the study.

The experiments were conducted by successively implementing different SRI functionality levels (0 to 3) through technical adaptations in two identical test buildings. Each configuration was tested under defined usage scenarios while outdoor temperature, energy consumption, and room temperatures were recorded and displayed via Grafana (see [64]).

Data were processed in multiple steps. First, energy consumption was standardized to outdoor temperature through linear regression, enabling a level-wise comparison of efficiency. Indoor comfort was quantified using the temperature deviation (absolute deviation, mean temperature and standard deviation). Energy flexibility was evaluated based on the system's ability to respond to external grid signals.

The derived metrics were then mapped to the SRI structure, allowing direct comparison with the SRI impact scores. This structured approach enhances the transparency and reproducibility of the study's findings.

4. Results

4.1. Standardized energy consumption

In order to standardize the energy consumption of the individual levels in accordance with prevailing weather conditions, a multiple linear regression is conducted. Then, the standardized coefficients of certain meteorological parameters are compared to each other. The influence of a variable is greater when the absolute value of the standardized coefficient is higher than coefficients of other variables. Data from a weather station nearby is utilized for this purpose.

Table 9 shows that the standardized coefficients of wind and relative humidity for level 1 and above are smaller compared to the coefficients of the temperature. Therefore the influence of these variables on energy consumption is small. The deviation of the coefficients of wind and humidity in level 0 can be explained by outliers in the measurement data. The analysis of the weather data shows that the wind mainly comes from the southwest, where the buildings are located in the lee of other buildings.

The energy consumption for heating is compared to the outdoor temperature at the same time and a linear regression is carried out. Fig. 5a shows this procedure using level 1 of H-2a. The measurement points are taken at half-hour intervals. This results in a function of energy consumption depending on the outdoor temperature.

Table 9
Standardized coefficients of meteorological parameters influencing energy consumption.

Met. param. \ Service/level	H-2a 0	H-2a 1	H-2a 2	H-2b 0	H-2b 1	H-2b 2	H-2b 3	H-2b 3_{ad}
Outdoor temperature	-0.91	-1.05	-0.89	-0.24	-0.68	-0.55	-0.54	-0.5
Wind	0.53	0.02	0.05	0.18	-0.02	0.00	-0.13	0.01
Relative humidity	-0.03	-0.15	0.00	0.27	-0.11	0.09	-0.03	0.08

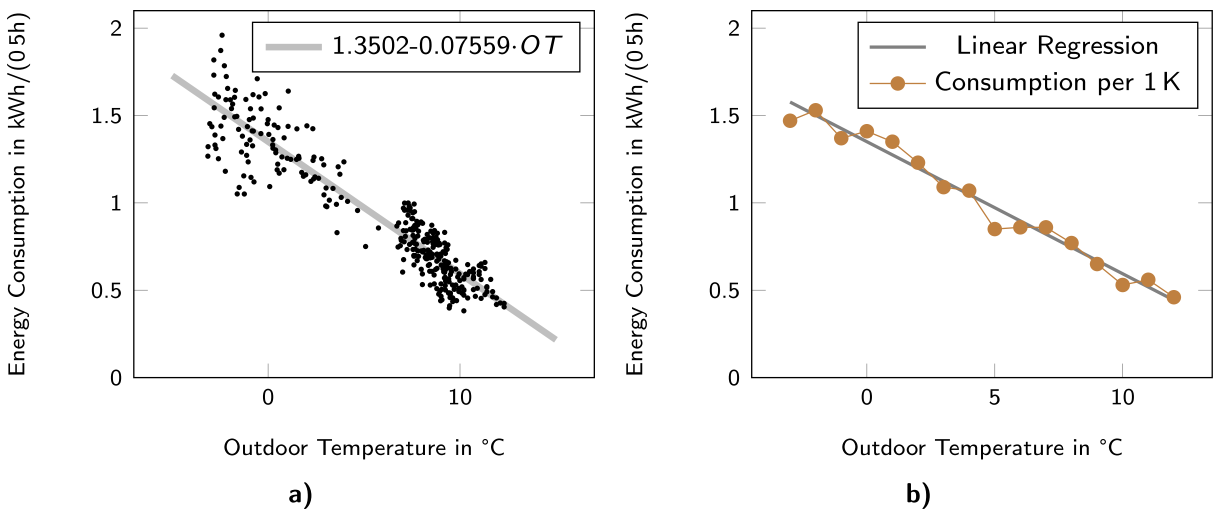

Fig. 5. 5a H-2a's energy consumption depending on outdoor temperature (OT) with corresponding linear regression of level 1; 5b validation of the linear regression with the average energy consumption in a 1K temperature range for H-2a Level 1.

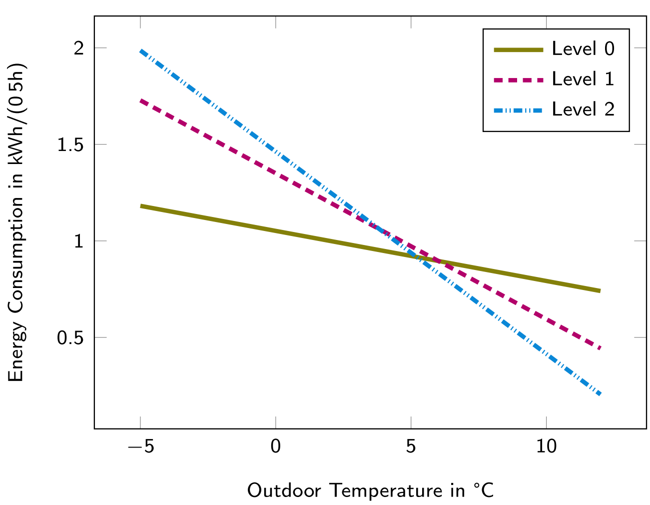

Fig. 6. Comparison of the linear regressions of energy consumption of H-2a's levels, depending on outdoor temperature.

This regression function is then validated using the average consumption per 1 K outdoor temperature range, as shown as an example in Fig. 5b. For this purpose, all energy consumption at the same outdoor temperature is averaged and compared to the linear regression.

As shown in Fig. 6, the energy consumption of H-2a's functionality levels depends on the outdoor temperature. This dependency varies from level to level. At outdoor temperatures below 5 °C, higher levels have a higher energy consumption than lower levels and vice versa. This means that energy savings in relation to lower levels only occur when outdoor temperatures are higher.

Table 10
Measured energy consumption (EC) standardized to outdoor temperature and energy savings by level increase.

Level	Standardized EC H-2a		Standardized EC H-2b	
0	0.8687 $\frac{kWh}{0.5h}$	↓ −6 %	1.0414 $\frac{kWh}{0.5h}$	↓ −30.6 %
1	0.8169 $\frac{kWh}{0.5h}$	↓ −11.5 %	0.7226 $\frac{kWh}{0.5h}$	↓ −7.9 %
2	0.7228 $\frac{kWh}{0.5h}$		0.6657 $\frac{kWh}{0.5h}$	↓ +8.5 %
3	-		0.7224 $\frac{kWh}{0.5h}$	↓ −30 %
3_{ad}	-		0.5072 $\frac{kWh}{0.5h}$	

The consumption can then be standardized to the average temperature during the experimental period, which is 7,06 °C (Table 10). This is done by inserting this temperature into the regression function.

4.2. Influence of the functionality levels

The measured and standardized energy consumption, shown in Table 10, is compared to the theoretical energy savings according to the SRI and EN ISO 52120 [19] in Tables 11 and 12. The comparison between the contribution to the SRI and the energy savings resulting from EN ISO 52120 shows that different statements are made: The SRI does not provide a quantitative statement about energy efficiency. Instead, it qualitatively assumes a steady increase in energy efficiency from level 0 to level 2, while EN ISO 52120 predicts an uneven increase.

It turns out that service H-2a does not achieve the energy savings predicted by EN ISO 52120, while H-2b exceeds them. A higher impact score according to the functionality level results in greater energy savings, but this only applies until level 2 is reached. H-2b level 3 shows that the savings are lower than those of the previous level 2. Level 3_{ad} exceeds the energy savings of level 2, although the same impact score is given for both levels. The hypothesis of the experiment can therefore not be confirmed. The energy savings do not adhere to the EN

Table 11
Calculated and measured energy efficiency (EE) depending on functionality level for service H-2a, referenced to level 0.

Level/impact score EE (SRI)	Contribution of EE (SRI)	BAC class/factors (EN ISO 52120)	Resulting savings (EN ISO 52120)	Measured energy savings
0 / 0	+ 0 %	D / 1.10	0 %	0 %
1 / 1	+ 5.2 %	C / 1.00	9 %	6 %
2 / 2	+ 10.3 %	A / 0.81	26 %	16.8 %

Table 12
Calculated and measured energy efficiency (EE) depending on functionality level for service H-2b, referenced to level 0.

Level/impact score EE (SRI)	Contribution of EE (SRI)	BAC class/factors (EN ISO 52120)	Resulting savings (EN ISO 52120)	Measured energy savings
0 / 0	+ 0 %	D / 1.10	0 %	0 %
1 / 1	+ 5.2 %	C / 1.00	9 %	30.6 %
2 / 2	+ 10.3 %	A / 0.81	26 %	36.1 %
3 / 2	+ 10.3 %	A / 0.81	26 %	30.6 %
3_{ad} / 2	+ 10.3 %	A / 0.81	26 %	51.3 %

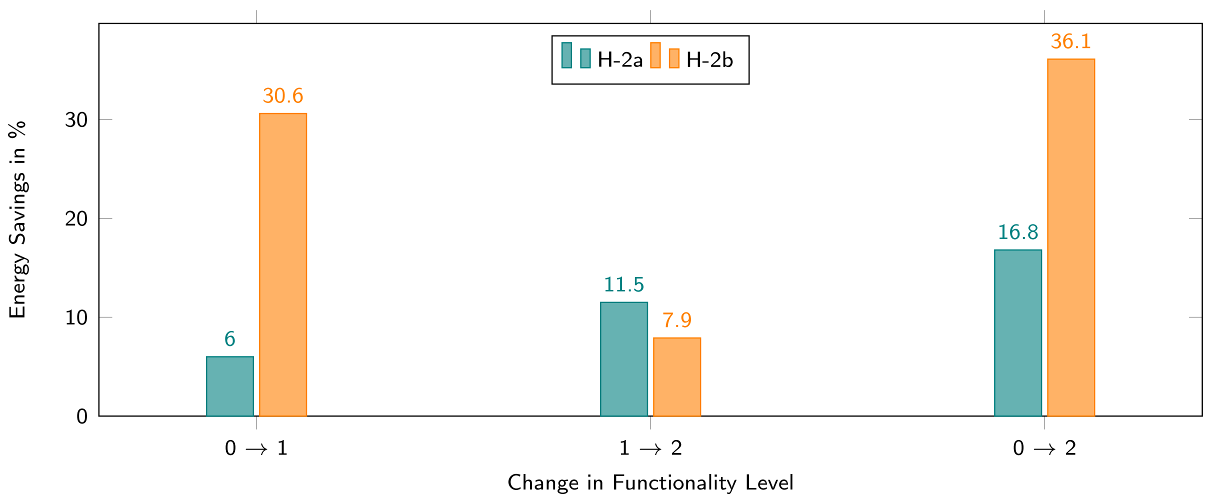

Fig. 7. Comparison of measured energy savings of service H-2a and H-2b during the night.

ISO 52120 specifications. Additionally, there is no steady increase in energy savings when increasing the level, which contradicts the SRI's statement.

4.3. Comparison of smart ready services H-2a and H-2b

Service H-2a and H-2b contribute equally to the SRI score, concerning the calculation methodology as they are weighted identically within the heating domain. The total energy consumption of the two heat generators cannot be compared because DH of H-2a is measured by the heat delivered, while electricity consumption is used to measure the HP's consumption of H-2b. Therefore, the percentage change in energy savings by increasing the levels is used to compare the two services (Fig. 7).

It can be stated that increasing the level of H-2b results in greater savings than H-2a compared to the reference level 0. However, an increase from level 1 to level 2 has a bigger impact on H-2a than on H-2b. Since the percentage savings are always greater with H-2b, the equal contribution of the two services to the total SRI score cannot be confirmed.

4.4. Influence of usage

Fig. 8 indicates that the *Night* scenario consumes the most energy in almost all levels. There is no clear trend in the distinction between the *Weekday* and *Weekend Daytime* scenario. In nearly all scenarios, regardless of the usage scenario, energy savings can be achieved by implementing a higher functionality level. In all cases, it can be observed that the buildings overheat during the day and store heat into the night.

4.5. Interior comfort

The indoor comfort during the *Night* scenario was assessed using multiple indicators, including average indoor temperature, standard deviation, and the Comfort Deviation Indicator (CDI). The indicators were calculated for each room individually over time and subsequently aggregated at the building level by weighting them according to the respective room volumes. The CDI is a simplified key performance indicator (KPI) that was calculated based on the deviation from setpoint temperatures. Specifically, the absolute integral of the difference between measured and setpoint room temperatures was calculated over the entire nighttime measurement period for each room. An increase of the value means less comfort.

Table 13 summarizes these factors. For service H-2a, the mean indoor temperature is lower with a higher level, and the temperature falls below the norm temperature. Concurrently, the standard deviation and the CDI value increase. For service H-2b, the mean indoor temperature is lower in level 1 and 2, but this brings it closer to the norm temperature. Furthermore, the standard deviation either decreases or remains nearly constant. The CDI value is lower than at level 0. Levels 3 and 3_{ad}, on the other hand, have an even higher mean indoor temperature. The standard deviation and the CDI value also increase.

For level H-2a, comfort tends to decline at higher functionality levels. For H-2b, there is a slight increase in comfort for level 1 and 2, while the comfort strongly decreases for level 3 and 3_{ad}.

The deviating norm temperature of level 3 and 3_{ad} is due to elevated setpoints because of the HP's SG Ready mode, which increases the set temperature at certain times.

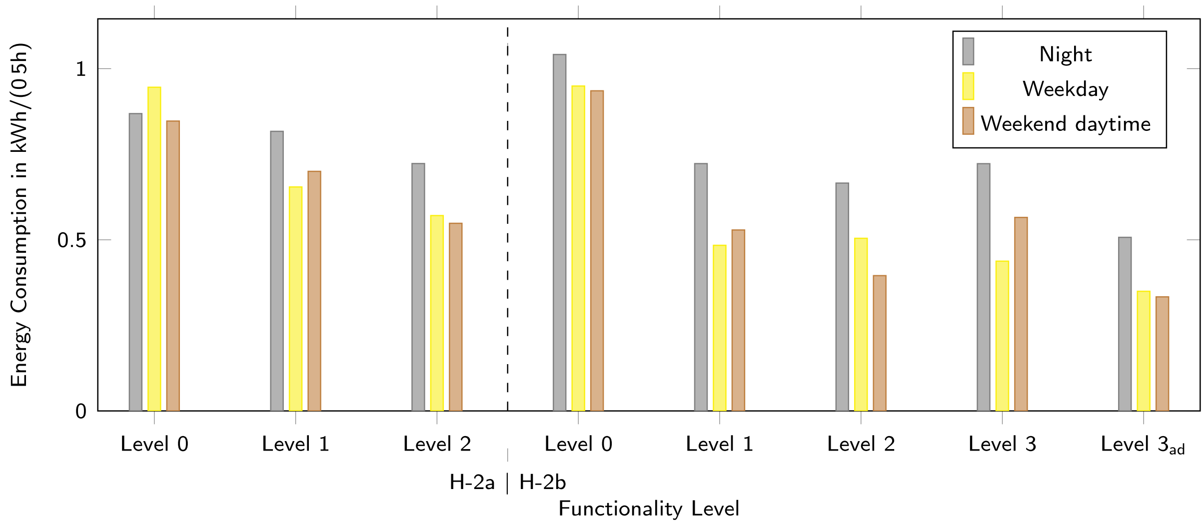

Fig. 8. Energy consumption of different scenarios during the night, standardized to outdoor temperature.

Table 13
Factors influencing indoor comfort.

Service	H-2a			H-2b				
Functionality Level	0	1	2	0	1	2	3	3_{ad}
Norm indoor temperature	20.25 °C	20.25 °C	20.25 °C	20.25 °C	20.25 °C	20.25 °C	21.35 °C	20.35 °C
Mean indoor temperature	20.50 °C	19.84 °C	19.81 °C	21.42 °C	20.97 °C	20.99 °C	22.23 °C	21.82 °C
Standard deviation	0.23 K	0.24 K	0.29 K	0.31 K	0.27 K	0.32 K	0.58 K	0.57 K
Comfort Deviation Indicator	0.29 K	0.62 K	0.80 K	1.14 K	0.91 K	1.02 K	1.27 K	2.71 K

4.6. Energy flexibility

For Level 1 and 2, the SRI indicates an impact score of 1 (see Tables 1 and 2). This becomes evident in the experiments, as the lower supply temperature leads to less HP power required. This causes the HP to be switched off for longer time periods, compared to level 0. In level 3, an impact score of 2 is given, meaning the energy flexibility is increased. To ensure this, the HP's existing SG Ready modes are used, that occasionally elevate the indoor temperature during periods of low electricity prices. It allows heat to be stored in order to reduce the HP operation during periods of high prices. This can result in compromises in comfort, as discussed in Section 4.5. The existing SG Ready modes have been demonstrated to result in a higher mean indoor temperature, in both level 3 and level 3_{ad} of H-2b, compared to the lower levels. As illustrated in Fig. 8, level 3_{ad} has been shown to result in the greatest energy savings.

5. Discussion

5.1. Experimental setup and execution

Every building is unique with regard to the heating demand, depending mostly on building physics aspects. Typical buildings with typical heat generators have been considered to depict a representative scenario. Due to the different heat generation, it is not possible to make a direct comparison of the energy consumption of the two services. DH in H-2a sources heat in nearly equal parts from the grid, while the HP in H-2b converts geothermal heat with the aid of electrical energy into heating energy. Additionally, the two systems experience different heat losses due to varying supply temperatures resulting from different heat emitters. For each heat generator and supply temperature, a suitable heat emitter is selected. Furthermore, there are differences in pipe routing and positioning within the floor structure, resulting in different heat losses.

Both heat generators are controlled using a wall sensor, which is a typical setup for underfloor heating in H-2b but less common for radiators in H-2a, where a thermostatic valve is typically used. The sensor is mounted on the wall, opposite the radiator. This can cause a reaction with a delay, compared to a thermostatic valve, especially in cases of low convection in the room caused by low supply temperatures. As a result, local overheating at the radiator may occur. The impact of this deviating control cannot be quantified, yet it represents a divergence from a genuine system.

When implementing H-2a level 2, a static approach is used to correct the supply temperature. Past data at a certain outdoor temperature is analyzed to determine the extent to which the supply temperature must be adjusted to maintain the desired spread. Dynamic control is not implemented, although it could maintain the spread more precisely.

Service H-2b utilizes a BWHP instead of the more commonly used AWHP. This choice is made due to the latter's higher dependence on outdoor temperature, which could result in increased energy consumption, especially at low outdoor temperatures. At such times, a higher supply temperature must be provided, and a high electricity demand would be required as less ambient heat is available compared to higher outdoor temperatures. The use of outdoor temperature-based control in level 1 and 2 would exacerbate this issue.

The recorded experimental period is limited to the heating period since the building is only heated during this time. Year-round operation is not monitored. However, domestic hot water is normally produced all year, often using the same heat generator as for building heating. This was not applied in the experiment, but can significantly impact the energy consumption of the heat generator. Additionally, the absence of a storage tank can also affect consumption [12]. Finally, implementing a night set-back for building heating could reduce overall consumption by lowering indoor temperatures.

Table 14
Average outdoor temperature during the night and delivered heat depending on service and functionality level.

	Outdoor temperature	Delivered heat	
Level	Median	H-2a	H-2b
0	8,75 °C	1.91 $\frac{kWh}{h}$	1.88 $\frac{kWh}{h}$
1	7,71 °C	2.02 $\frac{kWh}{h}$	2.0 $\frac{kWh}{h}$
2	8,24 °C	1.36 $\frac{kWh}{h}$	1.53 $\frac{kWh}{h}$
3	6,93 °C	–	1.91 $\frac{kWh}{h}$
3_{ad}	8,75 °C	–	0.89 $\frac{kWh}{h}$

5.2. Energy consumption

The evaluation of the measured data is subject to uncertainties. Other publications have analyzed longer time periods (weeks or months) to gather more data and to obtain a more reliable regression function [47,48,51,53].

The results indicate that in the present case with H-2a, operation in level 0 at outdoor temperatures below 5 °C would be more energy-efficient. An incorrect evaluation of the data can be excluded, as the linear regression of the energy consumption was validated with measurement data. The issue can be explained by the supply temperature being too low for the selected radiator in level 1 and 2. This is indicated by the manufacturer's specifications, which require a minimum supply temperature of 45 °C [66]. With the assumed heating curve, the specific supply temperature is often undershot, resulting in inadequate heat output and an increased flow rate. For comparison, a further investigation could therefore select a different heating curve that uses higher supply temperatures. However, energy savings are achieved through low supply temperatures resulting in less losses. Simply increasing the supply temperature may result in savings at higher levels compared to level 0, but the total consumption would be greater than with the selected heating curve as the losses would increase. It is also necessary to question the calculation of the heating load according to the standard, as well as the manner in which this is applied to the heating curve according to the standard. Consequently, the optimal operating point and heating curve for the building and heat generator must be determined iteratively, whereby the supply temperature should be as low as possible while still ensuring sufficient heating and not undercut the radiator's specifications.

Different weather conditions prevailed during the tests, which is evident from the mean outdoor temperatures at night in Table 14. The interaction of different average temperatures on the total energy consumption is considered by standardizing to the outdoor temperature but has not been precisely quantified. Compared to previous years, the outdoor temperature is significantly higher [67]. Therefore, forecasting consumption at low temperatures is subject to greater uncertainties, and energy consumption is likely to be higher if the overall outdoor temperatures are lower.

In order to estimate the workload of the heat generators, the delivered heat in the different levels is compared in Table 14. The values are measured over the experimental period during the night, standardized to the time, but were not standardized to outdoor temperature. In most levels, the amount of heat delivered in H-2b is less than in H-2a. This suggests that it takes longer to heat up with panel heating than with a radiator. However, there is a contradiction in the average temperatures of the houses, according to which H-2a is colder than H-2b, which was shown in Table 13. This can especially be explained by differences in the usage and occupancy of the buildings (see Section 5.4).

In the case of DH in H-2a, deviations in energy consumption throughout the levels should only result from lower losses with a smaller temperature gradient from the supply temperature to the ambient temperature. As the supply temperature is lowered as far as possible when the level is increased, the gradient is reduced accordingly. An increase in the amount of heat delivered can occur as a result of local overheating, which was described in Section 5.2. Service H-2a also applies to combustion heating systems. If such a system is used, the energy consumption may differ because an energy source (e.g. gas or oil) is converted into heat and heat is not drawn directly from the DH grid.

In the case of the HP in H-2b, reducing the supply temperature not only results in the aforementioned savings because of fewer losses, but also in a notable reduction in electricity consumption by the compressor. The lower the spread, the lower the consumption of the HP.

5.3. SRI evaluation

The technical implementation of the services and levels is a proposal for the practical application of the technology-neutral defined SRI levels. A discrepancy arises from the evaluation of the indicator: The impact scores are derived from EN ISO 52120, whereas the impact of energy efficiency on the total score is defined separately in the SRI and is not incorporated through the BAC factors of the standard. The indicator does not provide a direct statement about the energy savings with an increase in levels, but it does indicate the contribution of energy efficiency on the total score via the impact scores. This does not correspond to the calculated energy savings resulting from the BAC factors of EN ISO 52120. The impact scores serve as the sole metric for quantifying the effect on the impact criteria. The results of the experiments demonstrate that the scores are not suitable for use within a service or for comparison with other services, as the measured energy savings differ. A constant increase in impact scores, as in the present case of energy efficiency, could not be confirmed by a constant increase in energy savings. Neither the SRI impact scores nor EN ISO 52120 have proven to be suitable for quantifying energy savings. This confirms the discrepancies in the SRI impact scores and the factors of EN ISO 52120 in comparison to the actual energy performance, that were found by previous research, mentioned in Section 2.3. The score is not tangible or backed up by actual values, but serves only as a relative comparison with other buildings. An estimation of savings would be particularly useful for occupants. Services have been considered in isolation, whereas the effect of increasing the functionality level of several services may be greater [9].

Beyond these structural issues, the SRI does not reflect newer perspectives on smart readiness that have emerged in recent research. Several studies propose dynamic, performance-based interpretations of smart building intelligence. These include adaptive control strategies under uncertainty, optimizing demand response through real-time pricing and user-driven behavior [68–71]. Others emphasize the building's role as an active market participant, using local flexibility coordination and pricing feedback mechanisms [72–74]. Additionally, multi-energy scheduling frameworks consider environmental targets and carbon taxation as relevant control parameters [75,76]. These approaches extend the notion of smartness beyond technical implementation, toward measurable grid and system-level impacts-dimensions currently not represented in the SRI scoring logic.

Further experiments should quantify the effects of the impact scores on energy efficiency in more detail, especially for different services. EN ISO 52120 would need to be adjusted and adopted within the SRI. This would ensure consistency with the standard.

5.4. Influence of usage

Usage-related variability was minimized by focusing on the night scenario when no occupants were present. A correlation has been identified between a higher functionality level and the amount of energy saved, even in the other two scenarios.

During the day, no usage profile is implemented to account for its influence. Instead, actual usage is present, which can be discontinuous and variable. The presence of research staff is intended to simulate typical occupant daytime activity. While device usage may be higher than in a standard single-family home, the resulting thermal effects remain within a comparable range.

As shown, the usage leads to higher indoor temperatures and a lower heating energy demand due to the waste heat from people and devices during the day. Furthermore, the solar input heats the building. The solar input and internal heat gains are therefore greater than heat losses through manual ventilation, which results in less energy consumption during the day. It is not possible to ascertain whether the internal heat gains in the *Weekday* scenario compensate for the losses, as there is no discernible trend when compared to the *Weekend Daytime* scenario.

The building overheats during the day and stores the heat, which can affect the energy consumption during the *Night* scenario. Comparing the two buildings becomes more difficult, particularly if they are used differently. Although equal usage is assumed in both buildings, it can be inferred that the building using H-2a has a more sporadic usage. This could lead to different heat inputs throughout the day, which reduce the energy consumption in the night. It is probable that the house with H-2b will receive more sunlight in the evening than H-2a, resulting in increased heat input. Overall, it can be stated that usage has a positive impact on energy efficiency.

There is limited data available for the *Weekend Daytime* scenario, as only 2–4 days are included for the levels 1–3. The energy savings calculated are therefore subject to greater uncertainties compared to the other scenarios.

Although the buildings are not permanently inhabited, the experimental setup was deliberately designed to emulate typical residential usage patterns during the day. Room usage was mapped to typical household room types and standard heating setpoints were applied. While internal gains during the weekday scenario may differ from actual household behavior, the focus of the study lies on the *Night* scenario, where occupant interaction is minimized. From an energy performance perspective, this phase is comparable to a sleeping residence, as the building remains unoccupied and free from user influence.

While this study is based on real measurements under defined boundary conditions, the influence of occupant behavior, external weather, and load variability remains an inherent factor that affects the effectiveness of smart control systems. These uncertainties may partially explain the observed deviations between predicted and actual energy savings.

5.5. Interior comfort

Overall, no rating system has been established to assess occupant's comfort. The comfort criteria is determined by the indoor temperature according to standards [55,63]. During the experiment, norm temperatures in certain rooms are not reached. This could be a result of high norm temperatures that cannot be technically achieved by the technical adaptions used for the different levels. For instance, in the bathroom, the small surface area of a panel heating system is not sufficient to meet the high target temperature, and a high supply temperature is required for a radiator to reach the norm temperature of 24 °C. The further reduction of the supply temperature with increasing level reinforces this effect.

Temperature overshoots are partly caused by the pipe routing. In the house using H-2b, the underfloor heating supply line runs in the screed of the corridor, resulting in heat losses to the room. In H-2a, these pipes are better insulated under the screed and therefore do not heat the corridor through losses.

The calculated CDI, which quantifies the absolute deviation from the setpoint temperatures suggest that increased functionality levels can negatively impact thermal stability, particularly in H-2a and at the upper levels of H-2b. This is likely due to delayed response behavior and external signal overrides. While higher SRI levels are designed to improve energy efficiency and grid interaction, they do not inherently guarantee better indoor comfort.

The CDI serves as an initial approximation to assess thermal comfort under varying functionality levels. It does not replace established thermal comfort models, but enables a relative comparison of control performance in the experimental setup. The CDI should therefore be evaluated by occupants in order to better interpret the values.

Notably, the results for H-2b show that levels 1 and 2 yield slightly improved comfort compared to level 0, as indicated by a lower CDI and reduced temperature fluctuation. This suggests that under certain configurations, limited increases in smartness may stabilize indoor conditions rather than impair them. In contrast, all higher levels of H-2a, as well as level 3 and 3_{ad} of H-2b, exhibit stronger deviations and higher variability, consistent with more aggressive control strategies.

In summary, the findings suggest that smart control strategies may lead to comfort deterioration at higher SRI functionality levels unless carefully calibrated. This effect could potentially be mitigated by adapting supply temperatures or improving system response, but is unlikely to fully compensate under current boundary conditions. However, moderate levels, as seen in H-2b, can also offer marginal improvements, indicating that the relationship between smartness and comfort is not strictly linear.

5.6. Contribution to the grid

Maintaining a constant spread, which was defined in H-2a level 2 can be useful for the DH producer. If many DH consumers use this approach, the demand is more clearly defined and the supply and return temperature in the DH network can be better maintained. The SRI does not recognize this as only an impact score of 0 for energy flexibility is given.

For H-2b level 1 and 2, the HP is off for longer periods than in level 0, but the reduction in power and shutdown of the system cannot be planned or controlled. The grid therefore cannot benefit from this control, but the SRI indicates an impact score of 1. Level 3 did not result in energy savings compared to level 2, but the flexibility to the grid is increased, which can lead to monetary savings for the occupant [77]. This may lead to reduced energy costs despite higher energy consumption. The possible negative effects on energy demand can be mitigated by heat storage in the form of a storage tank or via the building by means of good insulation, which makes it easier to bridge periods of high prices.

The approach using the HP's existing SG Ready mode, applied a higher target temperature than the other tests, making a comparison more difficult. This can be explained by the fact that the building is occasionally overheated to store heat for high-price phases and reduce the HP's output. As level 3 leads to an overall higher temperature compared to the other levels, level 3_{ad} is also tested. This level leads to the highest energy savings of H-2b. An adaptation of the SG Ready mode to the proposed approach 'level 3_{ad}' should therefore be considered to ensure energy flexibility and efficiency at the same time. Different price signals could be used to adapt the indoor setpoint temperature or other signals from the electricity grid could trigger the HP's power directly, resulting in a deviating energy consumption.

5.7. Summary of trade-offs across impact categories

Table 15 summarizes the observed trade-offs between energy efficiency, indoor comfort, and energy flexibility across all tested SRI functionality levels. The CDI value was utilized to evaluate indoor comfort, as it is a quantifiable parameter for assessment. The percentage change in relation to level 0 is calculated in accordance with the same scheme as that employed in Eq. (1). A negative value is associated with a reduced level of comfort.

For H-2a, energy efficiency improves moderately at both levels 1 and 2, aligned with an increase in the SRI impact score from 0 to 2. However, indoor comfort deteriorates with increasing levels, despite also receiving higher SRI comfort impact scores (+1 and +2). Energy flexibility remains constant, which is consistent with an unchanged impact score of 0.

Table 15
Comparison of H-2a and H-2b in terms of the impact categories, compared to level 0.

	H-2a		H-2b			
	1	2	1	2	3	3_{ad}
Energy Efficiency	+6 %	+16.8 %	+30.6 %	+36.1 %	+30.6 %	+51.3 %
Impact Score EE	+1	+2	+1	+2	+2	+2
Indoor Comfort (CDI)	−116.6 %	−180 %	+20.7 %	+10.6 %	−11.3 %	−136.9 %
Impact Score Co	+1	+2	+1	+2	+2	+2
Energy Flexibility	Constant spread	Constant spread	Constant spread	Constant spread	Grid-friendly	Grid-friendly
Impact Score EF	+0	+0	+1	+1	+3	+3

In contrast, H-2b achieves strong energy savings at all levels. Notably, level 1 and 2 also show improved comfort, which aligns with the rising comfort impact scores. However, at levels 3 and 3_{ad}, comfort declines sharply, while the comfort score increases. Regarding flexibility, H-2b becomes grid-friendly from level 3 onward, reflected in an increase in the SRI impact score.

This overview illustrates that while increased functionality can enhance energy performance and flexibility, these benefits may come at the cost of reduced occupant comfort, especially at the uppermost SRI levels.

6. Conclusion

The present paper investigates whether the two SRI services, H-2a and H-2b, can increase energy efficiency by improving their functionality levels and if they result in the predicted energy savings concerning the SRI and EN ISO 52120. The experiments conducted on real buildings demonstrate that energy savings can be achieved by using smart technologies concerning the SRI. The maximum energy savings observed were 16.8 % for H-2a (at functionality level 2) and 51.3 % for H-2b (at level 3_{ad}). By comparing the measured to the predicted energy savings calculated using the BAC factors from EN ISO 52120, it becomes apparent that H-2a falls below them and H-2b exceeds them. Both services contradict the SRI's assumption that increasing the level results in a steady increase in energy efficiency. The varying energy savings of the two services show that despite being equally weighted in the heating domain, the actual contribution of the services to energy efficiency can differ significantly in practice.

The experiments indicate that the SRI may not provide a precise estimate of energy savings resulting from the use of smart technologies in the services H-2a and H-2b under the tested boundary conditions. While deviations from the predicted savings were observed, the SRI can still serve as a rough benchmark for estimating potential efficiency gains. The indicator's score should therefore be interpreted with caution and not directly equated with actual energy efficiency experienced by occupants. Moreover, smart technologies that receive the same scoring within the SRI framework can lead to substantially different energy savings in practice. Nonetheless, the technical implementation of increased SRI functionality levels did result in measurable energy savings for both services, confirming the general trend of improved performance with higher functionality levels.

In summary, the presented work contributes to advancing the evaluation of smart readiness by providing empirical evidence from controlled field experiments. It highlights discrepancies between theoretical assessments and real energy performance, and supports the need for a more performance-based refinement of the SRI framework. The results serve both as a validation reference and as a starting point to quantify the real efficiency potential of smart control technologies.

Future experiments could explore alternative technical implementations of the services, particularly with other heat emitters and heating curves. It should be analyzed whether the use of smart technologies in H-2a and H-2b can also achieve energy savings at low outdoor temperatures. Specific usage profiles could be implemented to better quantify energy savings according to usage patterns. During building usage, the focus shifts to occupant comfort, which needs to be analyzed in more detail. Moreover, multiple domains and services and their interactions should be analyzed. Future experiments should run over extended periods to ensure comparability regarding environmental conditions.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used DeepL in order to increase comprehensibility. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Luca Person: Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization; **Tristan Emich:** Writing – review & editing, Supervision, Resources, Conceptualization; **Luigi Spatafora:** Writing – review & editing, Supervision, Software, Project administration, Investigation; **Veit Hagenmeyer:** Writing – review & editing, Supervision, Funding acquisition; **Kunibert Lennerts:** Writing – review & editing, Supervision, Funding acquisition.

Data availability

The data underlying the findings of this study are available in the Zenodo repository and can be accessed via DOI: https://doi.org/10.5281/zenodo.14810476 [64].

Declaration of interests

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.

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