Technology Collaboration Programme

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IEA Technology Collaboration Programme

International Energy Agency

Technology Collaboration Programme on Energy Storage

(ES TCP)

Task 43

Storage for renewables and flexibility through standardized use of building mass

Final Report

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CONTENT

LIST OF ABBREVIATIONS

Below is the **List of Abbreviations (technical & policy only)** extracted from the report (organisations, companies, and software/tools excluded), in **English** and **alphabetical order**:

Abbreviation	**Meaning**
ADR	Active Demand Response
AMI	Advanced Metering Infrastructure
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEMS	Building Energy Management System
BIM	Building Information Modelling
BTM	Building Thermal Mass
CAPEX	Capital Expenditure
CCT	Concrete Core Temperature Control
CEN/CENELEC	European Committee for Standardization / European Committee for Electrotechnical Standardization
CFD	Computational Fluid Dynamics
CO_2	Carbon dioxide
COP	Coefficient of Performance
DAE	Differential-Algebraic Equation
DER	Distributed Energy Resource(s)
DHW	Domestic Hot Water
DIN	German standard / German Institute for Standardization
DSC	Differential Scanning Calorimetry
DSO	Distribution System Operator
EAG	Austrian Renewable Expansion Act (Erneuerbaren-Ausbau-Gesetz)
EBC	Energy in Buildings and Communities (programme)
EED	Energy Efficiency Directive
EFSI	Expected Flexibility Savings Index
EN	European Standard
EnWG	German Energy Industry Act (Energiewirtschaftsgesetz)
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EPP	Expanded Polypropylene
EPS	Expanded Polystyrene
ETICS	External Thermal Insulation Composite System
FEM	Finite Element Method
FERC	Federal Energy Regulatory Commission
FMI/FMU	Functional Mock-up Interface / Functional Mock-up Unit
FPI	Flexibility Performance Indicator
GDPR	General Data Protection Regulation
GFRP	Glass Fibre Reinforced Polymer
HAM	Heat, Air and Moisture
HTSS	High-Temperature Stone Storage
HVAC	Heating, Ventilation and Air Conditioning
IEC	International Electrotechnical Commission
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
KDI	Key Design Indicator

Abbreviation	Meaning
KNX	KNX (building automation standard)
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Cost(ing)
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer Nonlinear Programming
MPC	Model Predictive Control
OPC	Open Platform Communications
OPC UA	OPC Unified Architecture
OPEX	Operational Expenditure
PCM	Phase Change Material
PIPEDA	Personal Information Protection and Electronic Documents Act (Canada)
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PV	Photovoltaics
RC	Resistance–Capacitance (model)
RCS	Radiant Cooling System(s)
RED	Renewable Energy Directive
RH	Relative Humidity
SRI	Smart Readiness Indicator
SoC	State of Charge
STES	Seasonal Thermal Energy Storage
TABS	Thermally Activated Building Systems
TES	Thermal Energy Storage
TLS	Transport Layer Security
TLS/VPN	Transport Layer Security / Virtual Private Network
ToU	Time-of-Use (tariff)
TRY	Test Reference Year
VHCS	Ventilated Hollow Core Slab (as used in report)
VHF	Ventilated façade (as used in report)
VPN	Virtual Private Network
VRE	Variable Renewable Energy
WLG	Thermal conductivity class (German: Wärmleitgruppe)
XPS	Extruded Polystyrene

KEY MESSAGES AND POLICY RECOMMENDATIONS

With special thanks to Prof. Shady Attia, University of Liege, Belgium

Thermally activated building systems (TABS) are technically mature and can serve as a large, distributed thermal energy storage resource that supports electrified heating/cooling and renewable integration. The decisive bottleneck is not hardware performance, but non-technical conditions: today, flexibility from building mass is often invisible in regulation, hard to monetise in markets, and difficult to activate at scale due to gaps in tariffs, metering/data access, and clear roles for aggregation. Task 43 evidence across multiple countries shows that missing legal definitions, unclear responsibilities and value streams, and data governance constraints are persistent blockers for automated, grid-supportive operation. At EU level, the 2025–2030 policy window is particularly relevant: the Energy Performance of Buildings Directive recast (EPBD, in force 2024; transposition by 2026) provides a route to embed flexibility indicators into building assessment; the Electricity Market Design reform opens demand-response participation via aggregators; Renewable Energy Directive III (RED III) and Energy Efficiency Directive (EED) strengthen the case for demand-side flexibility and DSO-level integration; and the EU Grids Action Plan highlights digitalisation and data access as enabling infrastructure. Looking forward, building-mass storage is positioned as a system asset: by 2030, TABS and other thermal storage could contribute >10 GW of flexibility potential in Europe (≈15% of building-sector load), while by 2050 a climate-neutral, highly electrified system implies that buildings must act as “flexibility sponges.” Task 43 points to five policy levers that should be pursued —regulatory recognition, market access, skills, and demonstration—supported by digital/data measures.

Make flexibility visible in building regulation and certificates. Incorporate a thermal-storage flexibility KPI into Energy Performance of Buildings Directive (EPBD) implementation and associated Energy Performance Certificate methodologies so that dynamic operation and storage contribution are credited rather than ignored. Link this KPI to the Smart Readiness Indicator (SRI) where applicable and require that publicly supported renovations/new builds demonstrate “flex-ready” capability.

Open markets to building-scale flexibility via aggregation. Fully implement aggregator access under the Electricity Market Design reform and remove practical barriers that exclude building assets—explicitly enabling sub-100 kW resources to participate through aggregation. Align Renewable Energy Directive III (RED III) DSO flexibility intent with workable local market products (standardised procurement, transparent settlement) so buildings can provide services without bespoke contracts.

Ensure digital and data access as a public enabler, not a project-by-project hurdle. Treat data access (smart meter and relevant building signals) as essential infrastructure for flexibility. Implement secure, privacy-preserving access frameworks consistent with the EU Grids Action Plan: standard interfaces/open APIs, minimum datasets, clear consent and governance, and cybersecurity requirements so automated control can scale reliably.

Address the skills gap with targeted training and guidance. Expand professional training for architects, HVAC designers, commissioning agents, and facility managers—especially on storage-aware design, commissioning, and predictive control concepts—using EU-level skills initiatives (e.g., Pact for Skills modules) and national roll-outs.

Fund and label “Flex-Ready Buildings” to create visibility and trust. Establish dedicated programmes that finance monitored, replicable “Flex-Ready” demonstrations (new build and retrofit), with requirements for transparent reporting of comfort compliance and flexibility delivery. The intent is to make flexibility-ready buildings as visible and investable as PV deployments, accelerating learning curves and de-risking adoption for policymakers and industry.

MAIN RESULTS IN A NUTSHELL

Thermally activated building systems (TABS) are technically mature and ready to be used not only for low-temperature heating and cooling, but as a distributed thermal energy storage resource. The decisive shift is conceptual and operational: the value of TABS is highest when building elements are treated as multifunctional assets—structure, comfort delivery, and storage—rather than as “slow radiant systems.” Market-ready solutions already demonstrate that repeatable, industry-grade implementation is feasible, and refurbishment-oriented approaches (especially externally applied activated envelopes) provide a credible pathway into the existing building stock with minimal disruption.

The main challenge is no longer a lack of concepts, but scaling and utilisation. For large-scale uptake, Task 43 highlights that industrialisation and standardisation are essential: prefabrication, modular design, and validated component characterisation can reduce on-site complexity, improve quality assurance, and enable replication. In parallel, material and assembly diversity is an opportunity rather than a problem—provided that robust, validated datasets and characterisation methods allow planners to use non-standard or hybrid constructions with confidence. While phase-change materials (PCM) integrated into TABS are being explored as a means to increase effective storage capacity and smooth thermal loads, they currently remain a research-focused niche without widely available, market-ready products.

TABS can deliver system value only if they are operated “storage-aware.” Task 43 therefore positions modelling and simulation as targeted tools for innovation (new designs, prototypes, moisture-critical assemblies) and for advanced control development—not as a mandatory step for every project. Once component behaviour is characterised, deployment should rely on re-usable, standardised product knowledge. Control strategies should follow a pragmatic ladder: robust rule-based approaches for reliable comfort operation; forecast-driven operation where price signals, renewables, or grid services are relevant; and simplified optimisation methods where sophisticated operation is justified. Secure, interoperable, privacy-compliant digital interfaces are treated as prerequisites for any grid-interactive operation.

Across all technical areas, the most critical barriers are non-technical. The underutilisation of building-integrated storage is primarily driven by missing or fragmented frameworks that translate flexibility into clear roles, responsibilities, and value streams. Without time-resolved incentives, accessible participation routes for small assets, workable aggregation models, and clear data governance, the majority of TABS installations will continue to be operated conventionally, leaving flexibility potential untapped. Comfort is the hard boundary condition and must be protected through transparent safeguards and standards-based verification to maintain user trust and long-term participation.

To accelerate rollout, Task 43 recommends closing three gaps in parallel: (1) scale industrialised construction and refurbishment pathways through productisation, prefabrication, and validated design inputs; (2) make storage-aware operation practical through staged control concepts, simplified state-of-charge estimation, and secure digital integration; and (3) align regulation, incentives, metering, aggregation access, and privacy rules so flexibility becomes a routine, rewarded operating mode rather than an optional feature.

EXECUTIVE SUMMARY

1 Short Description of Task 43

1.1 Objectives and Scope

The main goal of this Task on "Storage for renewables and flexibility through standardized use of building mass" was to prepare the storage technology for widespread integration on an international level, harnessing the benefits of this storage on local, quarter and city level respectively. The Task provided answers to four main research areas vital for market uptake and future standardization, see Figure 1.

Figure 1: The four main research areas that are relevant for the usage of TABS as flexible energy storage. These include construction, control, business models and trust in the technology. Source: AEE INTEC

There are existing implementations and activities in international markets, however standardized fabrication and construction methods as well as cost predictions and flexibility related business models were missing and hampering market uptake. The Task generated necessary answers to those key barriers through the collaboration of many international experts working on the topic. The generated results are available for the public and relevant stakeholders via this report. The Task addressed relevant technical and non-technical open questions in key areas, which are vital to the widespread deployment of the technology. This included, in particular the following areas:

- How can thermal activated buildings mass be structurally integrated in buildings, both new construction and refurbishment?
- What design possibilities are available from a shape perspective (horizontal, vertical, floors, ceilings, walls) and material perspective (concrete, wood, clay)?
- How can energy flexibility be paired with user flexibility (multi-purpose buildings, rep-purposed buildings) and thermal comfort?
- How do future control systems need to be designed to ensure this user comfort at a local level and to enable flexibility services on a grid level simultaneously?
- How can thermally activated building mass synergistically interact with other storage types on local, quarter and city level and how can it be used efficiently for sector coupling?
- What business models are possible in the framework of sector coupling and demand side management and what incentives should be proposed for end users and system owners?
- What regulatory and legal frameworks hinder/enable thermal activated building mass and flexibility trading in different regions?
- How can storage and flexibility potential be assessed and quantified?
- What kinds of standards need to be implemented for thermal activated building mass for market uptake?

The ongoing transformation of the energy system—already driven by the widespread deployment of renewables such as PV and wind—creates a growing need to enhance system resilience, flexibility, and stability, thereby increasing the relevance of solutions such as thermal building mass storage. Storage will be required at massive scale and based on different technologies that need to complement each other within integrated and flexible energy systems and grids. Thus, the general scope of this Task was to work on the standardization and market readiness of thermal activated building mass as one crucial component of the future storage technology portfolio. The scope of this work was deliberately limited to buildings that employ directly activated building mass, meaning systems in which pipes or comparable heat transfer media are physically integrated into structural elements such as slabs, walls, or ceilings to enable active thermal exchange. This focus ensures a clear emphasis on technologies that explicitly utilise the thermal storage capacity of the building structure through controlled charging and discharging processes.

In contrast, the indirect use of building mass—such as in buildings heated or cooled via conventional systems like radiators or air-based distribution—was not considered within the boundaries of this project. While such systems may incidentally interact with the thermal mass of the building, they do not represent controlled or designed activation of structural elements and therefore fall outside the defined scope. These approaches, along with their respective performance characteristics and potential contributions, have already been examined in other IEA activities and are not revisited here.

1.2 Organisational Structure

Task 43 was organized in 4 interlinked subtasks, which correspond to the four main research areas presented previously. The three scientifically oriented Subtasks A, B and C worked on specific topics and are aimed at the collection and extension of existing knowledge in their respective areas as well as at generating new results in their fields, profiting from ongoing research projects of the Subtask participants. They provided their findings as a basis for generalization and market interaction carried out in the dedicated Subtask D, which was working on the pathway to standardization and KPIs for thermal activated building mass assessment. These KPIs formed the boundary conditions for the scientific evaluation in Subtask A, B and C, resulting in a bidirectional exchange between these two areas of the Task. Additionally, Subtask D collected the demo factsheets – an endeavor to collect the best practice examples of the technology that are already implemented today and to make them accessible and comparable in a uniform format (see Figure 2).

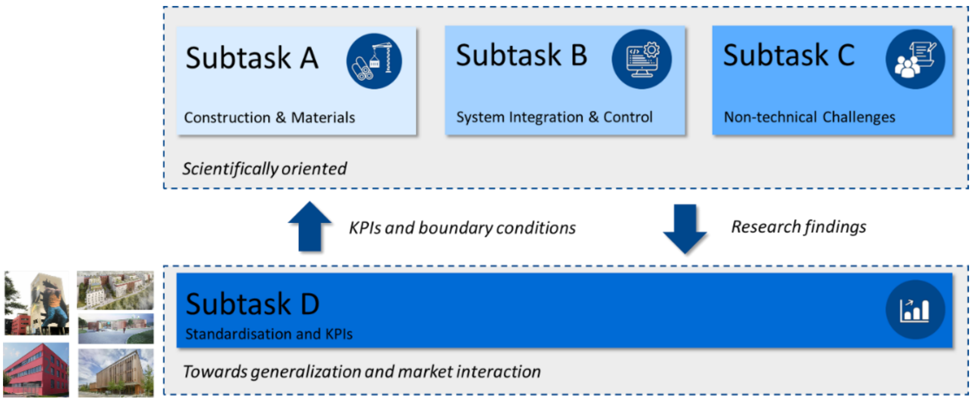


Figure 2: Overview of the 4 Subtasks of Task 43, including their relation to each other and how information flows between them. Source: AEE INTEC

1.3 Duration of Task

IEA ES Task 43 officially started on the 1st of January 2023 and concluded after three years on the 31st of December 2025.

1.4 Experts Meetings

Table 1 gives an overview of the expert meetings in this Task. 6 expert meetings have been conducted as hybrid events throughout Task 43.

Table 1: Details about the date and location of each expert meeting.

City	Country	Date	# of participants
Vienna/Hybrid	Austria	20th–21st March 2023	9 onsite / 26 online (35 total)
Copenhagen/Hybrid	Denmark	2nd – 3rd October 2023	12 onsite / 16 online (28 total)
Graz/Hybrid	Austria	8th – 9th April 2024	18 onsite / 10 online (28 total)
Dresden/Hybrid	Germany	21st – 22nd October 2024	19 onsite / 13 online (32 total)
Bilbao/Hybrid	Spain	08th – 09th May 2025	14 onsite / 15 online (29 total)
Rotterdam/Hybrid	Netherlands	10th November 2025	9 onsite / 16 online (25 total)

1.5 Participation

11 countries have declared their interest in participating in the Task at 94th ExCo meeting in November 2022 in Nagoya Japan/Hybrid. However, over the course of the Task 43 execution phase, participation of different partners varied between individual expert meetings, with new partners joining and others dropping out of the Task. To give a proper overview of the institutions and countries involved, 11 countries have declared their interest in participating in the Task at 94th ExCo meeting in November 2022 in Nagoya Japan/Hybrid. However, over the course of the Task 43 execution phase, participation of different partners varied between individual expert meetings, with new partners joining and others dropping out of the Task. To give a proper overview of the institutions and countries involved, **Table** 4 depicts all participants **that** attended one or more expert meetings from countries that are members of the IEA ES TCP or from institutions that joined via a limited sponsorship. Partners that attended regularly and were also actively contributing to the work in between the expert meetings are highlighted in bold. In general, the core of the active Task 43 community consisted mostly of partners from Austria, Belgium, Denmark, Germany and Spain.

Table 4 depicts all participants that attended one or more expert meetings from countries that are members of the IEA ES TCP or from institutions that joined via a limited sponsorship. Partners that attended regularly and were also actively contributing to the work in between the expert meetings are highlighted in bold. In general, the core of the active Task 43 community consisted mostly of partners from Austria, Belgium, Denmark, Germany and Spain.

Table 2: List of Task 43 partners participating in least one expert meeting, sorted by country. Core contributors are listed in bold font.

Name	Country	Institution
Christoph Rohringer, Manuel Baumgartner, Walter Becke	**Austria**	**AEE INTEC**
Daniel Muschick	**Austria**	**BEST – Bioenergy and Sustainable Technologies GmbH**
Alina Stipsits, Paul Lampersberger	**Austria**	**e7 energy innovation & engineering**
Daniel Heidenthaler, Markus Leeb, Michael Moltinger	**Austria**	**Salzburg University of Applied Sciences**
Sebastian Spaun	**Austria**	**VÖZ**
Attia Shady, Hammouma Thanina	**Belgium**	**University of Liège**
Gallardo, Andres	Canada	National Research Council Canada
Alireza Afshari, Mahmood Khatibi	**Denmark**	**Aalborg University**
Bo Nørregaard Jørgensen, Zheng Grace Ma	**Denmark**	**University of Southern Denmark**
Thomas Gröschke	Germany	Bau Projekt Dresden GmbH
Michael Barton	Germany	CENERGIE
Maximilian Fürst	Germany	Clina Heiz- und Kühlelemente GmbH
Matthias Kersken	**Germany**	**Fraunhofer Institute for Building Physics IBP**
Jonina Felbinger	Germany	German Aerospace Center, Institute of Engineering Thermodynamics
Pius Jung	Germany	Hochschule Biberach, IGE
Christian Schweigler, Niklas Fellner	Germany	Hochschule München
Udo Nagl	Germany	Hybridschalungsstein
Thomas Friedrich	**Germany**	**Innogration GmbH**
Hassan Mahach, Karsten Rauber	**Germany**	**IZES gGmbH**
Andreas Wagner, Petra Mann	Germany	Karlsruhe Institute of Technology
Eric Matthes	Germany	Nanolope
David Ritter, Benjamin Köhler	**Germany**	**Oeko-Institut**
Joris Burger	Germany	Sto SE & Co. KGaA
David Schmitt	Germany	Technische Hochschule Ingolstadt – Institute of new Energy Systems
Dr. Sebastian Fuchs , Florian Möbius	Germany	Tragwerk Ingenieure
Yang Xue, Joscha Reber, Nadja Bishara	**Germany**	**TU Darmstadt, Institute for structural mechanics and design**
Dirk Weiß, Katja Tribulowski, René Hoch, Dominik Schlüter, John Grunewald	**Germany**	**TU Dresden Institute of Building Climatology**
Maximilian Roedder, Ron Rieger	Germany	Vallaint
Rosie Christodoulaki	Greece	Centre for Renewable Energy Sources and Savings
Salvatore Vasta	Italy	National research council of Italy
Davide Fop	Italy	Politecnico di Torino
Carla Scordamaglia	Italy	RSE
Maurizio de Lucia	Italy	Università di Firenze
Ilaria Marotta	Italy	University of Palermo
Magnus Berg, Michaela Meir	Norway	Inaventasolar

Benjamin Manrique	Norway	Sintef
Fritz Zaversky	Spain	CENER
Antonio Villanueva, Jon Zubiaurre	Spain	IDOM CEA
Arregi Goikolea, Erik Maqueda Moro, Beñat Arregi	Spain	Tecnalia
Pablo Eguia	Spain	Universida de Vigo
Emiliano Borri, Gabriel Zsembinszki, Luisa F. Cabeza	Spain	University of Lleida
Aitor Erkoreka, Catalina Giraldo, Pablo Hernandez-Cruz	**Spain**	**University of the Basque Country**
Manuel Andrés Chicote	**Spain**	**University of Valladolid**
Pei Huang, Xaoli Zhang	Sweden	Dalarna University
Matthias Haase	Switzerland	Zürcher Hochschule für Angewandte Wissenschaften
Seamus Garvey	UK	University of Nottingham

1.6 Impact & Dissemination

Throughout its three-year runtime, IEA ES TCP Task 43 actively exchanged with adjacent international networks and stakeholder communities to (i) avoid duplication, (ii) align terminology and evaluation approaches, and (iii) accelerate uptake of thermally activated building systems TABS as building-scale, multi-energy-carrier storage interacting with electricity and thermal networks.

A central collaboration was established with the IEA EBC TCP, in particular EBC Annex 82 and EBC Annex 84. Both annex operating agents were already involved during the Task definition phase and received regular updates on Task 43 scope and progress. Dedicated online meetings were used to identify synergies, clarify overlap, and implement concrete scope adjustments, with the intent of maintaining continuous exchange of methods and results.

This cooperation also materialised in joint events. The 3rd Task 43 meeting (Graz, Austria; hybrid; 8–9 April 2024) included invited contributions from international experts and a joint on-site workshop with the EBC Annex 84 community, enabling direct cross-fertilisation between TABS-focused work and broader demand-management research in thermal networks. In the same week, Task 43 contributed to the ISEC 2024 conference in Graz, including the workshop “Flexibility and Load Management for Energy Grids: The Hidden Potential of Buildings”, presented alongside EBC Annex 84, explicitly targeting scientifically trained audiences beyond the immediate TABS expert community.

Task 43 also targeted scientific conferences, peer-reviewed journals, industry workshops and webinars for capacity building and increase of its outreach capabilities. In total, Task 43 achieved 16 scientific conference contributions, 5 publications in non-scientific journals and 4 peer-reviewed paper submissions in the journals “Smart Energy”, “Springer Nature Energy Informatics” and “Energy and Buildings”. Stakeholder engagement activities included one international Webinar and 4 industry workshops. Attended conferences with dedicated Task 43 presentations include 9th SES in Kopenhagen, the ISEC 2024 in Graz, the Enerstock 2024 in Lyon, the 34th Symposium Solar Heat in Germany and many others. Task 43 also hosted an entire session at the energy informatics academy conference 2025 in Malaysia, including the ongoing management and review of a Springer Nature Special collection on “Thermal Storage and Flexibility in Buildings: Digitalization, Control and Market Integration of Activated building mass” in the Journal “Energy Informatics” by the Task 43 leadership (link to the collection: https://link.springer.com/collections/aecdaghddj). To further broaden the audience of its results Task 43 conducted the 35th ES TCP On-Seminar in close cooperation with the ES TCP secretariat, allowing high level speakers from the Task group to present their solutions and findings. Within Subtask C – Non-technical challenges, also a peer reviewed publication was prepared in a transnational effort by the Task 43 participants. Key results of Subtask C are based on this original work, the paper itself is currently under review and is expected to be published in Summer 2026 in a special collection of "Springer Nature Energy Informatics".

On the national and stakeholder side, Task 43 engaged with the German funding coordination ecosystem via Projektträger Jülich (PtJ) (including exchange with the "Thermischer Verbund" initiative and associated projects), and with industry and implementation actors such as the Austrian Association of Cement Industries (VÖZ). VÖZ contributed national lighthouse examples and pointed to existing TABS planning guidance ("Energiespeicher Beton: Thermische Bauteilaktivierung"). Also, Task 43 supported in preparing and conducting the two final workshops of the Austrian Monitoring study "BTTAB", reaching 75+ participants from Austrian ministry, industry and academia in total.

Finally, Task 43 connected to the international standardisation and evaluation community through the IEA's EGRD workshop on "Developments in demonstrations, tests and standardization" (21–22 Nov 2024, Denmark), and through engagement with European standardisation activities (e.g., CEN/CENELEC workshop activity around thermal energy storage system integration).

2 Summary of Subtasks

2.1 Subtask A

Led by: Prof. John Grunewald, TU Dresden, Germany

2.1.1 Fundamentals and principles

Subtask A showed that TABS are no longer a niche HVAC option but a construction-relevant technology that directly responds to two structural trends: rising summer comfort needs for cooling (increasingly also in residential buildings) and the need to integrate variable renewables through low-temperature heating/cooling combined with inherent thermal storage. The subtask's key message is that TABS are most valuable when they are treated as multifunctional building elements: the same components provide load-bearing function, large-area heat and cold exchange, and usable thermal storage without additional tank volume, while remaining compatible with heat pumps, solar thermal, and other renewable sources. The chapter underlines that "classic" TABS construction is well understood: pipe registers are embedded in structural elements (typically steel-reinforced concrete) during new construction, most commonly placed on site before casting, with water as the heat transfer medium. At the same time, the Subtask made clear that the defining constraint of TABS is not the ability to move heat, but the need to keep surface temperatures within comfort bounds—this places a practical limit on allowable charging temperatures and therefore on storage density that is actually exploitable in buildings. A further key message is that TABS are not limited to horizontal slabs. The chapter differentiates horizontal vs. vertical activation and highlights activated façades as a particularly relevant pathway for scaling into refurbishment, because exterior application avoids interventions inside occupied buildings and turns the envelope into an active heat exchanger and storage interface.

2.1.2 Materials and construction

A core outcome of Subtask A is that material choice is not a secondary architectural detail—it is one of the main determinants of storage capacity, achievable power transfer, controllability, moisture robustness, and environmental footprint. The report presents material selection as an optimisation problem rather than a binary choice: concrete offers high volumetric storage and good conductivity, while timber can reduce embodied emissions but may require higher flow temperatures and tends to deliver lower transmissible power unless hybridised (e.g., timber structure combined with concrete core elements). However, these characteristics cannot be evaluated in isolation. The optimal choice also depends on building type, structural requirements, and usage patterns; for instance, high-rise buildings impose structural constraints that often limit or exclude timber-based solutions. As a result, material decisions must be made case by case, balancing thermal performance, structural feasibility, and environmental considerations. The predominant material used for activation is still steel-reenforced concrete. To make informed selections from the feasible materials in each implementation, the chapter stresses the importance of validated material data and hygrothermal characterisation. Simulation tools used for advanced component design (e.g., DELPHIN) rely on material libraries and high-quality input parameters (thermal conductivity, heat capacity, sorption behaviour, vapour diffusion resistance, liquid transport coefficients). In practice, novel or hybrid TABS assemblies often require adding and validating new datasets—otherwise modelling reliability is compromised.

Importantly, Subtask A used the material discussion to reinforce the deployment narrative: TABS storage is not “one material = one technology”. Rather, there is a broad palette (concrete, bricks/stone, insulation boards, engineered timber, hybrids), and progress toward wider adoption depends on turning this palette into standardised, validated design inputs that industry can use with confidence.

2.1.3 Market available, innovative TABS energy storage system designs for new construction and refurbishment

A market-level takeaway from Subtask A is that the discussion has moved beyond proving the basic principle of thermal mass activation. What dominated the discussions were scaling questions: how to industrialise installation and quality, how to make the storage effect operationally useful (i.e., real time shifting and peak management in daily operation), and—closely linked to deployment volumes—how to translate TABS storage into refurbishment with minimal disruption and low-temperature compatibility. The first two areas of interest are well illustrated by the Innogration GmbH approach to productised, prefabricated ceiling activation (CEILTEC® and related sandwich cross-sections). On the industrialisation side, the logic is to shift complexity from site to factory: controlled production, integrated building-services components, and a “puzzle-like” assembly of panels reduce on-site manual work and enable repeatable quality. At the same time, the same design choices are used to make the storage effect operationally relevant: the near-surface pipe placement in a sandwich cross-section increases responsiveness and usable thermal output (reported values up to ~70 W/m² for cooling and ~50 W/m² for heating), while the charging/discharging behaviour explicitly supports time shifting—under a 12 h charge / 12 h utilisation pattern, only about ~35% of supplied energy is released during the supply period and the remainder is stored and released later. This is the key point: the building element behaves as a controllable storage device, not merely as a slow emitter.

The refurbishment market is addressed through activated façade concepts, because they enable a storage-active interface to be added from the outside and therefore avoid the most common adoption barrier in existing buildings: invasive interior work. CEPA stands out here as a deliberately deployment-oriented solution: it combines heating, cooling, insulation and storage in one façade-based system, uses external piping so occupants do not need to move out, and is described as independent of both façade design and energy source—meaning it can be retrofitted, combined with existing systems, and adapted to future supply technologies. The narrative is not just technical feasibility but roll-out practicality: an “energy façade” that turns existing masonry into a storage unit while supporting low-temperature operation and broad retrofit applicability.

Within the same refurbishment framing, the IBRI & HOB Slot system complements CEPA by providing a particularly quantified heat-pump conversion storyline for a real case. The planning objective is to reduce maximum flow temperature from 75°C to 40°C while keeping existing radiators (accepting a reduction to 25% radiator output), supported by façade-integrated activation and envelope renovation. In the illustrated building (built 1967, 1080 m² living space), the wall U-value improved from ~0.9 to ~0.20 W/m²K, heating demand dropped from 80 to 32 kWh/(m²BGFa), and peak heating power from 80 to 30 W/m²NF. At 40°C flow and −10°C outside temperature, expected heat flux is ~16 W/m² of activated façade area, corresponding to roughly one quarter of the post-renovation peak room heating.

2.1.4 Research level, innovative TABS energy storage system designs for new construction and refurbishment

Research in Subtask A revolved less around proving that TABS storage works and more about answering a set of recurring deployment questions—and using concrete demonstrators to quantify the trade-offs. One central research area was how TABS concepts can be transferred to new material combinations without losing performance and controllability. This is addressed by the Smart-Skin Salzburg façade prototype, which uses wood for structure and concrete for heat distribution/storage. On a 23.39 m² exterior wall it maintained comfortable indoor conditions during a cold spell with outdoor temperatures below −13.2°C, while monitoring revealed clear optimisation needs: the supply/return temperature difference was only 0.45 K, driven by an excessive mass flow (0.69 m/s), with a recommendation to reduce below 0.50 m/s to increase ΔT and improve controllability.

Other works focused more on how to make building-integrated storage more “active” for peak shifting and flexibility. PCM-enhanced wall modules showed the principle with hard numbers: at feed temperatures of 5°C, 10°C, and 15°C, a wall with 30% PCM by mass achieved 2–3°C lower surface temperatures and about 24% higher cooling power than a reference wall—while also demonstrating the key trade-off for operation: more PCM extended discharge but slowed response. Grid integration beyond the diurnal cycle, i.e., storage that can bridge multi-day renewable patterns was of research interest as well in this context. Wind Heating 2.0 targeted 1–2 weeks of autonomy and explicitly dealt with comfort limits by using insulated-core concepts, since required storage temperatures around 45°C were too high for direct emission. Reported charging is 260–450 W/m² in the first hour, storing 1.5–2.5 kWh/m² over 9 hours, with a 7.5-day demand prognosis to avoid overheating.

Finally, several projects treat the dominant barrier as scale-up in the existing stock: serial, low-disruption refurbishment. AktivDHKS (Aktiv Dämmheizkühlsystem, combined insulation, heating and cooling system) combined insulation with façade-based heating/cooling via capillary tube mats under a recyclable insulation layer, mounted mechanically (dowels, no adhesives) and installed from the outside, keeping occupants in place and enabling low-temperature heat pump operation; it also targeted durability benefits (reduced condensation, frost damage, mould risk). LEXU+ quantified the renovation impact in simulations for an unrenovated reference building (~200 kWh/m²a heating demand), showing ~80% annual heating-demand reduction and demonstrating on-site feasibility (façade installed in two weeks). fronTherm framed the same scaling question from an industrialisation angle, moving toward controlled testing (December 2025 in a climate chamber) and a building demonstration planned for fall 2026.

2.1.5 Strategies for zoning

Zoning is a structural lock-in decision for TABS because embedded pipe systems are extremely difficult to modify after construction. Small zones are attractive for comfort and flexibility but quickly increase hydraulic complexity, commissioning effort, pressure losses, and pumping energy. Industry responses already point to pragmatic solutions: prefabricated activated elements that define the smallest modular zone and can be hydraulically coupled (e.g., Innogration GmbH), and façade-oriented zoning for retrofit that aligns with billing units (e.g., CEPA), illustrating how zoning can be made both technically manageable and economically meaningful.

2.1.6 Conclusions of Subtask A

Subtask A established three deployment-relevant conclusions. First, the TABS storage principle is robust across construction typologies and is already embodied in market-available systems and “usable storage” is already productised rather than theoretical. Second, the technology is not limited to one material: multiple structural and envelope materials can host activation, but wider adoption depends on validated material datasets and consistent characterisation methods—otherwise both simulation credibility and risk management remain barriers. Third, the innovation pipeline is strong and increasingly oriented toward the real scaling bottleneck: refurbishment, serial installation, and improved controllability, with demonstrators already delivering measurable figures and clear optimisation targets.

2.2 Subtask B

Led by: Dr. Daniel Muschich, BEST – Bioenergy and Sustainable Technologies, Austria

2.2.1 Simulation Models and Tools

Subtask B framed modelling and simulation as an enabler for confident design decisions, not as a mandatory step for every routine TABS application. The main point is that detailed simulation becomes most valuable when new component designs, prototypes, unusual material combinations, or moisture-critical assemblies are developed and need to be characterised before market deployment or for sophisticated predictive control strategies like MPC that might be employed to optimally control complex TABS storage systems. Once a component's dynamic behaviour has been robustly described (experimentally and/or through modelling), the pathway to industry uptake is to re-use validated component knowledge rather than to re-run bespoke simulations for each individual project.

To structure the tool landscape, the chapter compiles feedback from a survey returned by eleven experts and consolidates tools by scale and use case, from component-level hygrothermal analysis to whole-building/HVAC validation and even neighbourhood or district studies. It explicitly notes that tools "specialised" for TABS are rare; instead, many workflows rely on general-purpose environments that can represent TABS with appropriate modelling choices. The chapter illustrates this spectrum with representative tools and their typical strengths. On the component side, hygrothermal tools such as WUFI (1D/2D, plus whole-building hygrothermal variants) are highlighted for transient heat and moisture transport, mould-risk assessment options, and extensive material databases—useful when condensation, moisture buffering, or envelope-integrated activation are in scope. Tools such as DELPHIN and HTFlux are presented as strong options for coupled heat–moisture transport and FEM-based component studies, including surface temperature assessment and condensation risk investigations, while Physibel supports 2D/3D FEM modelling relevant for thermal bridges and dynamic behaviour of pipes embedded in concrete. At building and system level, platforms such as Modelica (Buildings Library), TRNSYS, and IDA ICE are positioned as practical environments for evaluating HVAC interaction, co-simulation, and control concepts (including advanced control development), where the main need is to capture dominant time constants and system constraints rather than every geometric detail. The practical takeaway is a "fit-for-purpose" selection: component tools are used when internal heat and moisture transport, layer build-ups, pipe depth/spacing, thermal bridges, or condensation and mould risks need to be assessed; more abstract building/system tools are preferred when the aim is to validate comfort, demand, and control behaviour at system level.

2.2.2 System Concepts

Section 3.2 in the final report shifts the focus from "activated components" to system concepts, stressing that performance is determined by how TABS are embedded into (i) building design, (ii) comfort-oriented operation, and (iii) an energy supply strategy that leverages low-temperature sources and renewables. Subtask B's core message is that TABS create value when they are treated as both distribution system and thermal buffer, enabling steadier generation operation and deliberate charging/discharging aligned with external signals such as renewable availability or dynamic prices. This system perspective is extended beyond individual buildings to grid-relevant operation. Wind Heating 2.0 is used as an illustrative case for multi-day flexibility: the concept converted surplus wind electricity to heat and stored it in building-integrated thermal storage, allowing the system to remain "off grid" for many days up to 1–2 weeks. The developed storages show charging rates of 260–450 W/m² in the first hour, averaging 130–260 W/m² over 9 hours, with 1.5–2.5 kWh/m² stored during that period. To avoid overheating, a thermal demand prognosis was applied to anticipate demand over the upcoming 7.5 days based on forecasts and historical consumption.

2.2.3 Control Strategies

TABS controls decide whether systems remain "slow radiant heating/cooling" or become actively managed storage. The chapter therefore organises control approaches by ambition and information needs, ranging from robust rule-based operation to forecast-driven strategies that explicitly use thermal inertia instead of counteracting it. For robust operation in standard applications, ad-hoc strategies based on current measurements are positioned as attractive due to their simplicity and reliability, especially when TABS act as base-load systems and faster subsystems cover short-term peaks. Hybrid concepts are explicitly highlighted: slow-acting TABS stabilise temperatures, while ventilation or other HVAC systems handle transient loads; in parallel, active shading is emphasised as a necessary companion in modern, highly glazed buildings to prevent cooling demands that exceed TABS capabilities.

When the aim includes load shifting, renewable integration, or price responsiveness, the chapter places predictive control in the foreground. It describes a pragmatic modelling hierarchy (white-box, grey-box, black-box) and notes that RC-based grey-box models are most common for TABS because they capture dominant time constants with manageable effort. Model Predictive Control (MPC) is described as a prominent implementation, able to incorporate forecasts and constraints; it also highlights that MPC hinges on reliable state and parameter estimation, with methods such as Kalman filtering improving robustness under measurement noise and uncertainty.

For the highest level of sophistication—explicit "thermal battery" operation—it is pointed out that optimisation quickly becomes computationally challenging when discrete decisions (e.g., heat pump on/off) are coupled with continuous variables (temperatures and flows). Therefore, practical simplifications are discussed, including linearisation and MILP formulations, and reduced-order storage representations that keep real-time optimisation tractable while preserving operational feasibility.

2.2.4 Digital Interfaces and Privacy

Section 3.4 in the final report links advanced control and grid interaction to the digital layer and treats secure, reliable, privacy-compliant data exchange as a prerequisite for flexibility services. The chapter stresses that grid interaction combines critical infrastructure signals (e.g., dynamic tariffs, balancing calls) with sensitive building-side data (PV surplus, battery state, indoor temperature/humidity/CO_2), making cybersecurity and privacy central design requirements rather than add-ons.

It outlines practical requirements for integrity and resilience: encrypted channels (e.g., TLS/VPN), authentication and authorisation, integrity checks, monitoring for anomalies, and secure firmware updates, complemented by redundancy and fallback modes to maintain safe operation when signals are missing or delayed. Privacy safeguards are framed through data minimisation, aggregation/pseudonymisation, and local processing aligned with GDPR expectations. Finally, interoperability is positioned as both a cost and risk lever: widely used building protocols (BACnet, KNX, Modbus, OPC UA) and energy-sector standards (IEC 61850, IEC 62351) are referenced, with the recommendation that protocols lacking strong security features should be isolated through gateways; practical integration tooling such as Node-RED is noted as a bridging option for heterogeneous ecosystems.

2.2.5 Conclusions of Subtask B

Subtask B outlined how TABS can be designed and operated as controllable thermal storage. It mapped the modelling toolbox from component hygrothermal analysis to whole-building/HVAC validation, stressing that detailed simulation is mainly needed for new component designs or prototypes and can be replaced by standardised product characterisation for routine deployment. It linked system concepts and grid interaction (e.g., Wind Heating 2.0: 1–2 weeks off-grid, 260–450 W/m² initial charging, 1.5–2.5 kWh/m² over 9 h) to control options from robust ad-hoc rules to forecast-driven MPC with state estimation and tractable MILP formulations. Secure, reliable, privacy-compliant communication is regarded as a prerequisite for flexibility services.

2.3 Subtask C

Led by: Prof. Alireza Afshari, Aalborg University, Denmark

2.3.1 Regional boundary conditions

Subtask C showed that the rollout of thermal flexibility from heat pumps and thermally activated building systems (TABS) is limited less by technical readiness than by the surrounding institutional and market framework. Across six countries which were analyzed through more than 50 expert interviews (Austria, Belgium, Canada, Denmark, Germany, Spain), the decisive barrier is the absence of consistent rules that translate "flexible operation" into clear rights, responsibilities, and value streams for households, aggregators, and grid operators. A recurring issue is that building codes and Energy Performance Certificates often evaluate performance on an annual basis, which fails to reflect temporal dynamics and therefore does not reward controllability or the storage potential embedded in building structures. More than 85% of stakeholders in the study identified the lack of an explicit legal definition of flexibility as a central barrier, and data governance and privacy constraints repeatedly appear as practical blockers for automated operation.

The country comparison highlights how different combinations of metering coverage, tariff design, and aggregator access determine what is feasible in practice. Denmark is consistently portrayed as the most advanced European setting, because flexibility is recognised as a grid service, aggregators can trade aggregated household loads, and hourly variable tariffs are mandated for customers with smart meters, reaching more than 98% coverage. This creates a rare "full chain" of enabling conditions: households can see time-resolved price signals, digital infrastructure allows measurement and verification, and market actors can monetise aggregated response. At the same time, the Danish case also illustrates that even strong electricity-side frameworks may remain only partially connected to building regulation, leaving administrative and data-sharing gaps that still constrain scale-up.

Germany and Austria represent an intermediate group: flexibility is prominent in policy discourse and grid-driven instruments exist, but participation pathways for small assets remain complex and often weakly remunerated. In Germany, Section 14a of the Energy Industry Act (EnWG) enables curtailment of heat pumps under grid congestion; however, the scheme's administrative burden and unclear remuneration has led to very low uptake, with fewer than 2% of German residential heat pumps registered in 2024. Austria supports collective self-consumption via the Renewable Expansion Act (EAG 2021), but does not yet provide robust mechanisms for flexibility aggregation or thermal storage participation, leaving unresolved ambiguity around aggregator roles and responsibilities.

Belgium and Spain illustrate how partial policy progress can coexist with fragmented implementation. Both have transposed elements of the EU Clean Energy Package, but secondary rules on participation, verification, and compensation remain incomplete, limiting coherent procedures for flexible markets. Belgium's context is further shaped by regional governance (Flanders, Wallonia, Brussels) and heterogeneous building regulation frameworks. Expert input stressed that TABS is not explicitly recognised as an energy storage or flexibility asset in design guidance or subsidy schemes, and that low awareness among architects and contractors reinforces conservative technology choices even where TABS would be suitable. Smart-meter penetration is reported at around 55%, and emerging tariff and grid-charge reforms remain voluntary and only weakly linked to building-integrated flexibility technologies.

Spain, by contrast, combines strong renewable variability with limited flexibility-market maturity. Renewables (especially wind and solar) account for more than 50% of electricity production in recent years, and the country's climate diversity makes electrified heating and cooling relevant across regions. Yet time-of-use tariffs remain insufficiently synchronised with real-time renewable patterns, independent aggregators are still unregulated, and existing participation thresholds (e.g., 1 MW for certain balancing services) exclude most building-scale assets. The Spanish case also highlights "soft" barriers: limited coordination between architects and engineers and low awareness of TABS among professionals and the public.

Outside Europe, Subtask C highlights how boundary conditions can shift the dominant pathway for flexibility. Canada's cold climate (mainly ASHRAE zones 7 and 8) makes winter peak management particularly relevant, while an electricity mix dominated by hydropower (~60%) reduces short-term variability compared with high-wind/high-solar systems. Smart-meter coverage is already high (~80%) and expected to reach 94% by 2029, yet dynamic tariffs are limited to select provinces and heat pump penetration remains modest (~6% of residential buildings). The main finding is that the technical foundation exists, but regulatory alignment and consistent aggregator participation frameworks are still emerging.

The United States is presented as a high-potential but highly heterogeneous setting. Renewables provided about 21.4% of utility-scale generation in 2023 (wind ~10%, utility-scale solar ~3.9%), climate diversity shifts the dominant value case between winter and summer peaks, and market rules vary across ISOs/RTOs and vertically integrated regions. Digital readiness is comparatively strong at scale (about 119 million AMI installations in 2022, ~72% of all meters and ~73% of residential meters), and FERC Order 2222 provides a federal-level pathway for aggregations of distributed energy resources to access wholesale markets—yet practical implementation remains uneven and depends on local market design and distribution-utility coordination.

China is included as a contrasting model in which flexibility is achieved less through individual residential assets and more through territorial-scale thermal systems integrating district networks, waste heat, electrification and storage. The chapter positions this as a high-density system strategy that could be informative for countries with similar urban forms.

Across all regions, the technical potential of TABS and heat pumps is well understood, but only a small fraction is currently utilised because legislation, pricing signals, metering, data governance, and market participation routes are not yet aligned to dynamic operation.

2.3.2 Best practice examples and incentives

Subtask C framed incentives as the practical "make-or-break" element for turning technical flexibility into persistent real-world operation. Experts across the six-country sample converge on the same central message: households and market actors engage when rewards are clear, fair, and simple, and when comfort risks are managed. Monetary incentives are identified as the strongest driver, with more than 80% of experts emphasising that variable pricing is needed to trigger systematic change—yet fewer than 15% of households across the six countries are currently exposed to real-time or dynamic tariffs. Denmark stands out as the exception, combining mandatory hourly variable tariffs with very high smart-meter coverage.

The chapter uses best-practice cases to illustrate how flexibility value can appear in different "economic channels," and why TABS can be attractive even without direct flexibility-market revenues.

One channel is CAPEX reduction through passive use of thermal inertia, where the building's activated mass allows smaller generation equipment by smoothing peaks. An Austrian monitoring example highlights this logic with unusually tangible numbers: the Steiner Haustechnik building is reported with a total building heating load of 1.1 MW, while the installed heating system comprises three two-stage brine/water heat pumps (45/90 kW each), i.e., 270 kW installed capacity. The message is not that peak load disappears, but that thermal mass and appropriate system design can shift sizing logic toward steady operation and buffering.

A second channel is OPEX savings through active load shifting enabled by predictive control combined with variable tariffs and PV availability. Here, the chapter's key point is that TABS' slow dynamics are not a limitation but an asset: preheating or precooling during lower-price hours and reducing operation during expensive hours can preserve comfort while lowering electricity bills and increasing PV self-consumption. The best-practice narrative stresses that control and market design must match; without time-resolved price signals and low-friction participation, much of the flexibility value remains invisible to end users.

A third channel is life-cycle economics, where TABS benefits accumulate through improved heat pump efficiency (low supply/return temperatures), free cooling opportunities (e.g., via ground sources), and reduced maintenance requirements. The chapter cites LCC evidence that TABS can be cheaper over lifetime than conventional systems, including an empirical comparison reporting up to 31% lower "global cost" over 15 years versus fan-coil systems. It also reports literature-based annual energy savings of about 15–40% versus convective systems when TABS are combined with variable electricity tariffs and free cooling. This reframes incentives from short-term payback to total cost of ownership, which is often more compatible with public and institutional building decision-making.

The chapter also includes examples that shift the perspective from single buildings to aggregated system value. A Danish best-practice case quantifies national-scale storage capacity of the building stock by combining building archetypes with registry data and interpreting flexibility as controlled setpoint modulation (e.g., ±2°C over different durations). The core message is that aggregated building thermal mass can become comparable, in magnitude terms, to other large flexibility assets, strengthening the policy rationale for dynamic pricing and smart controls as a national infrastructure strategy rather than a niche building feature.

Germany's "Wind Heating 2.0" is used to illustrate a value case relevant in systems with frequent wind oversupply and low or negative electricity prices: convert surplus electricity into heat and store it long-term, including in thermo-active building systems with room-side insulation, to bridge periods of high grid utilisation. The example emphasises that predictive operation is essential for long-duration use, with demand forecasting up to 7.5 days and targeted coverage periods described as one to two weeks; reported excess electricity demand coverage of 85% and above underscores that flexibility becomes most powerful when it is engineered as an energy system function, not merely a comfort feature.

To support implementation planning, the chapter provides a pragmatic "potential logic": flexibility is primarily influenced by insulation/envelope performance, thermal mass distribution, and heating system type, with TABS and underfloor systems enabling stronger activation of thermal inertia than conventional convective emitters. It then translates this into actionable recommendations that depend on local boundary conditions: where time-of-use pricing is static, strengthen time-resolved signals; where enrolment and verification are complex, simplify baselines and prequalification; where data exchange is fragmented, define a minimum dataset and interoperability requirements; and where awareness is low, prioritise pilots with standardised measurement and public reporting.

2.3.3 Guidelines for indoor comfort

Indoor comfort is a non-negotiable constraint for flexibility activation: if demand shifting undermines perceived comfort or trust, participation collapses regardless of technical potential. The chapter therefore focuses on making comfort measurable and verifiable under dynamic operation, anchoring the approach in established standards and in a minimal but robust sensing concept.

The key statement is that comfort verification in buildings with strong radiant components should not rely on air temperature alone. Instead, operative temperature and radiant effects must be captured in a way that remains representative during flexibility events, when transient gradients can occur. The text links this to EN 16798 comfort verification and ISO 7726 measurement practice and derives practical guidance on sensor placement: representative occupied-zone heights (0.6–1.1 m for seated activities and 1.1–1.7 m for standing) and avoidance of local bias from windows, doors, ventilation terminals, direct solar radiation, or hot spots.

A minimal equipment package is proposed to balance robustness and practicality: a standard black globe thermometer compliant with ISO 7726, a calibrated air temperature and relative humidity sensor, and optional fast-response elements (e.g., thermocouple-based globes or radiant arrays) where dynamic response is needed. For TABS specifically, the guidance recommends combining globe temperature with slab temperature sensors to interpret the dynamic radiant contribution during charging and discharging phases. The overall aim is to ensure that comfort remains within EN 16798 acceptable ranges while generating trustworthy data for control tuning and post-event verification.

2.3.4 Additional non-technical effects on TABS deployment

Beyond regulation and incentives, Subtask C highlighted three broader attributes that shape whether TABS is perceived as a “future-proof” technology: adaptability, circularity, and acceptability. The unifying message is that these attributes can strengthen the long-term case for TABS, but only if they are actively communicated and translated into decision-relevant criteria for owners, planners, and occupants.

Adaptability is framed as an intrinsic strength of large thermal mass systems: buildings can buffer temperature swings and shift heating or cooling loads to periods when energy is cheaper or cleaner, reducing dependence on peak electricity. This adaptability is amplified when combined with predictive and demand-responsive control, where operation anticipates external conditions rather than reacting late to indoor air temperature changes. In this framing, adaptability is not only a comfort feature; it becomes a resilience feature under climate change and under increasingly variable energy systems.

Circularity is presented as a structural advantage because TABS integrates hydronic pipes into long-lived slabs, enabling one component to deliver both load-bearing and thermal-conditioning functions with minimal replacement cycles. This aligns with circular construction strategies that prioritise long service life and high material utility. The chapter emphasises that, over decades, the embedded system can retain performance with limited intervention, while only peripheral equipment (pumps, manifolds, control units) typically requires updating—reducing waste compared with traditional HVAC replacement cycles.

Acceptability is discussed as a multi-actor perception issue: occupants value uniform, low-noise comfort, owners value longevity and low maintenance, and policy actors value compatibility with low-temperature heating and high-temperature cooling that supports renewable integration. At the same time, slow response can challenge user expectations for “instant” temperature changes, so clear communication and user-friendly interfaces become important for trust and satisfaction. The chapter links this to established comfort standards (e.g., ISO 7730 PMV–PPD framing) and to the broader point that successful flexibility programmes must remain transparent, protect comfort, and provide credible economic value to achieve sustained uptake.

2.3.5 Conclusions of Subtask C

Subtask C showed that the main barriers to using TABS as a flexibility resource are institutional, not technical. Across regions, progress depends on clear legal definitions, workable aggregator participation, time-resolved tariffs, high metering coverage, and data governance that enables automated yet privacy-safe operation. Incentives must make flexibility visible through CAPEX, OPEX and life-cycle value, supported by verified comfort under standards-based measurement. When these elements align—as illustrated by Danish market design, Austrian monitoring evidence and system-scale concepts such as Wind Heating 2.0—TABS can deliver reliable flexibility without eroding comfort or trust.

2.4 Subtask D

Led by: DI Joscha Reber, TU Darmstadt, Germany & DI Christoph Rohringer, AEE INTEC, Austria

2.4.1 Overview of most relevant KDIs/KPIs for TABS

Subtask D showed that scaling and benchmarking TABS requires a shared indicator logic that distinguishes what is built from how it performs. It therefore separated Key Design Indicators (KDIs)—the physical and geometric characteristics that define the intrinsic storage and transfer potential—from Key Performance Indicators (KPIs)—the dynamic outcomes observed in operation or simulation (e.g., load shifting, modulation, delay). KDIs are organised along material properties (e.g., density, thermal conductivity, specific heat capacity), cross-sectional choices (e.g., pipe spacing and concrete cover), and system-integration parameters (e.g., design supply temperature and mass flow), with the explicit reminder that operational flexibility is bounded by these design constraints.

At the same time, the chapter highlights that the KPI landscape is broad and often difficult to apply in practice; usefulness depends on transparency, measurability, and alignment with the intended operational target. Comfort is treated as a governing boundary condition, because admissible temperature bands directly limit usable storage density and thus the flexibility that can be offered.

2.4.2 Deep dive thermal storage capacity

This section turns thermal mass as storage into a quantifiable concept and, importantly, begins to derive simplifications that reduce effort for planners and operators. The key point is that storage capacity depends not only on material properties, but also on (i) the effective activated mass (which may be smaller than the geometric slab due to insulation and construction layering) and (ii) the comfort-driven temperature band, which changes over seasons and usage patterns and therefore makes the state of charge (SoC) inherently time-dependent.

A central contribution is showing where simplified estimation is sufficiently accurate. For SoC calculations, the report concludes that using bulk-material properties can be an acceptable approximation for real implementations. Workable approximations are possible: for prototypical slabs, using only the bulk material properties (e.g., concrete) to estimate volumetric heat capacity yields an acceptable error (~1.3% under the evaluated assumptions). Even when "non-bulk" fractions (steel, pipe material, heat transfer medium) are inflated beyond typical practice, the error in volumetric heat capacity remains below ~6%, while the scenario with four-times non-bulk fraction is explicitly described as unrealistic.

The section also treats measurement reality as part of the method. Since extensive sensor networks are rarely feasible, it explores which limited sensor signals can best approximate average slab temperature and SoC. Based on a simulation study, the surface temperature sensor, if properly protected from direct solar radiation, can act as a good approximation of the average slab temperature while at the same time providing a crucial measurement for determining the current indoor climate comfort.

2.4.3 Deep dive flexibility potential

Task 43 defined flexibility as the ability of TABS to shift, modulate, or delay heating and cooling demand in response to external signals (prices, renewables, grid constraints) without violating comfort. The challenge for this operations is not a lack of metrics, but their abundance, and selecting suitable KPIs requires clarity on the business case and the time scale of interest.

To make this actionable, the chapter contrasts baseline-free and baseline-required KPI families. Baseline-free metrics (e.g., the Flexibility Factor, typically ranging from -1 to 1) can be computed from a single operational dataset, while baseline-required metrics (e.g., the Flexibility Index) depend on a reference operation without demand-response actions.

The chapter then demonstrates how KPI choice affects design evaluation using a validated single-family-house model: multiple TABS design parameters (pipe spacing, number of parallel loops, installation depth) were simulated over one year and assessed with 21 KPIs. A key outcome is that event-based metrics (e.g., “Storage Capacity” computed per event) become statistically noisy across a year and may fail to show significant differences between design variants, whereas annual aggregated KPIs more consistently differentiate designs. It also highlights redundancy: some KPIs behave similarly under comparison (e.g., Outlay Shifting Ability showing a similar pattern to the Flexibility Factor), adding little extra information for design discrimination.

2.4.4 Suggested procedure and simplification for planning and operation of energy flexible TABS

This section translates Task 43’s scientific findings into industry-ready guidance, acknowledging that many scientific tools are perceived as too complex for routine practice. The core statement is that successful flexible TABS require early, iterative alignment across building design, hydraulics, control, HVAC equipment, and increasingly grid interaction, and that return on investment limits how much complexity is justified.

Three simplification lines are emphasised. First, simplified SoC estimation can be implemented with feasible instrumentation: SoC can be derived from temperature measurements plus known material and hydraulic parameters, reducing the need for complex simulation environments during operation and supporting both feasibility checks in design and “how much capacity is available now” assessments in use. Second, the intended use case must be explicit, because TABS storage is a system interaction of charging technology, the activated mass, and discharge pathways (often passive). Their sizing sets time constants and usable capacity that control alone cannot fundamentally change. The report illustrates this with two contrasting examples: undersized charging equipment limits grid-responsive operation but can still enable major CAPEX benefits (one Austrian example reports 75% downsizing of installed heat-pump capacity without comfort loss), while purpose-limited designs can be cost-optimal e.g., sizing only to bridge night hours without PV in the AktivDHKS context(Aktiv Dämmheizkühlsystem, combined insulation, heating and cooling system). Third, KPI and control selection should match stakeholder needs and data availability, avoiding unnecessary indicator sets and overly sophisticated control where monitoring and value streams do not justify it.

2.4.5 Conclusions of Subtask D

Subtask D separated KDIs (design constraints) from KPIs (operational outcomes) and showed how thermal storage capacity and SoC can be estimated with simplified inputs and feasible sensing by using bulk-material properties with small error margins. For flexibility assessment, it demonstrates that KPI choice matters: event-based indicators can be noisy over a year, while aggregated annual KPIs better distinguish design variants, with some metrics proving redundant. It concludes with a pragmatic workflow for planning and operation that prioritises clear use-case definition and simplified SoC methods. Reference implementations from real construction are included in the appendix as lighthouse projects, highlighting versatility but also showcasing the fact that flexible operation is still rarely applied in practice.

3 Comprehensive Results and Recommendations for Deployment

In the area of materials and construction, the key takeaway is that thermally activated building systems (TABS) are ready to function as multifunctional building elements—structure, large-area heat exchange, and usable thermal storage in one—supporting low-temperature heating and growing cooling needs. Deployment is no longer limited by missing concepts: industrialised solutions already show how to scale. Prefabricated ceiling elements illustrate the shift from site complexity to factory quality, while quantified behaviour demonstrates real time energy shifting: near-surface pipe layouts can deliver up to ~70 W/m² (cooling) and ~50 W/m² (heating), and under a 12 h charge / 12 h utilisation pattern only ~35% of supplied energy is released during charging, with the remainder stored and released later. For the existing stock, externally applied activated façades are a decisive pathway because they avoid invasive interior work; "energy façade" concepts combine heating, cooling, insulation and storage and are designed to remain compatible with different future supply technologies. Quantified retrofit cases confirm heat-pump conversion potential in legacy buildings, for example by reducing maximum flow temperatures from 75°C to 40°C while keeping existing radiators, alongside envelope improvements (U-value ~0.9 to ~0.20 W/m²K) and major reductions in demand and peak power (80 to 32 kWh/(m²BGFa); 80 to 30 W/m²NF). The practical gap is therefore less about hardware than about repeatable planning (including early zoning decisions) and validated material characterisation—especially when moving beyond "standard concrete" assemblies.

In the area of system design, modelling and control, the message is pragmatic: advanced tools are an enabler for innovation, not a mandatory burden for every project. Detailed simulation matters most for new component designs, prototypes, unusual material combinations, moisture-critical assemblies, and for sophisticated predictive control; once behaviour is characterised, validated product knowledge should be re-used rather than re-simulated case by case. At system level, TABS create the most value when treated as both distribution system and thermal buffer, enabling steady generation and deliberate charging/discharging aligned with renewable availability or dynamic tariffs. This extends beyond daily shifting: multi-day concepts show how surplus wind electricity can be converted to heat and stored to bridge periods of 1–2 weeks, with reported charging rates of 260–450 W/m² in the first hour and 1.5–2.5 kWh/m² stored over 9 hours, supported by demand prognosis to avoid overheating. For real-world rollout, the recommendation is staged: robust measurement-based control for standard operation; forecast-driven strategies and MPC where price responsiveness or grid services are targeted; and secure, interoperable digital interfaces so that flexibility can be automated without compromising privacy or safety.

In the area of policy, markets, and user acceptance, the dominant message is that the largest obstacles are non-technical. Expert evidence across multiple countries shows that the main limitation is not equipment readiness, but missing or fragmented frameworks that translate "flexible operation" into clear rights, responsibilities, and value streams for households, aggregators, and grid operators. More than 85% of stakeholders identify the absence of a clear legal definition of flexibility as a central barrier, while data governance and privacy constraints often block automated operation. Where the full enabling chain exists—high smart-meter coverage, time-resolved tariffs, and functioning aggregation pathways—flexible operation becomes implementable at scale; where it does not, even mature technologies remain operated conventionally. Incentives also need to be visible and simple: variable pricing is widely seen as essential, yet household exposure to dynamic tariffs remains low in many contexts. Comfort is the hard boundary condition, so standards-based measurement and transparent verification are required to build trust; minimal sensing packages and good sensor placement matter as much as control algorithms for sustained participation.

In the area of performance metrics and deployment workflows, the priority is to make storage and flexibility measurable in a way that industry can apply routinely. A shared indicator logic separates design constraints (materials, geometry, hydraulic integration) from operational outcomes (how much can be shifted, modulated, or delayed). Importantly, the work shows that simplified estimation can be accurate enough for practice: using bulk material properties to estimate volumetric heat capacity can yield very small errors (~1.3% under assessed assumptions), supporting simplified state-of-charge approaches rather than high-effort modelling in everyday operation. The deployment recommendation is therefore a lean KPI set matched to the intended use case, combined with feasible sensing and simplified state-of-charge estimation, so that flexibility becomes verifiable, bankable, and operable without turning every building into a research project. Executable recommendations for such simplifications of KPIs and workflows are provided in the Task 43 report.

Overall, broad use of TABS as thermal energy storage depends on closing three gaps:

Scale industrialised construction and retrofit pathways

Task 43's recommendation is to shift from one-off engineering to productised, repeatable construction solutions and to prioritise refurbishment-ready concepts. In practice that means: (i) accelerate prefabrication and modularisation (factory-defined quality, reduced on-site effort) and treat activated elements as standard building products; (ii) use external, low-disruption retrofit routes—especially activated façades—as the main scaling lever for the existing stock; and (iii) reduce perceived risk by consolidating validated material datasets and characterisation methods so planners can rely on standard design inputs even for non-concrete or hybrid assemblies. The "lighthouse" implementations in the appendix support this roll-out logic: mature solutions exist and should be replicated rather than reinvented each time.

Make operation storage-aware with practical digital integration

Task 43's recommendation is to make storage operation implementable at low effort and to reserve complexity for cases where it creates value. Concretely: (i) do not frame simulation as a prerequisite for every project; instead, characterise components once (testing/modelling) and then re-use validated behaviour as a product property; (ii) deploy a staged control strategy—robust rule-based operation for standard comfort operation, and forecast-driven control (including MPC) where price signals or grid services are targeted; (iii) ensure that storage-aware operation is measurable through simple state-of-charge estimation based on feasible sensing (temperatures + known material/hydraulic parameters), rather than requiring high-end models in daily operation; and (iv) treat cybersecurity, interoperability, and privacy as design requirements so buildings can exchange the minimum necessary data reliably and safely.

Align regulation, incentives, and market access so flexibility becomes routine

Task 43's recommendation is to remove the "non-technical lock" by building the full enabling chain: (i) introduce clear legal definitions and roles (especially for aggregators) so rights, responsibilities, and liability are unambiguous; (ii) expand metering and time-resolved tariffs so building owners can see and benefit from temporal value (rather than only annual performance); (iii) lower participation barriers for small assets by simplifying verification/baselines and enabling aggregation at building scale; (iv) set data governance rules that allow automated operation while protecting privacy (data minimisation, local processing where possible); and (v) make comfort verification credible by anchoring flexibility programmes in standards-based comfort measurement and transparent safeguards—because sustained participation depends on trust.

FINAL REPORT

1 Objectives, Structure, and Approach of Task

1.1 Objectives

The main goal of this Task on "Storage for renewables and flexibility through standardized use of building mass" was to prepare the storage technology for widespread integration on an international level, harnessing the benefits of this storage on local, quarter and city level respectively. The Task provided answers to four main research areas vital for market uptake and future standardization, see Figure 3.

Figure 3: The four main research areas that are relevant for the usage of TABS as flexible energy storage. These include construction, control, business models and trust in the technology. Source: AEE INTEC

There are existing implementations and activities in international markets, however standardized fabrication and construction methods as well as cost predictions and flexibility related business models were missing and hampering market uptake. The Task generated necessary answers to those key barriers through the collaboration of many international experts working on the topic. The generated results are available for the public and relevant stakeholders via this report. The Task addressed relevant technical and non-technical open questions in key areas, which are vital to the widespread deployment of the technology. This included, in particular the following areas:

- How can thermal activated buildings mass be structurally integrated in buildings, both new construction and refurbishment?
- What design possibilities are available from a shape perspective (horizontal, vertical, floors, ceilings, walls) and material perspective (concrete, wood, clay)?
- How can energy flexibility be paired with user flexibility (multi-purpose buildings, rep-purposed buildings) and thermal comfort?
- How do future control systems need to be designed to ensure this user comfort at a local level and to enable flexibility services on a grid level simultaneously?
- How can thermally activated building mass synergistically interact with other storage types on local, quarter and city level and how can it be used efficiently for sector coupling?
- What business models are possible in the framework of sector coupling and demand side management and what incentives should be proposed for end users and system owners?
- What regulatory and legal frameworks hinder/enable thermal activated building mass and flexibility trading in different regions?
- How can storage and flexibility potential be assessed and quantified?
- What kinds of standards need to be implemented for thermal activated building mass for market uptake?

1.2 Scope

The ongoing transformation of the energy system—already driven by the widespread deployment of renewables such as PV and wind—creates a growing need to enhance system resilience, flexibility, and stability, thereby increasing the relevance of solutions such as thermal building mass storage. Storage will be required at massive scale and based on different technologies that need to complement each other within integrated and flexible energy systems and grids. Thus, the general scope of this Task was to work on the standardization and market readiness of thermal activated building mass as one crucial component of the future storage technology portfolio. The scope of this work was deliberately limited to buildings that employ directly activated building mass, meaning systems in which pipes or comparable heat transfer media are physically integrated into structural elements such as slabs, walls, or ceilings to enable active thermal exchange. This focus ensures a clear emphasis on technologies that explicitly utilise the thermal storage capacity of the building structure through controlled charging and discharging processes.

In contrast, the indirect use of building mass—such as in buildings heated or cooled via conventional systems like radiators or air-based distribution—was not considered within the boundaries of this project. While such systems may incidentally interact with the thermal mass of the building, they do not represent controlled or designed activation of structural elements and therefore fall outside the defined scope. These approaches, along with their respective performance characteristics and potential contributions, have already been examined in other IEA activities and are not revisited here.

1.3 Structure and Approach

Task 43 was organized in 4 interlinked subtasks, which correspond to the four main research areas presented previously. The three scientifically oriented Subtasks A, B and C worked on specific topics and are aimed at the collection and extension of existing knowledge in their respective areas as well as at generating new results in their fields, profiting from ongoing research projects of the Subtask participants. They provided their findings as a basis for generalization and market interaction carried out in the dedicated Subtask D, which was working on the pathway to standardization and KPIs for thermal activated building mass assessment. These KPIs formed the boundary conditions for the scientific evaluation in Subtask A, B and C, resulting in a bidirectional exchange between these two areas of the Task. Additionally, Subtask D collected the demo factsheets – an endeavor to collect the best practice examples of the technology that are already implemented today and to make them accessible and comparable in a uniform format (see Figure 4).

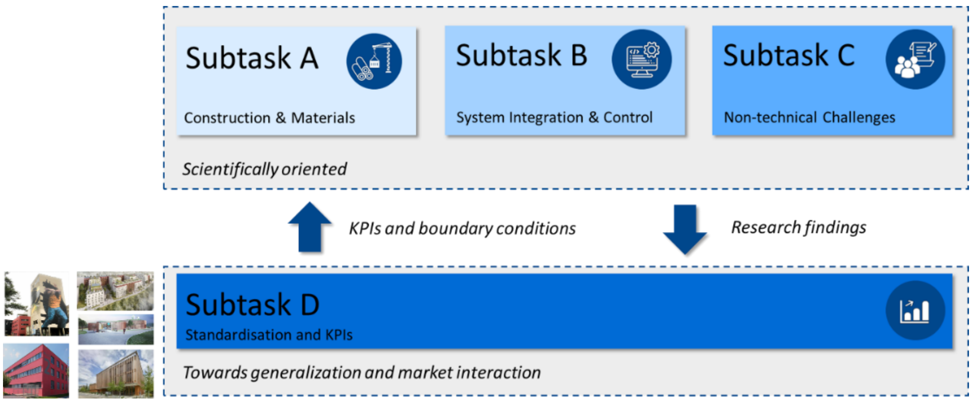


Figure 4: Overview of the 4 Subtasks of Task 43, including their relation to each other and how information flows between them. Source: AEE INTEC

Task 43 also defined 15 deliverables across its 4 Subtasks which were then compiled in this final report and partially organized under new headings to improve readability. The location of the results of those deliverables within the report is presented here as a guidance.

Subtask A

DA.1 Report on materials: The majority of the content is located in the corresponding chapter *2.2. Materials and Construction*. In addition, the benefits and drawbacks of unusual materials in prototypes (e.g. PCM) are discussed in the descriptions of the prototypes in section *2.4 Research level, innovative TABS energy storage system designs for new construction and refurbishment*.

DA.2 Report on construction and manufacturing strategies in new buildings: The authors decided to differentiate between industrial and research systems instead of new buildings and refurbishment. The motivation for this decision was, that several systems are suitable for application in both new and existing buildings. Therefore, the content of this deliverable is shared between chapter *2.3 Market available, innovative TABS energy storage system designs for new construction and refurbishment* and *2.4 Research level, innovative TABS energy storage system designs for new construction and refurbishment.*

DA.3 Report on construction and manufacturing strategies for refurbishment: The authors decided to differentiate between industrial and research systems instead of new buildings and refurbishment. The motivation for this decision was, that several systems are suitable for application in both new and existing buildings. Therefore, the content of this deliverable is shared between chapter *2.3 Market available, innovative TABS energy storage system designs for new construction and refurbishment* and *2.4 Research level, innovative TABS energy storage system designs for new construction and refurbishment.*

DA.4 Strategies for zoning and repurposing of buildings: Located in chapter *2.5 Strategies for zoning*.

Subtask B

DB.1 Model Factsheets: 15 model factsheets are submitted in Appendix 3. An overview and discussion of the different models is located in chapter *3.1 Simulation Models and Tools*.

DB.2 Report on System concepts: Located in chapter *3.2 System Concepts.*

DB.3 Report on control strategies: Located in chapter *3.3 Control Strategies*.

DB.4 Digital interfacing and privacy: Located in chapter 3.4 Digital Interfaces and Privacy.

Subtask C

DC.1 Report on regional boundary conditions: Located in chapter *4.1 Regional boundary conditions*.

DC.2 Collection of successful business models, end user incentives and best practices examples: Located in chapter 4*.2 Best practice examples and incentives*.

DC.3 Guidelines for indoor climate: Located in chapter *4.3 Guidelines for indoor comfort*.

Subtask D

DD.1 KPIs for TABs: Subtask D looked at TABS KPIs in general, but also decided to investigate two critical ones in detail, the thermal storage capacity and the flexibility potential. The general KPI topic is covered in chapter *5.1 Overview of most relevant KDIs/KPIs for TABS*, whereas the detailed discussion of the two stand-out KPIs is covered in the dedicated chapters *5.2 Deep dive thermal storage capacity* and *5.3 Deep dive flexibility potential*.

DD.2 Design guidelines for TAB construction: During the Task 43 duration, it became apparent that a lot of issues arise because TABS requires cooperation of crafts (architect, construction company, HVAC, control, energy supplier) the usually act rather independently. Therefore, Task 43 decided to present the guidelines for construction and automation and control in one coherent workflow instead of separate chapters. This work can be found in chapter *5.4 Suggested procedure and simplification for planning and operation of energy flexible TABS*.

DD.3 Design guidelines for automation and control: During the Task 43 duration, it became apparent that a lot of issues arise because TABS requires cooperation of crafts (architect, construction company, HVAC, control, energy supplier) the usually act rather independently. Therefore, we decided to present the guidelines for construction and automation and control in one coherent workflow instead of separate chapters. This work can be found in chapter *5.4 Suggested procedure and simplification for planning and operation of energy flexible TABS*.

DD.4 Demo factsheets: 25 demo factsheets are submitted in Appendix 3. An overview is presented in chapter *5.5 Real scale implementations as showcase for TABS versatility*.

1.4 Meetings and Participating Countries/TCPs

The official start of the Task was 01.01.2023. Table 3 gives an overview of the expert meetings in this Task. 6 expert meetings have been conducted as hybrid events throughout Task 43.

Table 3: Details about the date and location of each expert meeting.

City	Country	Date	# of participants
Vienna/Hybrid	Austria	20th–21st March 2023	9 onsite / 26 online (35 total)
Copenhagen/Hybrid	Denmark	2nd – 3rd October 2023	12 onsite / 16 online (28 total)
Graz/Hybrid	Austria	8th – 9th April 2024	18 onsite / 10 online (28 total)
Dresden/Hybrid	Germany	21st – 22nd October 2024	19 onsite / 13 online (32 total)
Bilbao/Hybrid	Spain	08th – 09th May 2025	14 onsite / 15 online (29 total)
Rotterdam/Hybrid	Netherlands	10th November 2025	9 onsite / 16 online (25 total)

11 countries have declared their interest in participating in the Task at 94th ExCo meeting in November 2022 in Nagoya Japan/Hybrid. However, over the course of the Task 43 execution phase, participation of different partners varied between individual expert meetings, with new partners joining and others dropping out of the Task. To give a proper overview of the institutions and countries involved, Table 4 depicts all participants that attended one or more expert meetings from countries that are members of the IEA ES TCP or from institutions that joined via a limited sponsorship. Partners that attended regularly and were also actively contributing to the work in between the expert meetings are highlighted in bold. In general, the core of the active Task 43 community consisted mostly of partners from Austria, Belgium, Denmark, Germany and Spain.

Table 4: List of Task 43 partners participating in least one expert meeting, sorted by country. Core contributors are listed in bold font.

Name	Country	Institution
Christoph Rohringer, Manuel Baumgartner, Walter Becke	**Austria**	**AEE INTEC**
Daniel Muschick	**Austria**	**BEST – Bioenergy and Sustainable Technologies GmbH**
Alina Stipsits, Paul Lampersberger	**Austria**	**e7 energy innovation & engineering**
Daniel Heidenthaler, Markus Leeb, Michael Moltinger	**Austria**	**Salzburg University of Applied Sciences**
Sebastian Spaun	**Austria**	**VÖZ**
Attia Shady, Hammouma Thanina	**Belgium**	**University of Liège**
Gallardo, Andres	Canada	National Research Council Canada
Alireza Afshari, Mahmood Khatibi	**Denmark**	**Aalborg University**
Bo Nørregaard Jørgensen, Zheng Grace Ma	**Denmark**	**University of Southern Denmark**
Thomas Gröschke	Germany	Bau Projekt Dresden GmbH
Michael Barton	Germany	CENERGIE
Maximilian Fürst	Germany	Clina Heiz- und Kühlelemente GmbH
Matthias Kersken	**Germany**	**Fraunhofer Institute for Building Physics IBP**
Jonina Felbinger	Germany	German Aerospace Center, Institute of Engineering Thermodynamics
Pius Jung	Germany	Hochschule Biberach, IGE
Christian Schweigler, Niklas Fellner	Germany	Hochschule München
Udo Nagl	Germany	Hybridschalungsstein
Thomas Friedrich	**Germany**	**Innogration GmbH**
Hassan Mahach, Karsten Rauber	**Germany**	**IZES gGmbH**
Andreas Wagner, Petra Mann	Germany	Karlsruhe Institute of Technology
Eric Matthes	Germany	Nanolope
David Ritter, Benjamin Köhler	**Germany**	**Oeko-Institut**
Joris Burger	Germany	Sto SE & Co. KGaA
David Schmitt	Germany	Technische Hochschule Ingolstadt – Institute of new Energy Systems
Dr. Sebastian Fuchs , Florian Möbius	Germany	Tragwerk Ingenieure
Yang Xue, Joscha Reber, Nadja Bishara	**Germany**	**TU Darmstadt, Institute for structural mechanics and design**
Dirk Weiß, Katja Tribulowski, René Hoch, Dominik Schlüter, John Grunewald	**Germany**	**TU Dresden Institute of Building Climatology**
Maximilian Roedder, Ron Rieger	Germany	Vallaint
Rosie Christodoulaki	Greece	Centre for Renewable Energy Sources and Savings
Salvatore Vasta	Italy	National research council of Italy
Davide Fop	Italy	Politecnico di Torino
Carla Scordamaglia	Italy	RSE
Maurizio de Lucia	Italy	Università di Firenze
Ilaria Marotta	Italy	University of Palermo
Magnus Berg, Michaela Meir	Norway	Inaventasolar

Benjamin Manrique	Norway	Sintef
Fritz Zaversky	Spain	CENER
Antonio Villanueva, Jon Zubiaurre	Spain	IDOM CEA
Arregi Goikolea, Erik Maqueda Moro, Beñat Arregi	Spain	Tecnalia
Pablo Eguia	Spain	Universida de Vigo
Emiliano Borri, Gabriel Zsembinszki, Luisa F. Cabeza	Spain	University of Lleida
Aitor Erkoreka, Catalina Giraldo, Pablo Hernandez-Cruz	**Spain**	**University of the Basque Country**
Manuel Andrés Chicote	**Spain**	**University of Valladolid**
Pei Huang, Xaoli Zhang	Sweden	Dalarna University
Matthias Haase	Switzerland	Zürcher Hochschule für Angewandte Wissenschaften
Seamus Garvey	UK	University of Nottingham

1.5 Impact & Dissemination

Throughout its three-year runtime, IEA ES TCP Task 43 actively exchanged with adjacent international networks and stakeholder communities to (i) avoid duplication, (ii) align terminology and evaluation approaches, and (iii) accelerate uptake of thermally activated building systems TABS as building-scale, multi-energy-carrier storage interacting with electricity and thermal networks.

A central collaboration was established with the IEA EBC TCP, in particular EBC Annex 82 and EBC Annex 84. Both annex operating agents were already involved during the Task definition phase and received regular updates on Task 43 scope and progress. Dedicated online meetings were used to identify synergies, clarify overlap, and implement concrete scope adjustments, with the intent of maintaining continuous exchange of methods and results.

This cooperation also materialised in joint events. The 3rd Task 43 meeting (Graz, Austria; hybrid; 8–9 April 2024) included invited contributions from international experts and a joint on-site workshop with the EBC Annex 84 community, enabling direct cross-fertilisation between TABS-focused work and broader demand-management research in thermal networks. In the same week, Task 43 contributed to the ISEC 2024 conference in Graz, including the workshop "Flexibility and Load Management for Energy Grids: The Hidden Potential of Buildings", presented alongside EBC Annex 84, explicitly targeting scientifically trained audiences beyond the immediate TABS expert community.

Task 43 also targeted scientific conferences, peer-reviewed journals, industry workshops and webinars for capacity building and increase of its outreach capabilities. In total, Task 43 achieved 16 scientific conference contributions, 5 publications in non-scientific journals and 4 peer-reviewed paper submissions in the journals "Smart Energy", "Springer Nature Energy Informatics" and "Energy and Buildings". Stakeholder engagement activities included one international Webinar and 4 industry workshops. Attended conferences with dedicated Task 43 presentations include 9th SES in Kopenhagen, the ISEC 2024 in Graz, the Enerstock 2024 in Lyon, the 34th Symposium Solar Heat in Germany and many others. Task 43 also hosted an entire session at the energy informatics academy conference 2025 in Malaysia, including the ongoing management and review of a Springer Nature Special collection on "Thermal Storage and Flexibility in Buildings: Digitalization, Control and Market Integration of Activated building mass" in the Journal "Energy Informatics" by the Task 43 leadership (link to the collection: https://link.springer.com/collections/aecdaghddj). To further broaden the audience of its results Task 43 conducted the 35th ES TCP On-Seminar in close cooperation with the ES TCP secretariat, allowing high level speakers from the Task group to present their solutions and findings. Within Subtask C – Non-technical challenges, also a peer reviewed publication was prepared in a transnational effort by the Task 43 participants. Key results of Subtask C are based on this original work, the paper itself is currently under review and is expected to be published in Summer 2026 in a special collection of "Springer Nature Energy Informatics".

On the national and stakeholder side, Task 43 engaged with the German funding coordination ecosystem via Projektträger Jülich (PtJ) (including exchange with the "Thermischer Verbund" initiative and associated projects), and with industry and implementation actors such as the Austrian Association of Cement Industries (VÖZ). VÖZ contributed national lighthouse examples and pointed to existing TABS planning guidance ("Energiespeicher Beton: Thermische Bauteilaktivierung"). Also, Task 43 supported in preparing and conducting the two final workshops of the Austrian Monitoring study "BTTAB", reaching 75+ participants from Austrian ministry, industry and academia in total.

Finally, Task 43 connected to the international standardisation and evaluation community through the IEA's EGRD workshop on "Developments in demonstrations, tests and standardization" (21–22 Nov 2024, Denmark), and through engagement with European standardisation activities (e.g., CEN/CENELEC workshop activity around thermal energy storage system integration).

2 Subtask A: Construction and materials

Led by: Prof. John Grunewald, TU Dresden, Germany

Subtask A deals with the investigation and improvement of construction techniques, implementation processes on site as well as material selection for thermal activated building mass storage. The scope of this work was deliberately limited to buildings and systems that employ directly activated building mass, meaning systems in which pipes or comparable heat transfer media are physically integrated into structural elements such as slabs, walls, or ceilings to enable active thermal exchange. This focus ensures a clear emphasis on technologies that explicitly utilise the thermal storage capacity of the building structure through controlled charging and discharging processes. The selection of materials, sizing of components and reduction of embedded carbon through alternatives to concrete are vital for the flexible deployment of the technology. New materials like micro-encapsulated PCM can for example increase energy density and improve charging and discharging temperature curves while wood offers an attractive option for both circular economy designs as well as low carbon builds. In order to allow for widespread deployment of thermal activated building mass, Subtask A will analyse and further develop construction and manufacturing techniques for both new construction and refurbishment, paving the way for the activation of the existing building stock. Since building are a long-term investment that often experiences changing owners and use cases, especially the flexible design of the thermal activated components is investigated to allow adjustable operation throughout the life cycle.

2.1 Fundamentals and principles

2.1.1 Climate change as a challenge for the construction industry

Thermally Activated Building Systems (TABS) represent a future-oriented concept for construction and planning that specifically addresses the challenges of climate change. Since it does not seem realistic that current global warming can be stopped or even significantly slowed in the foreseeable future, planners and all professionals working in the construction industry are forced to incorporate future outdoor climatic conditions into their concepts at an early stage. TABS, which perform both heating and cooling functions and can act as a flexible energy storage, are becoming increasingly important for future-oriented planning in this context.

The possibility of cooling has proven to be indispensable for year-round thermal comfort, not only to office or administrative buildings, but increasingly also to residential buildings. Given the increasing frequency of heat waves, it can be assumed that cooling residential buildings will no longer be considered an exception, but a necessary standard. The widely held belief that residential buildings do not need conditioning in summer months will therefore soon no longer be tenable. In this context, TABS can be classified as a key and forward-looking planning measure.

2.1.2 Basic functionality of TABS and classic construction techniques for new construction

The functional principle of TABS is based on the integration of heating and cooling registers into the building structure, either during construction or subsequently. The classic approach of installing TABS in new construction uses steel re-enforced concrete as structural component, resin pipes and water as heat transfer media. The pipes are layed into the concrete in-situ via manual labour on the construction site (compare Figure 5).

Figure 5: During component activation, a system of water-conduction pipelines is laid into concrete components via manual labour on site. Source: Innogration GmbH

Due to the large effective heat exchanger surface, these systems can be operated at very low flow or cooling medium temperatures, which are only slightly above or below the desired room temperature. This not only ensures high thermal comfort but also increases the system's energy efficiency. The heat storage capacity of TABS depends on the material properties of the components. High density, a high specific heat capacity, and good thermal conductivity ensure that the heat transported in the pipe registers can quickly penetrate the surrounding material, where it is available as a heat storage medium. The result is a significant smoothing of temperature fluctuations in the interior spaces. Large, moderately heated surfaces, as is the case with ceiling activation systems, ensure uniform and consistent surface temperatures across all room-enclosing surfaces, thus ensuring a particularly comfortable indoor climate.

Another advantage lies in the hygiene and health aspects. Since TABS does not use localised, highly heated radiators, there is no need for convective air exchange, which often stirs up dust and particles. Thermal comfort is ensured by the uniform radiant heat, which gives the rooms a healthy indoor climate and a high level of comfort.

In summary, the advantageous functionality and properties of TABS are:

- **Surface heating and cooling:** The large transfer surface enables low flow temperatures close to the room's target temperature.
- **Heat storage:** The storage capacity depends on material density, specific heat capacity, and thermal conductivity.
- **Energy efficiency:** Large surfaces enable cooling even at cooling medium temperatures of around 20°C.
- **Condensation resistance:** Temperatures above 19°C prevent condensation. This makes TABS a powerful, energy-saving cooling system for hot periods.
- **Thermal comfort:** Evenly heated surfaces, especially ceilings, reduce temperature fluctuations and ensure comfortable conditions.
- **Health aspects:** The low convective component prevents dust from being stirred up and improves the indoor climate.

- **Competitive investment costs:** Regular TABS already offers investment costs in the same range as floor heating and can compete with it in the open market. Industry feedback highlights that for e.g. Vienna, almost all funding tenders for new buildings include TABS due to its comparable cost and added value as cooling technology. However, to leverage the full potential of the storage capabilities of TABS, additional investment into sensors and control logic are required.

The cooling function, in turn, is particularly effective during hot periods, as the ceiling surfaces can absorb large amounts of heat without the surface temperature dropping significantly. However, optimal function requires adequate limitation of internal heat sources, particularly through effective solar shading measures. Without such a supplement, even powerful TABS can reach their limits.

2.1.3 Heat Transfer and radiation effects

Surface heating systems primarily work through thermal radiation, as surface temperatures remain low and convection plays a negligible role. A common misconception about ceiling heating is that "heat rises." However, this assumption overlooks the fact that at moderate surface temperatures, surface heating systems work almost exclusively through radiation. Radiant heat requires no transfer medium but spreads directly from warm to cooler surfaces. In a room, this leads to temperature equalisation between ceilings, floors, and walls, with the differences between the surfaces usually not exceeding one Kelvin. This effect also works in high rooms, as the radiation is barely attenuated by the air. Heat exchange works reliably evenly at high ceilings, as radiation is transferred with virtually no loss. The fear that the floor will remain cold with a heated ceiling is therefore unfounded.

In short, surface heating and cooling systems provide:

- **Radiation transfer:** Occurs directly between warm and cool surfaces, without a transfer medium.
- **Equalisation effect:** Favourable temperature equalisation of the room's enclosing surfaces.
- **Thermal comfort:** Temperature differences remain minimal at around 1 K.

Another key feature of TABS is its self-regulating behaviour. Since the differences between the surface temperature and the target temperature in the room are very small, the heating or cooling output automatically adapts to requirements. Complex control strategies, such as those required with conventional radiators, are eliminated. The flow temperatures of the heating medium in TABS are often only slightly above 30°C, even in cold weather, enabling particularly efficient use of heat pumps, solar thermal energy, or electricity from wind turbines and photovoltaic systems. This makes TABS a crucial link between building technology and the goals of the energy transition. Surplus renewable electricity can be temporarily stored in thermally activated concrete ceilings and released again with a time delay without compromising comfort in the rooms.

2.1.4 Use of renewable energies and energy storage

ABS not only enable highly efficient heating and cooling of individual buildings, but also open up new possibilities for urban energy systems and district-scale energy management. Due to the high thermal mass of concrete slabs, TABS inherently provide decentralized thermal energy storage, allowing buildings to temporarily store heat or cooling with minimal impact on occupant comfort. This storage capability creates flexibility between energy generation and demand and enables buildings to actively support the energy transition. While conventional district heating networks often operate at flow temperatures that are too high for direct TABS operation, integration remains possible through mixed controls and secondary circuits. As a result, TABS can become part of municipal energy infrastructure while simultaneously improving grid utilization, increasing renewable energy integration, and reducing peak loads.

TABS offers particularly favorable conditions for coupling thermal storage with renewable and flexible energy systems:

- **Heat pumps:** Highly efficient operation due to the low supply temperatures of TABS and the ability to shift heat pump operation to periods of favorable ambient conditions or low electricity prices.
- **Solar energy:** Utilization and temporary storage of short-term solar heat surpluses in the building mass without compromising thermal comfort.
- **Grid integration:** Conversion and storage of excess renewable electricity as thermal energy in concrete slabs, enabling load shifting and peak shaving.
- **Public utilities:** Integration with district heating and cooling networks through secondary circuits and mixed controls, allowing buildings to act as distributed thermal storage capacities within municipal energy systems.

The use of TABS as active thermal storage through deliberate preheating or “overcharging” of the building mass can, however, increase transmission heat losses to the environment. Higher slab and indoor temperatures raise the temperature difference between the conditioned space and the outdoor environment, thereby increasing conductive heat transfer through the building envelope. The magnitude of this effect depends strongly on insulation quality, climatic conditions, storage duration, and the level of temperature increase. In well-insulated modern buildings, studies generally report relatively moderate additional losses compared to the flexibility benefits gained, particularly when temperature increases remain within 1–3 K above normal operating conditions. Nevertheless, excessive overheating can reduce overall system efficiency and may also impair thermal comfort if poorly controlled. To minimize these drawbacks, predictive control strategies are essential. Model-based or weather-compensated control can limit charging periods to times of renewable energy surplus or low electricity prices while avoiding unnecessary heat accumulation. In addition, low-temperature operation, high-performance building envelopes, and short storage cycles help maintain high storage efficiency and reduce unwanted losses. At the same time, the evaluation of these additional losses must consider the origin of the stored energy. In many applications, TABS are charged using energy that would otherwise be curtailed or remain unused, such as short-term surplus electricity from renewable generation or excess heat from solar thermal systems. In such cases, the alternative is often not a more efficient use of the energy, but its complete loss. The thermal storage capacity of the building therefore enables a partial recovery and temporal shift of otherwise wasted energy, which can outweigh the moderate increase in transmission losses. From a system-level perspective, controlled overheating through TABS can thus improve overall renewable energy utilization and contribute to grid stabilization despite slightly higher building heat losses.

2.1.5 Building Envelope Requirements and Influence of Building Use

For TABS to fully develop its effectiveness, however, a high-quality building envelope is essential. Even with generously activated surfaces, the maximum possible heating or cooling capacity is limited. Therefore, the building's heat load must be reduced to the point where it remains within the limits that can be maintained with moderate surface temperatures. Good insulation, airtight connections, the avoidance of thermal bridges, and, if necessary, a ventilation system with heat recovery are key requirements. In highly insulated buildings, even small amounts of heat are sufficient to achieve a comfortable room temperature in winter, while in summer, even small internal loads can lead to overheating. Therefore, sun protection measures and the correct use of shading systems are becoming increasingly important. The ventilation strategy is also crucial: the building envelope should remain closed during the day, while intensive ventilation is advisable on cool nights.

A high-quality building envelope is a prerequisite for the sole use of TABS.

- **Heat load limitation**: good insulation, airtight construction, and avoidance of thermal bridges
- **Ventilation with heat recovery:** Reduces heat loss and lowers the required heating load.
- **Summer thermal protection:** Optimised window areas and effective shading are essential.

User behaviour is also crucial:

- **Shading:** Only effective if used promptly and consistently.
- **Ventilation:** During hot periods, preferably at night; the building envelope should remain closed during the day. This allows the advantages of TABS to be fully exploited even in extreme summer conditions.

2.1.6 Planning and Interdisciplinary Collaboration

For the planning stage, the decision in favour of TABS means that architects, structural engineers, building physicists, and building services engineers must collaborate early on. The integration of pipe registers into the floor slabs influences not only the dimensioning of the supporting structure, but also the architectural design and the building services systems. However, this interdisciplinary collaboration is not a burden, but rather an opportunity for the development of innovative building concepts. The decision to implement TABS requires early coordination among all stakeholders:

- Architects, building physicists, and building services engineers must plan together.
- This collaboration is not a burden, but a prerequisite for innovative building concepts.

Current standardisation poses a problem. Common methods for calculating heat loads are designed for conventional buildings with high heat losses and consider extreme outdoor temperatures in stationary approaches. For low-energy and passive houses, these methods lead to significantly inflated results and thus to oversized systems. Furthermore, internal heat sources, such as solar radiation or waste heat from appliances, are not considered in all relevant standards (DIN EN 12831-1:2017-09), even though they can significantly reduce the heat load, especially in well-insulated buildings. Therefore, adapted calculation methods are required for the realistic dimensioning of TABS. Current standards for heat load calculations are not suitable for low-energy and passive houses:

- **Over-sizing:** Stationary calculation approaches with extreme outdoor temperatures (-10 °C) lead to unrealistically high heat loads.
- **Internal heat sources:** Contributions from solar radiation or appliances are not considered, even though they are significant in well-insulated buildings. Realistic dimensioning of TABS therefore requires adapted calculation methods.

2.1.7 Vertical versus horizontal TABS sections and comparison to floor heating systems

Ceiling activation offers large, evenly effective surfaces that provide both high comfort and significant thermal inertia. Wall activation, by contrast, can be used to specifically enhance comfort in selected areas but is more dependent on furnishings and construction details. Internally activated walls react more quickly and have a direct impact on room conditions, while externally activated walls mainly contribute to thermal storage capacity and the coverage of base loads. Compare Figure 6 for a schematic comparison of the installation options.

Figure 6: Schematic representation of vertical versus horizontal sections and floor heating systems. Source: TU Dresden

From a structural engineering perspective, the thermal activation of ceilings presents notable advantages. The installation of pipe registers can be carried out easily, quickly, and therefore cost-effectively. Moreover, ceiling systems ensure that the activated surfaces are not separated from the interior by insulation, allowing for efficient thermal interaction with the indoor space. Ceiling activation also provides higher installation safety compared to wall heating, as the risk of damage - such as from drilling or dowel mounting - is minimal. Overall, ceilings combine structural simplicity, building-physical effectiveness, and a high level of operational safety.

In terms of heat transfer, ceilings release heat primarily through downward radiation and, to a lesser extent, convection. During cooling operation, heat is absorbed mainly through radiation and some downward air movement. Since the ceiling surface usually remains unobstructed, the overall efficiency of heat exchange is high. Wall systems, on the other hand, also rely mainly on radiant heat transfer, but their effectiveness depends more strongly on the directionality and visibility of the surfaces. The performance of wall systems is therefore influenced by the room's layout, furnishing, and usage patterns as well as the cubature of the building. With respect to thermal comfort, radiant heat from ceilings is typically perceived as neutral to pleasant, and the risk of drafts is very low. Ceiling systems can also provide effective cooling as long as condensation is avoided. Radiation from walls, in contrast, is perceived more directly by occupants; warm wall surfaces significantly enhance comfort, whereas cold walls can be experienced as unpleasant. In terms of thermal dynamics, ceilings generally exhibit a large thermal mass and are therefore more inert, meaning that temperature changes occur slowly. Walls can react more quickly, depending on their construction and material composition. Especially interior walls with low mass show shorter response times than solid concrete ceilings. From a planning and construction perspective, ceiling activation is relatively straightforward to implement. Integration into cast-in-place concrete slabs or prefabricated elements is common practice, providing large, homogeneous surfaces that are ideal for thermal activation. Wall activation, by contrast, is more challenging due to the presence of installations, penetrations, and furnishings, which limit the usable surface area and complicate integration.

2.1.8 Internal and exterior wall activation

Internal wall activation enables direct heat transfer into the indoor space, resulting in short thermal transmission paths and a fast dynamic response. The system provides uniform surface temperatures that enhance thermal comfort, particularly along exterior walls where cold surface effects are otherwise noticeable. However, the performance of internal activation depends strongly on interior furnishings. Large pieces of furniture such as cabinets, shelves, or built-in units can obstruct radiant heat exchange and thereby reduce the active surface area and overall system effectiveness. Additionally, internal wall activation might lead to risks involving the residents and users of the building accidentally damaging the pipes while mounting e.g. furniture. Compare Figure 7Figure 6 for a schematic comparison of the installation options.

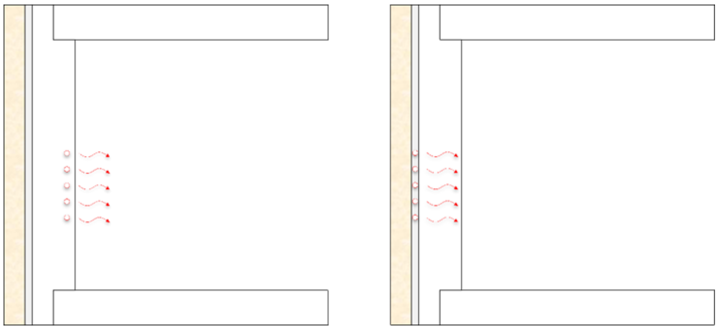


Figure 7: Schematic representation of internal and exterior wall activation. Source: TU Dresden

Exterior wall activation, by contrast, involves heating or cooling the wall from the outside, allowing thermal energy to be introduced externally and conducted through the wall structure. This configuration enables thermal storage across the entire wall thickness, which enhances the building's thermal stability and contributes to reducing heating and cooling peak loads. On the other hand, this approach is characterized by a greater degree of inertia, as thermal energy must first penetrate the wall before influencing indoor conditions. Furthermore, insufficient insulation can lead to increased heat losses to the exterior, which may compromise overall system efficiency.

In practice, a combination of internal and external wall activation can be advantageous. Internal activation allows for rapid adjustment of indoor climate conditions and improved comfort, while external activation is particularly effective for thermal load management, energy storage, and summer heat protection. Moreover, exterior activation can be synergistically integrated with renewable energy systems, such as solar thermal collectors, to enhance the overall energy performance and sustainability of the building. The thermal behaviour and comfort characteristics of activated surfaces differ depending on their orientation and function in heating or cooling operation. **During heating operation**, ceiling systems provide an even temperature distribution throughout the room, with radiant heat perceived as comfortable and natural. Interior wall activation produces a particularly pleasant radiant effect because the heat is emitted laterally and interacts directly with occupants and surrounding surfaces. Exterior wall activation, by contrast, responds more slowly due to the greater thermal mass involved and is therefore better suited for covering base loads rather than for rapid temperature adjustments.

In cooling operation, ceilings again demonstrate clear advantages. The downward radiant exchange allows for efficient cooling with minimal air movement, thereby avoiding drafts and maintaining a high level of thermal comfort. Interior wall activation can also contribute effectively to cooling, but its performance may be compromised when wall surfaces are partially covered by furniture or fixtures, which reduce active surface area and heat exchange efficiency. Exterior wall activation, on the other hand, is only suitable for cooling to a limited extent, as the thermal delay through the wall and potential heat gains or losses to the outside significantly reduce its effectiveness.

2.1.9 Thermal activation of the building envelope in energy efficient renovation

The energy-efficient renovation of buildings through the thermal activation of exterior walls is an emerging concept that integrates insulation and active temperature control into a single façade system. Instead of relying solely on passive insulation, this approach uses the building envelope itself as an active thermal component capable of both storing and exchanging heat.

In such systems, pipe or capillary structures are embedded within the outer wall or within an added façade layer. A heat transfer medium, typically water or brine, circulates through these structures, allowing the façade to act as a large-area heat exchanger. During the heating season, low-temperature heat—sourced from renewable systems such as heat pumps, geothermal fields, or solar collectors—is supplied to the wall, gently raising its temperature. This results in warmer interior wall surfaces, reduced heat losses, and improved thermal comfort. In the cooling season, the same system can be operated in reverse to extract heat from the building, using the façade for passive or active cooling.

Thermally activated façades thus provide a dynamic interface between the indoor environment and the outdoor climate. By continuously balancing heat flows, they stabilize interior temperatures and make use of the wall's thermal storage capacity. Such systems operate efficiently with low supply temperatures, which makes them particularly compatible with low-exergy and renewable energy sources.

From a retrofit perspective, the installation of an external activation layer offers significant advantages. Since the system is applied from the outside, no interventions within the interior are required—an important benefit for occupied buildings. The active façade can be combined with conventional insulation measures or integrated into new façade constructions, thereby improving both the building's energy performance and its aesthetic quality.

Overall, the thermal activation of building envelopes represents a promising pathway toward sustainable and climate-adapted renovation strategies. It enhances the functionality of façades, supports the use of renewable heat sources, and contributes to the decarbonization of existing building stock while maintaining high levels of indoor comfort and architectural flexibility.

2.1.10 Summary

Overall, TABS is far more than an alternative heating system. It combines heating, cooling, and energy storage in a single approach, thus opening up the possibility of operating buildings comfortably, energy-efficiently, and in line with the goals of the energy transition. Combined with high-quality building envelopes and conscious usage behaviour, this enables buildings to be constructed that meet both the challenges of climate change and the requirements of sustainability and quality of life. Thermally activated building systems combine heating, cooling, and energy storage in a single system. Combined with high-quality building envelopes, renewable energies, and thoughtful building use, they enable high levels of comfort, energy efficiency, and future viability. TABS is therefore a central element of innovative, climate-adapted construction methods.

2.2 Materials and construction

2.2.1 Basic hygrothermal material parameters

Simulation models – such as DELPHIN - require input material data for the adjustment of their parameters. This material data has to be determined by measurement from different experiments and is regarded as the basis of material modelling. Therefore, these material properties are called basic material properties and the corresponding methods for their determination are regarded to as basic experiments. An overview of the basic material properties and the experiments they are determined with is given in Table 5.

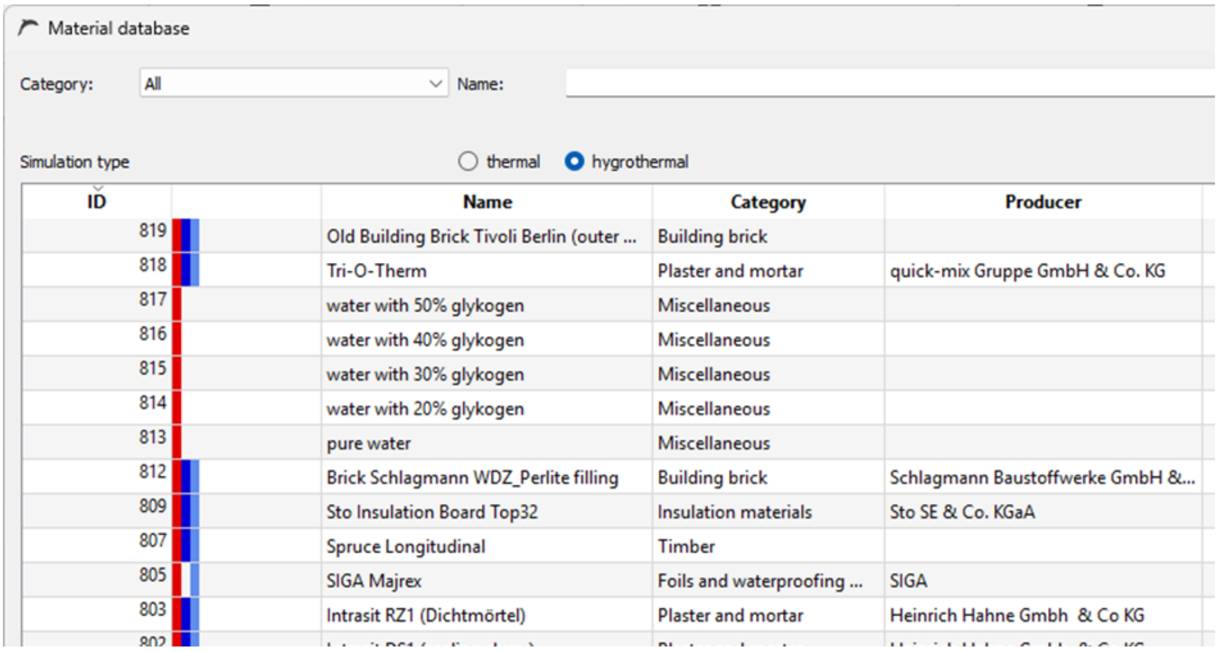
Table 5: Common hygrothermal material properties. Source: TU Dresden

Name of the material property / experiment	Symbol	Unit
Bulk (raw) density	ρ_b	kg / m^3
Matrix (particle) density / helium pycnometer	ρ_m	kg / m^3
Porosity	θ_{por}	m^3 / m^3
Thermal conductivity / heat flux measurement	λ_{dry}	W / mK
Specific heat capacity / calorimeter experiment	c	J / kgK
Sorption isotherm	$\theta_l(\varphi)$	m^3 / m^3
Water retention characteristic	$\theta_l(p_c)$	m^3 / m^3
Effective saturation moisture content	θ_{eff}	m^3 / m^3
Dry-cup vapour diffusion resistance factor	μ_{dry}	---
Wet-cup vapour diffusion resistance factor	μ_{wet}	---
Water absorption data / water uptake experiment	$\theta_l(t)$	m^3 / m^3
Water uptake coefficient	A_w	$kg / m^2\sqrt{s}$
Capillary saturation moisture content	θ_{cap}	m^3 / m^3
Drying data / drying experiment	$\theta_l(t)$	m^3 / m^3
Conductivity at effective saturation / Darcy flow measurement	$K_l(\theta_{eff})$	s
Unsaturated liquid water conductivity	$K_l(\theta_l)$	s

The different material models imply different requirements on material data. Therefore, within this chapter, the experiments the author considers to be both, applicable and appropriate for a general but advanced material characterization are briefly introduced. This comprises customary procedures for density, porosity and thermal property determination, different techniques for the measurement of moisture storage data with respect to the different moisture content ranges as well as experiments to investigate the moisture transport properties for both, vapour and liquid water. While most of the methods are to be outlined in principle, there will be placed some more emphasis on two transport experiments. These are the water absorption and the drying experiment, which are important due to their exposed position within material characterization and due to the developments carried out.

The DELPHIN software, developed by the Institute of Building Climatology at TU Dresden and distributed by Bauklimatik Dresden Software GmbH, is designed for dynamic hygrothermal simulation of building components. It models coupled heat, moisture, and mass transport in porous materials and includes an integrated material database that provides a wide range of predefined building materials, see Figure 8.

This database contains two main sections: a system database with standard materials supplied by the software, and a user database in which individual users can define and store their own material datasets. The predefined materials cannot be modified directly, ensuring consistency and reliability, while the user section allows for flexibility in defining new materials with specific thermal and hygric properties.


Material database

Category: All Name:

Simulation type ○ thermal ● hygrothermal

ID	Name	Category	Producer
819	Old Building Brick Tivoli Berlin (outer ...	Building brick	
818	Tri-O-Therm	Plaster and mortar	quick-mix Gruppe GmbH & Co. KG
817	water with 50% glykogen	Miscellaneous	
816	water with 40% glykogen	Miscellaneous	
815	water with 30% glykogen	Miscellaneous	
814	water with 20% glykogen	Miscellaneous	
813	pure water	Miscellaneous	
812	Brick Schlagmann WDZ_Perlite filling	Building brick	Schlagmann Baustoffwerke GmbH &...
809	Sto Insulation Board Top32	Insulation materials	Sto SE & Co. KGaA
807	Spruce Longitudinal	Timber	
805	SIGA Majrex	Foils and waterproofing ...	SIGA
803	Intrasit RZ1 (Dichtmörtel)	Plaster and mortar	Heinrich Hahne Gmbh & Co KG

Figure 8: Screenshot of the hygrothermal material data base of the software DELPHIN, the blue and red colours indicate whether full hygrothermal or only thermal material parameters are available. Source: TU Dresden

Material entries in the database include essential parameters for thermal transport, such as thermal conductivity, specific heat capacity. In addition, parameters for moisture transport, such as vapor diffusion resistance, sorption isotherms, and liquid transport coefficients are often included as well. Users must therefore verify whether the selected materials contain complete data for their intended simulation type. For advanced research applications - such as simulations involving thermally activated building systems, geothermal components, or novel insulation technologies - new materials often need to be added and validated.

The database interface supports filtering by category, name, manufacturer, or simulation type, which facilitates material selection for specific modelling tasks. A formal specification document ("Material File Specification") defines the structure and parameters of these data files, ensuring compatibility across DELPHIN versions. The quality and accuracy of the material data have a decisive influence on simulation reliability. Consequently, in the context of validating simulation software such as DELPHIN, careful assessment of the material data and their physical plausibility is essential. The DELPHIN material database thus serves as both a comprehensive reference library and a flexible framework for integrating custom-defined materials that support innovative building technologies.

2.2.2 Experimental determination of material properties

Density and porosity

There exist two kinds of density which have to be distinguished: The bulk and the matrix density. The bulk density characterizes the density of the material as it is. The volume of both, material matrix and pores, is comprised. The bulk density is defined as the ratio of the dry mass and the volume of the dry specimen following Equation 1.

Equation 1:

$$\rho_b = \frac{M_{dry}}{V_{bulk}}$$

The matrix density specifies the density of the material matrix without the pore space. It can be determined by helium pycnometer. There, the crushed dry material is put into a vessel of defined volume. Then, a measured amount of helium is given into the vessel until a certain pressure is reached. Since helium is the smallest element, any space not occupied by another element will be entered. From the difference in the amount of helium which could be given to the empty vessel under the same pressure, the volume of the crushed material can be determined. The matrix density is then determined as the ratio of the dry material mass and the determined volume, following Equation 2. For natural stones, DIN EN 1936 proposes a similar procedure using a pycnometer with deionized water. However, the use of helium offers a higher degree of precision.

Equation 2:

$$\rho_m = \frac{M_{dry}}{V_{matrix}}$$

From both densities, the total porosity of the material can be derived. It is defined in Equation 3 as the volume fraction which is not occupied by the material matrix.

Equation 3:

$$\theta_{por} = 1 - \frac{\rho_m}{\rho_b}$$

Sometimes, the open porosity is used as a material parameter, too. It gives a measure for the pore volume which is connected to the pore system and can thus be entered by water. The open porosity can be determined by saturation under vacuum conditions. The primary desorption function starts at open porosity. However, as these conditions are hardly reached in practice, this parameter is not considered within the frame of this work.

Thermal conductivity and specific heat capacity

The thermal properties of interest are the heat capacity and the thermal conductivity. The heat capacity can be measured by the calorimeter experiment where a heated specimen of defined temperature is placed into water with another (lower) defined temperature. Knowing the heat capacity of water, the heat capacity of the material specimen can be derived, if the final equilibrium temperature, which the water and the specimen have reached, is measured.

The thermal conductivity of a dry porous material basically includes three effects: heat conduction in the solid material and in the pores, as well as (long wave) radiation and air convection in the pores. These three effects cannot be separated in experiments and form together the apparent dry thermal conductivity. In cases of in-built moisture or moisture accumulation in the material, the thermal conductivity increases as shown in Figure 9. The moisture dependent thermal conductivity is usually measured at the effective saturation moisture content and then interpolated and calibrated between the dry and saturated points.

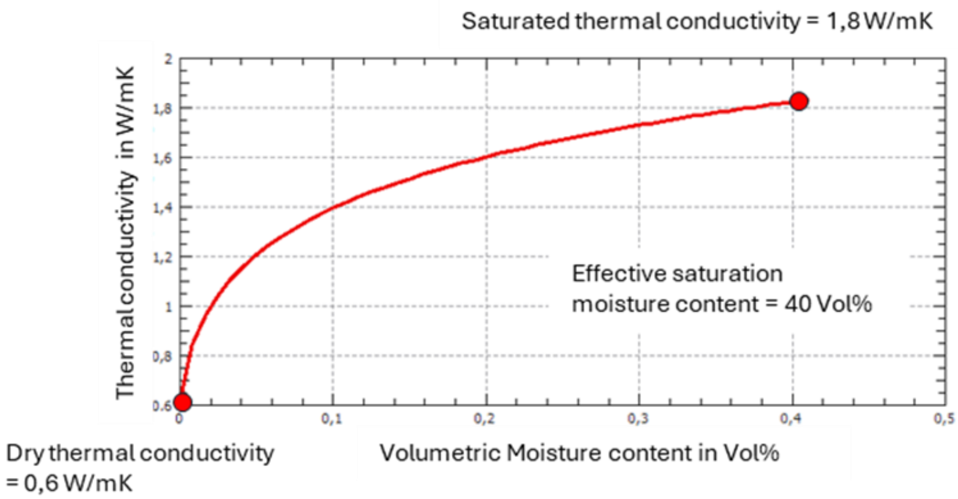


Figure 9: Typical curve of a moisture dependent thermal conductivity of porous materials. The curve rises steeply at first and then flattens out at higher moisture levels. Source: TU Dresden

The thermal conductivity can be determined by the help of heat flow experiments. A most common thermal conductivity meter - since applicable for most building materials - is the plate apparatus shown in Figure 10. Different regulations and standards exist on that, e.g. *ISO 8302 (1991)*, *DIN EN ISO 12664* and *WärmeleitRechenWRL (1999)*, on which no further emphasis is placed here. The principle is to apply a temperature difference versus the thickness of the dry specimen and measure both, the temperature on either side and the heat flux through the specimen. From that, the thermal conductivity of the dry material can be derived.

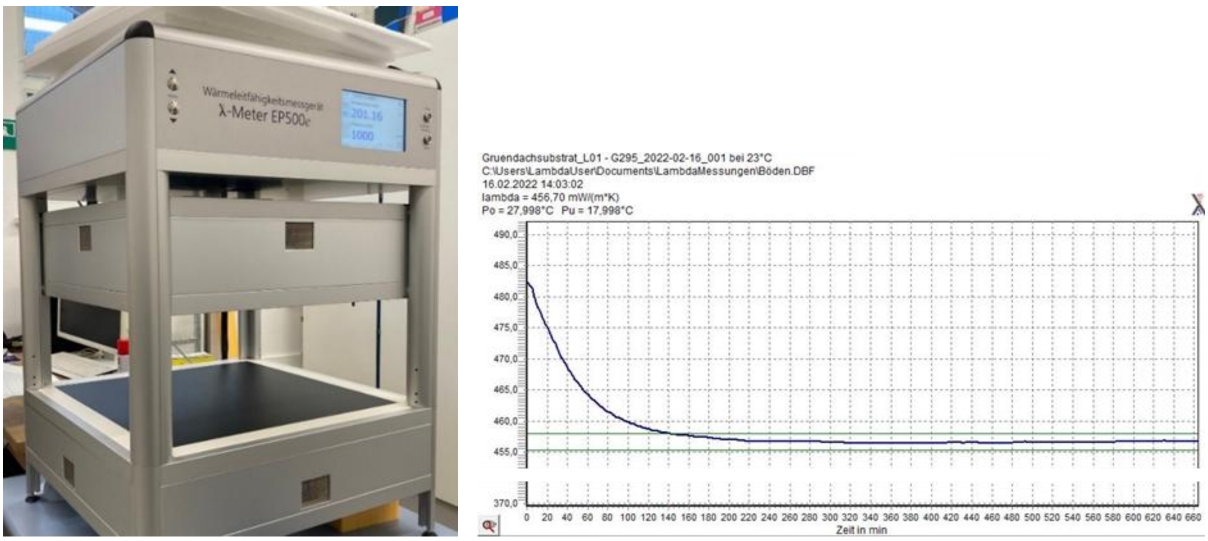


Figure 10: Thermal conductivity meter: l-MeterEP 500e from the TUD Building Physics Lab (left) and measurement protocol (right) showing transient phase in the beginning and a stationary flow afterwards. Source: TU Dresden

Another possibility deriving both properties at the same time is the use of a device that is placed on a specimen applying a dynamic circle of heating and cooling. The advantage of such a device is, that the measurement result can be obtained much faster, since no steady state conditions are reached, both thermal properties can be determined at the same time and - which is most important - small specimen can be used, as it is often the case for materials taken from the building stock. The disadvantages comprise limited accuracy especially for anisotropic materials and the dynamic conditions, which sometimes might represent a different behaviour than steady state conditions do.

Moisture storage function

Moisture storage data in general comprises the hygroscopic and the overhygroscopic moisture content range. Since different procedures and measurement technologies are applied in both moisture regions, a further distinction is made for moisture sorption and moisture retention. For each, a general introduction is given, while the focus is then placed on the measurement techniques applied for the investigated building materials.

Figure 11: Desiccator with salt solution for moisture sorption measurements. Source: TU Dresden

The measurement of moisture storage within the hygroscopic moisture content range is widely done by exposing a material specimen to a defined relative humidity, waiting until equilibrium (constant mass) is reached and gravimetrically determining the corresponding moisture content (compare Figure 11). Either a complete device, as the IGASORP, a micro balance system (as e.g. used by *Johannesson & Janz (2002)*) or a sorption calorimeter (see e.g. *Adan (1994)* and *Broken (1998)*), can be applied adjusting the relative humidity and performing the gravimetric measurements automatically, or the conventional desiccators with saturated aqueous salt solutions, are employed (as reported e.g. by *Burch et al. (1992)* and *Broken (1998)*). Here, it is referred to the latter one, which is standardized in *DIN EN ISO 12571*.

To adjust a defined relative humidity inside a desiccator, saturated aqueous salt solutions are used. A fan inside the desiccator causes quick equilibration of the humidity conditions. To keep the temperature constant, either a water bath for the desiccators, or a temperature-controlled room can be used. The material specimens are placed into the desiccator and left there for a certain time, normally two to four weeks, until equilibrium is reached. The employed criterion for the equilibrium is the one defined in *DIN EN ISO 12571*: The mass change of the specimen of three subsequent measurements within 48 hours has to be less than 0.1% of the dry mass of the specimen. Once the equilibrium is reached, the material specimen is weighed. From the ratio to the dry weight, the moisture content can be derived.

Vapour diffusion resistance factors

The principle of measuring vapour transport through a building material is based on steady state flow conditions which develop under a constant potential gradient. The potential, i.e. the vapour pressure, can be adjusted by controlling the relative humidity and keeping the temperature constant. The relative humidity can either be adjusted by saturated aqueous salt solutions or by a climatic chamber. If the flow rate through the material is measured, the transport properties can be derived for the corresponding potential gradient.

For vapour diffusion measurements, so called cups are used, see Figure 12. Inside the cup, the relative humidity is adjusted whether with a drying agent or with a salt solution. A material specimen is sealed into the lid of the cup providing one-dimensional transport. The cup is closed with the lid allowing vapour to enter (or leave) only through the investigated material. The whole cup is placed either into a climatic chamber or into a desiccator, where another relative humidity is adjusted. Depending on the vapour pressure gradient, vapour will enter or leave the cup. From gravimetric measurements, the flow rate can be obtained and, after a steady state flow has been developed, the vapour diffusion coefficient can be derived.

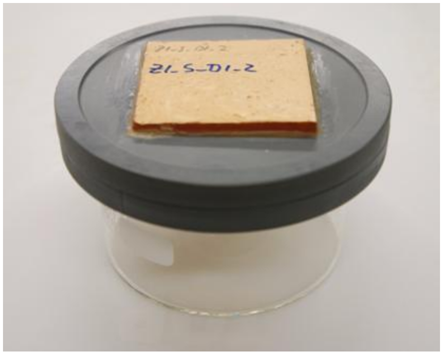


Figure 12: Cup for measurement of vapour diffusion. The material specimen is sealed into the removable lid enabling preconditioning and easy change of boundary humidity conditions. Source: TU Dresden

With the choice of different relative humidity conditions, the vapour diffusion coefficient can be determined for different potential gradients and correspondingly for different moisture contents. With this regard, the experiment is often called dry-cup or wet-cup experiment. For higher relative humidities, not only vapour diffusion proceeds, but also liquid conduction. In combination with an assumption on up to which relative humidity does only vapour transport proceed, the liquid transport rate and, thus, the liquid water conductivity can be determined from the wet-cup measurements, too.

To achieve reliable measurement results, from the authors point of view it is recommended to keep the relative humidity difference rather small (i.e. 10% to 20% RH). By preconditioning the material specimens at a mean relative humidity of the planned experiment, the time the steady state flow conditions require to develop can be significantly reduced. This is the reason for the special cup design where the lid can be easily removed for that purpose. Moreover, the mean moisture content of the specimen can be determined at the beginning and at the end of the experiment which is important if no assumption is to be implied whether the adsorption or the desorption storage characteristic is to be used to assign the transport coefficient to a moisture content.

Material property measurements

A large number of building materials has been investigated with regard to the basic hygrothermal material properties, of which four commonly used materials are selected for the special studies reported below. These materials are a typical building brick, a calcium silicate inside insulation board, an autoclaved aerated concrete and a lime-sand brick.

The selection is made from two different points of view. On the one hand, all materials should be frequently used building materials with a wider range of application. Thus, three chosen materials are building stones representing different structural types, whereas the fourth choice is made for an insulation material. On the other hand, the materials should also be representative for the whole range of hygrothermal behaviour, i.e. from light and vapour open to dense and tight, from slow water conducting up to capillary active building materials.

The chosen building brick is a dense but fine-porous material with a relatively high capillary conductivity, a mean vapour diffusion resistance and a low hygroscopic moisture storage characteristic. The calcium silicate is a light and highly porous insulation material with a fine pore structure. It has a very high capillary conductivity, is vapour open, but contains a low hygroscopic moisture capacity. It is used as an inside insulation material, especially for thermal rehabilitation of historical buildings.

The autoclaved aerated concrete represents a light, thermally insulating building stone with a high porosity. It has a wide pore range with several pore maxima and a high hygroscopic moisture capacity. It is a vapour open material with a low capillary conductivity. The lime-sand brick, finally, is a dense and vapour tight building stone. Its pore structure contains several maxima with a distinct moisture capacity already within the hygroscopic moisture range. The liquid transport properties are very low.

According to their moisture transport behaviour, the calcium silicate and the building brick can be classified as well conducting materials, whereas the lime-sand brick and the autoclaved aerated concrete can be regarded as slow conducting materials. A selection of specimens of the first group is shown in Figure 13. The following Table 6 to Table 9 contain specific basic material information for each material.

Figure 13: Left picture: Selection of material samples of the building brick (left) and the calcium silicate insulation board (right). The legend shows divisions of 0.5 cm. Right picture: Selection of material samples of the lime-sand brick (left) and the autoclaved aerated concrete (right). The legend shows divisions of 0.5 cm. Source: TU Dresden

Table 6: Characteristic material properties of building brick (Source: PhD Gregor Scheffler).

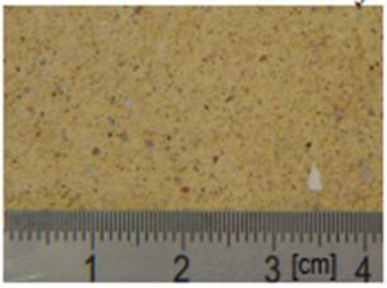
Material property	Value	Unit	Miscellaneous
Dry bulk density ρ_b	1790	kg/m^3	The brick is a typical building stone frequently used, especially in Northern Germany.
Porosity θ_{por}	0.353	m^3/m^3	
Capillary saturation θ_{cap}	0.257	m^3/m^3	
Moisture content at 85% RH θ_{85}	0.0025	m^3/m^3	
Water absorption coefficient A_w	0.227	$kg/(m^2\sqrt{s})$	
Dry vapour diffusion resistance μ_{dry}	13.5	---	
Thermal conductivity λ_{dry}	0.87	$W/(mK)$	

Table 7: Characteristic material properties of calcium silicate board (Source: PhD Gregor Scheffler).

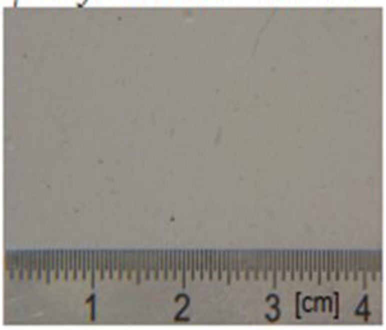
Material property	Value	Unit	Miscellaneous
Dry bulk density ρ_b	270	kg/m^3	The calcium silicate is used as a capillary active inside insulation.
Porosity θ_{por}	0.91	m^3/m^3	
Capillary saturation θ_{cap}	0.79	m^3/m^3	
Moisture content at 85% RH θ_{85}	0.006	m^3/m^3	
Water absorption coefficient A_w	1.11	$kg/(m^2\sqrt{s})$	
Dry vapour diffusion resistance μ_{dry}	4.0	---	
Thermal conductivity λ_{dry}	0.069	$W/(mK)$	

Table 8: Characteristic material properties of autoclaved aerated concrete (Source: PhD Gregor Scheffler).

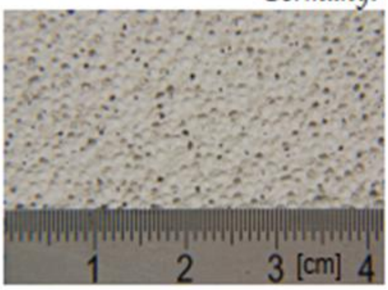
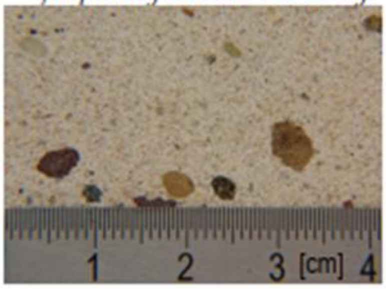
Material property	Value	Unit	Miscellaneous
Dry bulk density ρ_b	390	kg/m^3	The aerated concrete is a building material often applied in Germany.
Porosity θ_{por}	0.87	m^3/m^3	
Capillary saturation θ_{cap}	0.26	m^3/m^3	
Moisture content at 85% RH θ_{85}	0.023	m^3/m^3	
Water absorption coefficient A_w	0.043	$kg/(m^2\sqrt{s})$	
Dry vapour diffusion resistance μ_{dry}	7.5	---	
Thermal conductivity λ_{dry}	0.095	$W/(mK)$	

Table 9: Characteristic material properties of lime-sand brick (Source: PhD Gregor Scheffler).

Material property	Value	Unit	Miscellaneous
Dry bulk density ρ_b	1810	kg/m^3	*The investigated lime-sand brick is a typical building stone frequently used in Germany.*
Porosity θ_{por}	0.345	m^3/m^3	
Capillary saturation θ_{cap}	0.218	m^3/m^3	
Moisture content at 85% RH θ_{85}	0.037	m^3/m^3	
Water absorption coefficient A_w	0.052	$kg/(m^2\sqrt{s})$	
Dry vapour diffusion resistance μ_{dry}	40.0	---	
Thermal conductivity λ_{dry}	1.05	$W/(mK)$	

2.2.3 Implications for TABS design and material selection

Thermally Activated Building Systems (TABS) can, in principle, be implemented using various structural materials. While reinforced concrete remains the most common and widely applied material, alternative construction materials such as engineered timber or masonry elements are also being explored. However, the physical properties of these materials differ significantly, and these differences directly influence storage capacity, heat transport behavior, system efficiency, and environmental performance, see

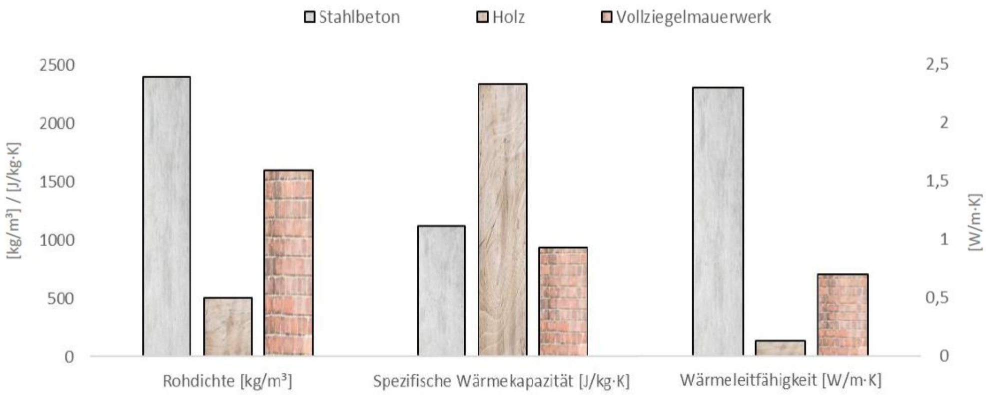


Figure 14: Comparison of physical properties of steel-reinforced concrete, timber and brick. Source: AEE INTEC

From a thermal storage perspective, two material properties are particularly critical: density and specific heat capacity. Together, they determine the volumetric heat storage capacity of a material — that is, how much energy can be stored per unit volume for a given temperature difference. Materials with higher density and higher specific heat capacity can store more energy in the same structural volume. Concrete, due to its relatively high density and favorable heat capacity, offers substantial thermal storage density. This makes it particularly suitable for applications where significant intraday or multi-day load shifting is intended.

In contrast, materials such as wood typically exhibit lower density. Although wood may have a comparable or even favorable specific heat capacity per unit mass, its lower density reduces its volumetric storage capacity. As a result, a timber slab of equal thickness generally stores less thermal energy than a concrete slab. For applications targeting significant energy flexibility, this reduced storage density may limit achievable performance unless compensated by increased material thickness or additional storage components. Equally important is thermal conductivity, which governs the rate at which heat can be transported within the slab and from the embedded pipes to the surface. High thermal conductivity supports more uniform temperature distribution and higher achievable transmission power. Concrete, with moderate thermal conductivity, enables relatively efficient heat transport within the activated element. This facilitates lower supply temperatures in heating mode and controlled surface temperatures in cooling mode. Wood, by comparison, has significantly lower thermal conductivity. This reduced conductivity leads to several practical implications. First, higher supply temperatures may be required to achieve comparable heating power, as depicted in Figure 15.

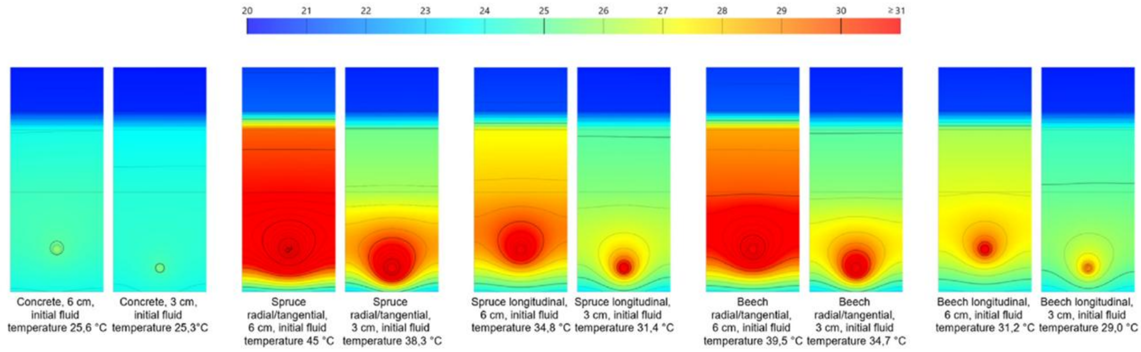


Figure 15: Comparison of simulated temperature profiles in TABS elements for varying materials with concrete (left), and spruce and beech timber (middle to right) as specimens. To reach the same surface temperatures and therefore heating and/or cooling powers, significantly higher flow temperatures within the timber elements is necessary due to the much lower heat conductivity. Source: (Heidenthaler, Leeb, Schnabel, & Huber, 2021).

Second, temperature distribution across the slab surface may become less uniform, potentially creating uneven comfort conditions. Third, the maximum transmissible heating or cooling power is typically lower compared to concrete-based TABS. These characteristics make timber-based activation more suitable for comfort-oriented applications with moderate power demand rather than high-load flexibility scenarios. However, thermal performance is only one side of the design equation. Increasingly, environmental considerations, such as embodied carbon and grey emissions, play a decisive role in material selection. Concrete production is associated with significant CO_2 emissions, primarily due to cement manufacturing. Timber construction, in contrast, often exhibits lower embodied carbon and may even function as a temporary carbon sink during its service life. From a sustainability perspective, this introduces a complex trade-off. Concrete-based TABS offer superior thermal storage density and heat transfer performance, enabling greater operational flexibility and potentially larger operational energy savings. Timber-based solutions may reduce embodied emissions but may offer reduced storage performance. A holistic life-cycle assessment is therefore required to evaluate whether lower embodied carbon offsets potential differences in operational flexibility. In practice, hybrid approaches are increasingly considered. For example, timber structures may incorporate concrete core elements or composite slabs to combine favorable environmental performance with sufficient thermal mass. Such integrated solutions demonstrate that material selection for TABS should not be viewed as a binary choice, but rather as an optimization problem balancing structural requirements, flexibility goals, comfort performance, and life-cycle sustainability.

Material properties play a decisive role in determining the achievable storage capacity, heat transfer performance, and environmental footprint of TABS. Density and specific heat capacity define storage potential, thermal conductivity governs power transfer and temperature uniformity, and embodied carbon considerations influence long-term sustainability. Successful implementation therefore requires careful evaluation of both thermal and environmental criteria, aligned with the intended flexibility objectives of the building.

2.3 Market available, innovative TABS energy storage system designs for new construction and refurbishment

The following product descriptions are based primarily on information provided by the respective industry partners. To preserve technical accuracy and reflect the different development approaches, the original structures and terminology were retained to a large extent. Consequently, the level of detail and emphasis differs between the presented systems. To ensure a scientific approach and allowing for comparison between the systems, each section ends with a discussion of the products' core principles, advantages and disadvantages.

2.3.1 Concrete sandwich panels CEILTEC for new construction and refurbishment

Link to company and product: https://www.innogration.de/

The urgent need to reduce CO_2 emissions inevitably leads to a reduction in concrete mass in order to use less cement. Since the slab and roof construction account for 44 % of the total grey emissions in a solid building, solutions for reducing of the concrete mass must be sought.

The use of multifunctional precast concrete elements for the controlled management of renewable energy is a promising option. Concrete components, in conjunction with the embedded reinforcement, not only perform load-bearing functions but can also be used for other purposes. Compared to other materials, concrete has a high heat storage capacity but also high thermal conductivity. Therefore, concrete is ideally suited for both heat generation and heat storage. Existing concrete components for foundations, ceilings, and potentially walls can thus be used for multiple purposes.

The experience of traditional builders with solid construction compared to lightweight construction shows that solid construction is advantageous in several ways: it protects the building from the elements, stores heat and releases it gradually into the rooms. Typical examples of this construction method are the large houses in the Alpine region (e.g., Engadine house, see Figure 16) with their massive stone walls and stone slab roofing. The wall thickness is evident in the deep window recesses. This type of house is particularly resilient in harsh climates because the walls not only protect against the weather but also act as thermal storage in both winter and summer.

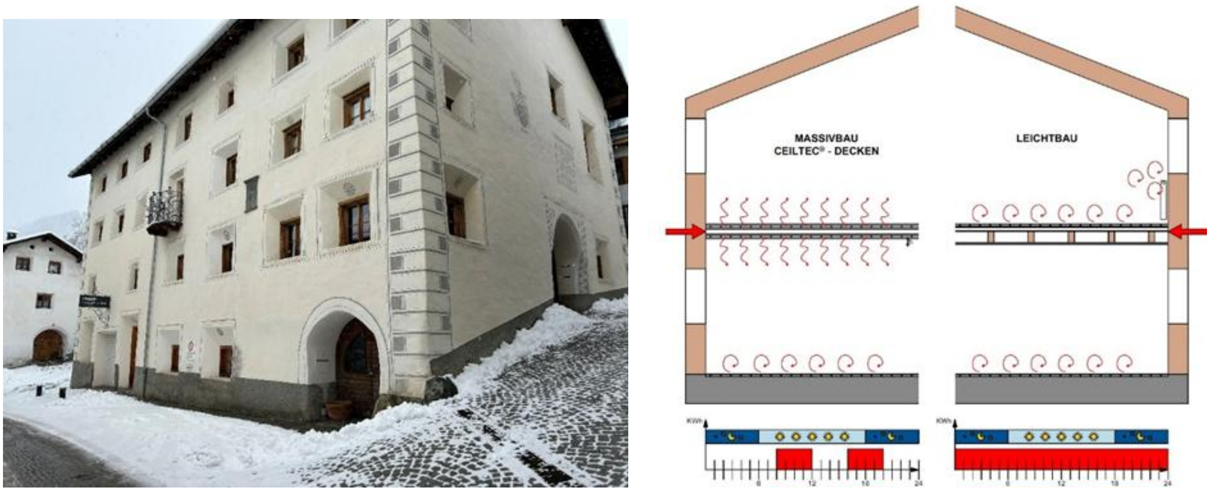


Figure 16: Engadine house with solid walls for protection against the elements and for storing heat as example for traditional construction (left) and System comparison of buildings in lightweight construction and in solid construction (right). Source: Innogration GmbH

In contrast to this massive construction method, lightweight construction is predominantly used today. The wall cross-section is functionally motivated. Instead of a monolithic cross-section, individual layers are found, such as for the load-bearing structure, insulation, and the outer weatherproofing. However, this can also cause problems when separating the materials later.

The cross-sectional structure in lightweight construction generally provides little mass and is also unsuitable for storing thermal energy. Therefore, other components must provide the necessary mass for heat storage. For example, the required mass for thermal storage in lightweight wall constructions can be provided by the solid-construction ceilings.

Massive Ceiling Construction as a Component of Heat Storage

A major advantage of a massive ceiling construction lies in its multiple functions: it simultaneously distributes the supplied or stored heat energy evenly across the ceiling surface. The ceiling's underside, free of any built-in elements or suspended components, can distribute the temperature very evenly throughout the room thanks to thermal activation. Heat transfer across the large ceiling surface requires only low supply temperatures to heat or cool the room.

Furthermore, heat transfer into the room occurs via radiation, which is perceived as exceptionally pleasant by the occupants. Here, it is not the air that is heated, but rather the objects in the room. These objects, in turn, envelop the occupants, warming them from all sides, and the occupants feel the radiant heat from every direction. The radiant heat and the low supply temperatures reduce energy consumption and result in very economical building operation.

The effective use of the ceiling cross-section for both storing and releasing thermal energy depends crucially on its structural design. The concrete mass should be chosen to allow for sufficient storage capacity while also ensuring a rapid response from the heating and cooling system. Furthermore, high thermal performance is desired. This requirement can only be optimally met with a sandwich-type cross-section, compare Figure 17.

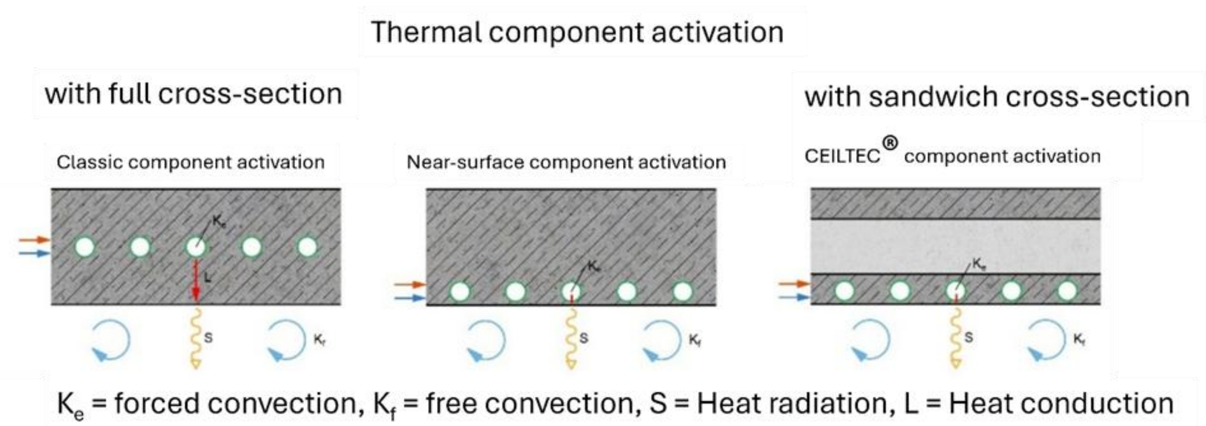


Figure 17: Performance of component activation as a function of the position of the pipes in the cross-section. Source: Innogration GmbH

Traditionally, the pipes for thermal activation in cast-in-place concrete slabs with a solid cross-section were installed centrally within the cross-section. The solid cross-section has a large mass that absorbs thermal energy. Especially with the pipes located centrally, the supplied heat is absorbed throughout the entire cross-section, meaning it is also conducted upwards, resulting in a lack of heat at the underside of the slab. The lower temperatures at the underside of the slab compared to the concrete core led to low thermal output. The output of the activated slab is determined by the temperature difference between the room and the underside of the slab. Consequently, the thermal output is low, but the energy stored in the cross-section is slowly conducted to the underside due to the temperature gradient. The result: low output but long-lasting availability of the stored energy.

Component activation with a sandwich cross-section

Under these aspects, the effect of component activation must be reassessed. For example, when using the sandwich cross-section, only the lower shell is available for installing the pipe registers. Accordingly, only this mass can be used for energy storage. However, this cross-section offers significant advantages for the actual operation of component activation. For example, due to the near-surface arrangement of the pipes, the thermal output can be significantly increased. This is typically up to 70 W/m² for cooling and approximately 50 W/m² for heating. These values are largely sufficient to ensure satisfactory conditioning on their own and without additional energy distribution systems. A further advantage is the increased responsiveness, allowing the system to react very quickly to temperature changes in the room. This creates the conditions for implementing highly efficient and economical conditioning across the ceiling area.

For example, flat slabs with dispersed cross-sections can now be constructed, which already save up to 40 % of concrete mass (Figure 18 and Figure 19). This saving can be achieved without changing the function or appearance of the flat slab. From a static perspective, two dispersed and thin shells are sufficient for the load-bearing cross-section to absorb the bending moment. The upper shell absorbs the compressive load, and the reinforcement is integrated into the lower shell. A hollow space remains between the two shells, which can be used, among other things, for cable routing. Only individual connections between the two shells are required to absorb the shear forces. The cavity can be created in various ways, for example, by installing displacement elements or as a hybrid precast construction with permanent formwork.

Figure 18: Sandwich-type cross-section: slabs with dispersed cross-sections, which save up to 40 % of concrete mass (left) and air conditioning via thermally activated ceiling (right). Source: Innogration GmbH

Figure 19: Integration of sandwich-type cross-section elements in the building's structure. Source: Innogration GmbH

If the sandwich cross-section is used, it can be constructed with prefabricated concrete components. The ceilings are delivered as individual precast panels and assembled on-site to form the sandwich structure, then structurally connected (Figure 20). The bottom layer of the cross-section is delivered with the ribs. The top layer is then placed on the ribs on-site and monolithically connected to them. This creates a cross-section that is rigid in both flexural and shear resistance. With comparable cross-sectional resistances, the sandwich cross-section offers advantages such as low self-weight and the option of utilizing the ceiling cavity for utility installations.

Figure 20: Installation of the pipe registers in the central position of the solid cross-section in a cast-in-place concrete ceiling (left) and Flat slab with sandwich cross-section, separate upper and lower slabs with a cavity (right). Source: Innogration GmbH

Factory production of panel elements

Thanks to the prefabrication of the panel elements, it is possible to install a pipe register on each panel, which is individually controlled. Thanks to the prefabrication of the ceiling elements, all installation work for building services is also carried out in the precast concrete plant under optimal working conditions (compare Figure 21). The pipes for the thermally activated building system are installed precisely and tested for leaks. Distribution boxes for the pipe registers can also be pre-installed. Additional components such as electrical conduits and junction boxes, as well as cutouts for acoustics, are installed in a protected environment at the factory. Factory production ensures high quality for both the ceiling elements themselves and the building services components. Damage to the components on the construction site is eliminated by their installation within the concrete ceiling.

The practical implementation is ensured by the aforementioned high thermal performance and rapid response time. Several of the individual registers are combined in a decentralised manifold. The assignment of the individual registers corresponds to the thermal zoning. The division into individual registers according to the expansion grid also allows for zone-specific cooling and heating in parallel operation. This only requires the decentralized manifolds to be alternately supplied with cooling or heating. Implementation follows a detailed planning process. An element plan is created for each floor plan, including the dimensions and structural details of the individual ceiling panels.

This planning process can also be applied to other components in the element plan, such as electrical wiring, ventilation ducts, and integrated acoustic absorbers. The process in the element plan thus defines the components of the concrete core temperature control (CCT) for each individual prefabricated panel. The individual panels are then manufactured in the factory with the associated components. The entire panel assembly forms a well-ordered puzzle that is precisely fitted together during assembly. Transitions, connections, and connections for the pipes fit together across the panels. Once connected, the pipes form a single unit with the aforementioned properties for efficient conditioning.

Figure 21: Installation of high-quality building services components in the precast plant, Source: Innogration GmbH

Characteristics of the Sandwich Cross-Section regarding thermal storage and responsiveness

Experience with the thermal activation of flat slabs with sandwich cross-sections shows ideal results for both heat storage and heat distribution. When thermal energy is transferred into the concrete mass via the pipes, the temperature rises in proportion to the heat transport within the cross-section. The room temperature changes only slightly during this process. This ensures that the usability of the thermal energy remains highly flexible, allowing for a rapid response to changes in the room climate.

The differences in thermal properties are also evident when comparing the thermal output of the two cross-sections. These differences become apparent when the panels are charged with thermal energy for 12 hours and then utilized over the following 12 hours. The thermal output of the sandwich-section ceiling is significantly higher. Heat storage is only slightly lower, as demonstrated by the low output after 12 hours without further heat input (compare Figure 22).

The thermal properties of the sandwich cross-section are characterized by moderate storage capacity and a rapid response to desired changes in the room climate. Only about 35% of the heat energy supplied to the cross-section within a given time period is directly released into the room during that period. The remaining energy is stored within the cross-section (in this case, the thin lower layer) and can then be released into the room later. Although the temperature within the cross-section rises sharply, the room temperature changes only slightly. The energy stored within the cross-section is released into the room over the following period until the room temperature returns to its initial value. The energy input leads to significant temperature changes within the cross-section, while the change in the room temperature remains moderate (approximately 1/3 of the temperature within the cross-section). The utilization of the total supplied energy can be divided into the period of supply (1/3 of the total time) and the consumption of the stored energy (2/3 of the total time).

This behaviour now makes it possible to supply energy in specific time intervals and to benefit from the stored energy during the remaining time. This, in turn, enables phased operation of the energy generator. Energy generators belonging to a radiant heating system, such as heat pumps, benefit enormously from this possibility. The heat pump is only switched on when electricity is either available (from a private photovoltaic system) or is provided at a low price (dynamic electricity tariffs in 15-minute increments). This allows every homeowner to save money on energy generation.

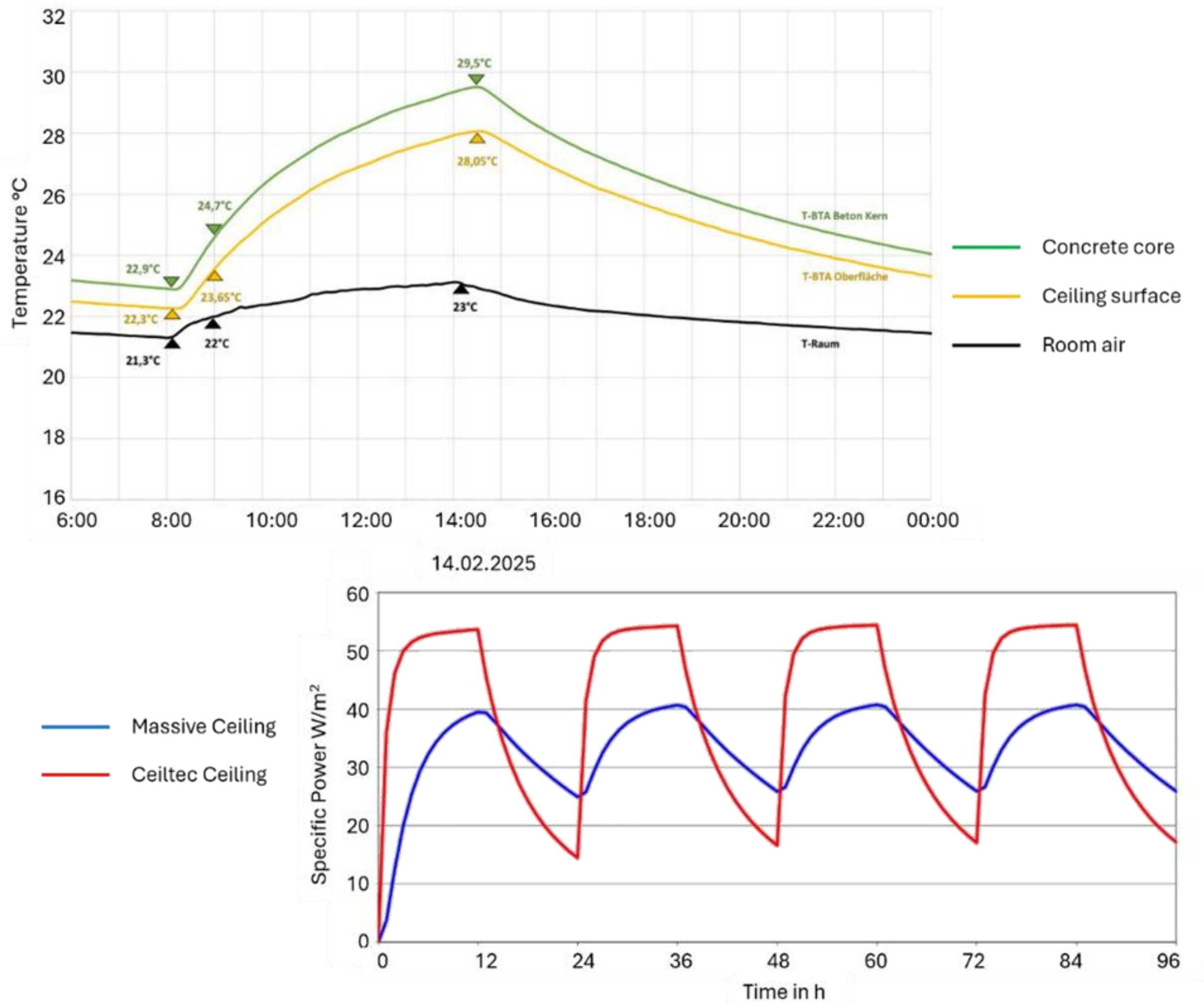


Figure 22: Thermal behavior of room and ceiling with a sandwich cross-section (top left) and Comparison of thermal performance when installing the pipes in solid cross-section and sandwich cross-section (bottom right). Source: Innogration GmbH

In the past, large water storage tanks were used as buffer storage for this phase shift. The space required for the water storage tanks can be used for other purposes, especially in houses without basements. The high temperatures in water storage tanks cause heat losses, which do not occur at all with thermally activated building components. The necessary mixing of water temperatures can also be eliminated. The intervals for the energy supply are adjusted according to the temperature in and outside the room.

The benefits of heat storage in the concrete ceiling can be extended to several days, depending on the weather. This also utilizes additional internal loads (people, equipment) as well as external thermal influences such as solar radiation through the windows. The massive concrete elements largely regulate energy absorption and release independently (self-regulating effect of a concrete ceiling). If the room temperature is higher than the surface temperature of the concrete ceiling or wall, energy is extracted from the room and stored. As soon as the room temperature falls below the surface temperature, the stored heat energy is released back into the room (compare Figure 23). By consistently utilizing this self-regulating effect, the period during which no self-generated energy is supplied can be extended.

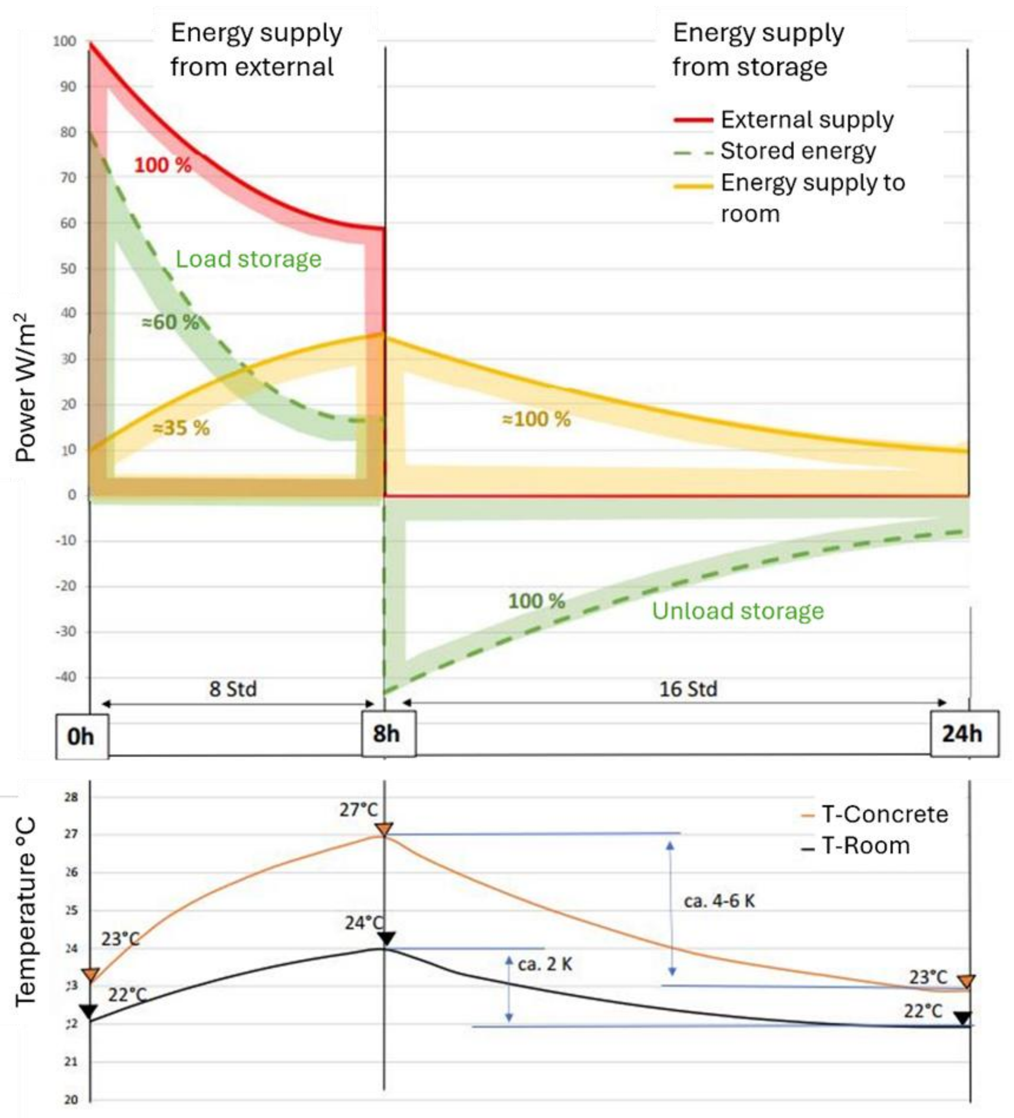


Figure 23: Thermal behavior of a sandwich cross-section: proportion of thermal energy storage and release as a function of energy input. Source: Innogration GmbH

The new designs for high-rise slabs fulfil several functions at once. The use of sandwich-section ceilings instead of solid cross-sections offers the following advantages:

- Savings in concrete/cement and thus a reduction in CO2
- A performance-enhancing effect of the CCT with additional comfort features
- Separate functions for the storage and distribution of thermal energy
- Prefabrication including the controlled installation of all building services components

The CEILTEC® ceiling, as a complete system, offers these aforementioned properties. Today's energy policy framework requires a change in current construction methods. Efficient components with multifunctional properties are in demand. Furthermore, further industrialisation of production is needed, and due to the shortage of skilled workers, a reduction in manual labour on the construction site is needed.

Discussion of core principles, advantages and limitations - CEILTEC

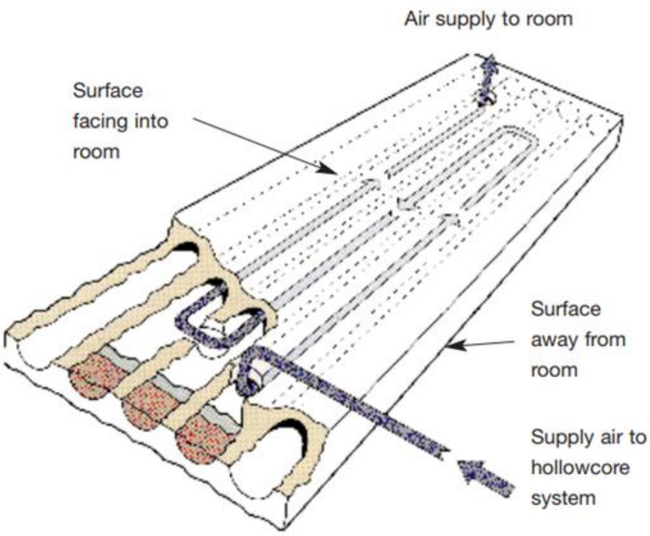
The core principle of the CEILTEC system is the functional separation of structural performance, thermal storage, and thermal output within a prefabricated sandwich-type concrete slab. Compared with conventional solid TABS, the near-surface pipe position increases thermal responsiveness and heating or cooling capacity, while the reduced concrete volume contributes to lower embodied emissions. This makes the system particularly relevant for new construction and for projects where industrialized prefabrication, reduced on-site labour, and integrated building services are important design objectives.

At the same time, the system represents a trade-off between storage mass and dynamic controllability. While the sandwich cross-section improves response time and thermal output, only part of the slab mass is available for active storage compared with a fully solid slab. This makes CEILTEC more suitable for short- to medium-term load shifting, PV self-consumption, and heat pump optimization than for very long storage periods. In comparison with TermoDeck, CEILTEC is less directly coupled to ventilation, but offers stronger potential for architectural integration and zone-specific hydronic control.

2.3.2 TermoDeck HVAC system for new construction

Link to company and product: https://termodeck.com/

Thermal energy storage (TES) systems can profoundly reduce the installed cooling- and peak power loads. TES systems today often refer to ice storage and chilled water systems which are expensive to install and have high running costs due to their complexity. By using the building structure for energy storage, no extra equipment, such as water tanks, cooling refrigerant circuits, air/water heat exchangers is needed. Thermal storage in building needs materials with a high specific heat capacity. Load bearing building materials such as concrete, bricks and stone have a high specific capacity. The described system is a ventilated hollow core concrete slab (VHCS), see Figure 24. The concrete slab can easily be connected to other building element e.g. external walls.



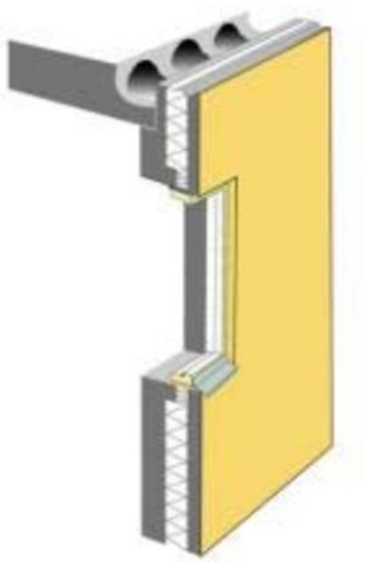


Figure 24: The TermoDeck System: A ventilated hollow core concrete slab (left) and Connection between the slab and external wall (right). Source: TermoDeck

The system offers a heat exchange between the supply air and the slab that could be around 85-90% which ensures that the whole concrete slab is cooled down. This leads to that the heat generated during the day (from people, lights, equipment and sun radiation) is efficiently absorbed by the cool concrete slab. However, the heat exchange between the slab surface and the indoor air will reduce when the concrete slab is covered by flooring or by suspended ceilings such as mineral boards. TermoDeck is a building concept that integrates the HVAC system and the thermal mass of the building. TermoDeck is used for ventilation, cooling and heating. The system lets the supply air pass through the cores of a standard hollow core slab before entering the room. As the slabs will be cooled or heated by the air they can be used for storing energy. The slabs will act as large heat exchangers. Many advantages are thus achieved.

In cooling mode most of the heat gains in the room (occupants, lights, equipment, sun) are stored in the hollow core slabs during daytime. This stored energy is removed during the night by cool air. In temperate climates, free night cooling via outdoor air is often sufficient, so no (or a small) chiller is required. In warmer climates, a chiller is needed and the cooled air is re-circulated through the slab at nights. The next morning, the slabs will be cool and ready to store the heat in the room. Most modern office buildings, universities and schools are so airtight and well-insulated that cooling is often required during daytime even when it is very cold outside. Conventional AC systems remove the daytime excess heat with the exhaust air. During nights, heating is required to compensate for heat losses through the envelope. With TermoDeck, the heat gains in the room are stored in the hollow core slabs during daytime and this stored energy is released during the night in heating mode to keep the building warm so wasteful cooling and heating in the same 24-hour period can be avoided. For very cold night and for weekends, additional heating might be necessary.

The TermoDeck system operates most efficiently in buildings sporting good quality of the building envelope. New commercial and institutional buildings (offices, hotels, shopping malls, universities, etc) are most suitable for TermoDeck. There are also advantages using TermoDeck in residential multifamily buildings. However, the system cannot economically be integrated into existing buildings and is therefore a product for new construction. TermoDeck is a patented system, proven in all climatic conditions. Since the first building was erected in Stockholm, Sweden, in 1978, more than 430 buildings (offices, universities, schools, hotels, shopping centres, etc) incorporating TermoDeck have been completed throughout the world. TermoDeck projects exist in Northern Europe, in the Middle East, Canada, Southern Africa and Australia.

Benefits in Hot Climates

Experiences from several buildings in the Middle East show a 50% reduction in installed cooling load (capacity) required for the TermoDeck system compared to conventional air-conditioning systems. This results in reduced capital costs for air-conditioning by 15-30% due to much smaller dimensions on chillers, fans, etc. Also, the total energy costs will be 20-30% lower compared to an identically building due to lower energy consumption (the ambient air is cooler at night, which increases the efficiency of the chiller & night cooling can be used during parts of the year). The reduced installed power means lower electrical connection and distribution charges

Benefits in Cold and Temperate Climates

In milder climates, such as Sweden and UK, the slabs are primarily cooled during night with the outdoor air. Small chillers, if any, are needed. Heating will also be reduced since the heat accumulated in the slabs during daytime can be used to warm the building during cold nights. The energy savings will therefore be up to 20 %.

Discussion of core principles, advantages and limitations - TermoDeck

The TermoDeck system uses the hollow cores of precast concrete slabs as air pathways, thereby combining ventilation, heating, cooling, and thermal storage in one integrated building concept. Its main advantage lies in the direct coupling between air distribution and building mass: internal and solar gains can be stored during the day and removed or reused during the night. This makes the system particularly suitable for offices, schools, universities, and other buildings with predictable occupancy patterns, significant internal loads, and a strong cooling demand.

The TermoDeck system performs best in combination with high-performance envelopes and early integration into the architectural and HVAC design process. Suspended ceilings, floor coverings, or later fit-out decisions may reduce the effective heat exchange between the slab and the room. Compared with CEILTEC, TermoDeck offers a deeper integration of ventilation and storage, but this also makes it more system-dependent.

2.3.3 CEPA prefabricated energy façade elements for new construction and refurbishment

Link to company and product: https://www.cepa-solutions.com/

The CEPA® ENERGY FACADE combines the functions of insulation, heating, cooling, and storage in a single system. It utilizes the surface potential of building envelopes by managing and distributing energy through the exterior wall. Due to the type of installation, or rather, the external attachment of the façade, CEPA® as an integrated concept is particularly relevant for properties undergoing renovation. The large heat transfer surfaces and storage capacities created by a building's exterior envelope enable the energy flow to be converted to low temperatures, thus enabling the use of renewable energies much more efficiently.

CEPA®'s innovative solution enables low-temperature energy distribution across the exterior shell of existing buildings. This makes the facade the perfect ecological choice for buildings undergoing renovation. Due to the external piping, the method is minimally invasive, eliminating the need for relocation of the occupants during the renovation. The technology functions like an energy-saving underfloor heating system with heating and cooling functions, promoting comfort 365 days a year. The existing masonry becomes an energy storage unit.

Figure 25: CEPA® System Demonstrator on the crane with visible thermal layer (left) and during mounting on the existing wall (right). Source: Climate and Energy Fund, Krobath

CEPA® essentially works like a low-temperature underfloor heating system installed on the exterior wall of a building (compare Figure 25). It performs heating and cooling, as well as insulation and storage functions, all in one. The entire system is completely independent of both the facade design and the energy source. Because the piping is installed from the outside, the method is minimally invasive, and residents or users do not have to move out during the renovation.

As CEPA® partners, tradespeople can receive training from us and thereby expand the skills of their employees. This strengthens their market positioning and generates demand. CEPA® therefore pays for itself in multiple ways. CEPA® leads to lower energy consumption. This benefits both the residents and the environment, while simultaneously maintaining or increasing the value of the property and improving rental potential. With the CEPA® façade, the pipes are installed from the outside. This requires minimal intervention in the existing building structure, allowing the property users to remain in the building during the renovation. The CEPA® concept relies on existing building fabric, some of which was constructed decades ago, i.e., on already bound CO2, which is retained through the renovation and, consequently, the continued use of the property. The conversion to low-temperature operation by utilizing the large heat storage capacities on the façade represents an enormous gain in terms of energy savings, especially in typical old buildings with high ceilings.

System description

Energy optimization and energy management via the exterior shell of buildings is, in essence, not only the most obvious, but above all the most logical answer to the need for ecological, sustainable construction. We're talking about a simple central energy distribution system that's open to all energy sources and product manufacturers. There are no limits to the building's design freedom – whether it's a green facade, a wood, stone, or photovoltaic facade: In any case, the implementation of CEPA technology results in an "energy facade." Such a facade can be implemented as a ventilated facade (VHF) or as an external thermal insulation composite system (ETICS).

The system's efficiency has been validated and verified through the countless studies, test results, and sample facades that Towern3000 and its technology partner AEE INTEC, the Institute for Sustainable Technologies, have compiled over years of research. The technology is there, as are a multitude of buildings. The intelligent energy façade is not only interesting for new construction, but most importantly brings ecological benefits to the activation of existing buildings, i.e., renovations.

Innovation potential

The enormous advantage of CEPA technology is that it operates completely independently of the type of energy source and the supply system (electricity, gas, photovoltaics, geothermal energy, pellet central heating system, etc.). Any existing system can be retrofitted and combined with CEPA (see Figure 26).

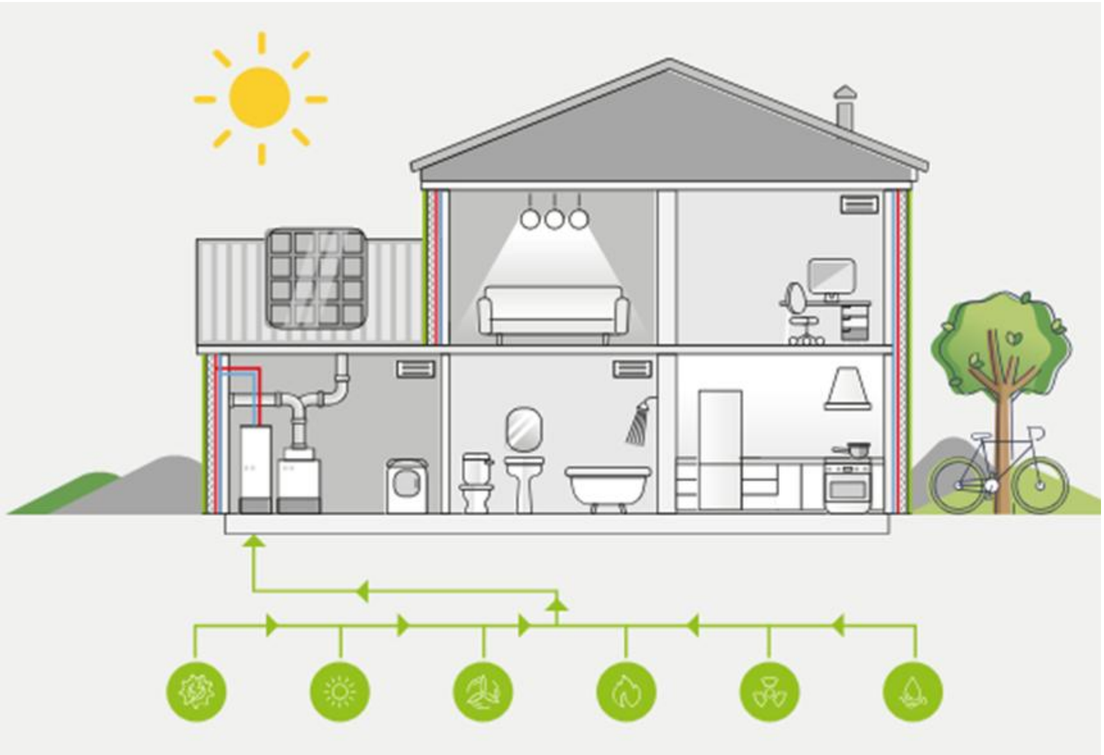


Figure 26: Schematic of CEPA deployment for a single-family house, including different options for energy supply technologies. Source: Towern3000

This system independence also means absolute flexibility regarding any future changes, as retrofitting can be carried out easily and economically at any time if necessary. The exterior walls of a building, whether residential, office, commercial, school, etc., can be centrally equipped with CEPA in cooling or heating mode for energy efficiency and low-temperature operation. Retrofitting is possible even while the building is occupied and can be implemented with various mounting technologies (compare Figure 27).

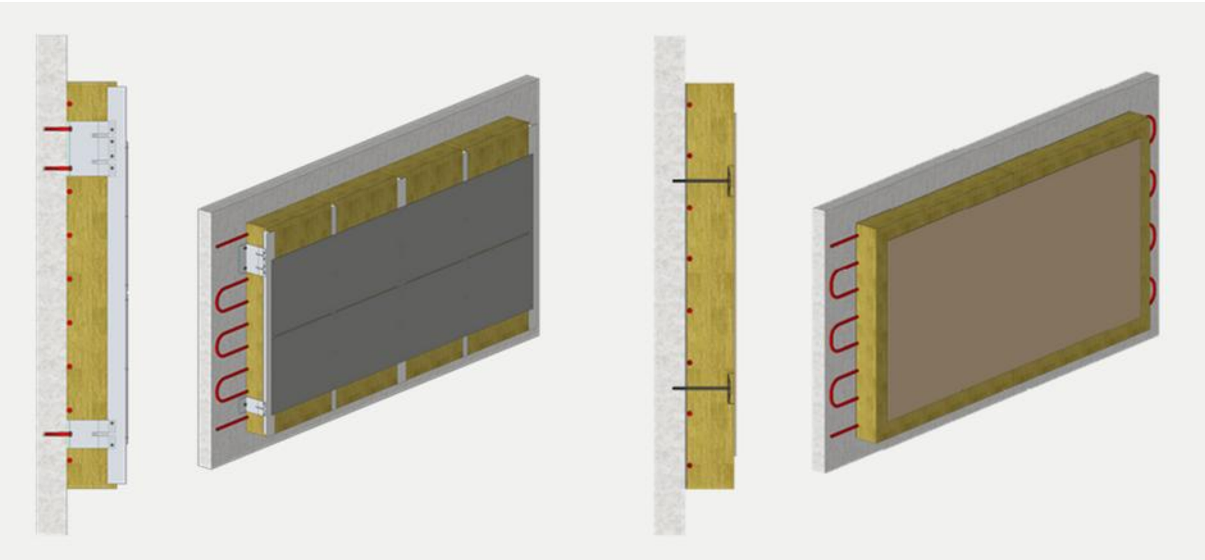


Figure 27: CEPA can be perfectly integrated into ventilated facade systems (VHF) and ETICS (external thermal insulation systems). Source: Towern3000

An added value for building owners is that the facade also simultaneously covers the air conditioning solution, enabling heating and/or cooling via the exterior wall – the future energy storage of a building. The Austrian VHF trade association has already recognized this possibility. Thus, building design, independent of CEPA facade cladding and, for example, metal elements, can now indirectly make a significant contribution to the storage and distribution of peak loads. The possibility of optimally enveloping the building with thermal insulation as part of this technological advancement gives the thermal insulation itself an additional function. The structure remains the same, but the ventilated facade (VHF) gains enormous added value.

Discussion of core principles, advantages and limitations - CEPA

The CEPA energy façade is based on the idea of converting the exterior wall into an active low-temperature heating, cooling, and storage surface. Its strongest advantage is the suitability for renovation: the system can be installed from the outside, can use the existing building fabric as thermal mass, and enables a transition to low-temperature operation without major intervention inside the apartments. This is especially relevant for occupied buildings, where replacing internal distribution systems or radiators would be costly and disruptive.

From a critical perspective, CEPA's broad system openness is both an advantage and a challenge. The possibility of combining the façade with many energy sources and façade designs increases applicability, but it also means that performance will strongly depend on building-specific boundary conditions, hydraulic design, insulation quality, control strategy, and installation quality. Compared with the IBRI & HOB slot system, CEPA appears broader and more product-oriented, while the IBRI & HOB approach is more directly tied to a specific measured renovation case.

2.3.4 IBRI & HOB Slot system for refurbishment

Link to company and product: https://www.sozialbau.at/

Conversions from fossil fuels to heat pumps in existing heating systems always raise the question of whether the existing radiators can still be used with reduced heating circuit temperatures and thus reduced heat output.

In a residential complex owned by the Viennese non-profit developer SOZIALBAU with 20 apartments, a "facade-integrated component activation" system is currently being installed as part of a heating conversion from an oil-fired boiler to a central brine-water heat pump, coupled with a thermal renovation of the building envelope. Water-carrying pipes are milled into the existing wall on the outside and insulated with the new full thermal insulation. This measure absorbs heat losses through the facade and also provides basic heating output to the room. This relieves the load on the existing radiators, allowing them to remain in operation even with a significantly reduced flow temperature.

Construction Work on Existing Buildings

Construction work on the building is taking place while the building is occupied (compare Figure 28) via milling of pipe grooves in the existing walls. No interventions in the apartments themselves are required. The project is currently underway. The activated facade has already been completed, and the heat pump is about to be commissioned.

Figure 28: Installation of the heating pipes in the exterior wall. Source: Michael Müller, Hausservice Objektbewirtschaftungs GmbH

The facade-integrated component activation project is being scientifically supported by a consortium consisting of the Institute of Building Research, the Vienna non-profit housing cooperative "FAMILIE" of the SOZIALBAUVerbund, the University of Natural Resources and Life Sciences - Institute of Process and Energy Engineering, and Vasko+Partner Engineers, and is receiving research funding from the City of the Future program, 8th call for proposals.

Planning Objectives

The overarching planning objective is to reduce the maximum flow temperature for space heating from the previous 75°C to 40°C while simultaneously preserving the existing radiators. This change entails a reduction in the heat output of the panel radiators to 25 percent, a reduction that, even with the thermal renovation, would have required the replacement of the existing radiators and the renewal of the connecting pipes in numerous rooms. The thermal activation of the exterior wall is intended to provide a baseline heating load, allowing the radiators to remain in place. In addition, the exterior wall activation is intended to dissipate heat from the rooms in summer, thus providing cooling.

Energy-Relevant Key Data

The residential complex was built in 1967. The living space is 1080 m². The building is constructed of reinforced concrete with load-bearing facades made of encased concrete blocks. The thermal transmittance of the existing exterior wall is approximately 0.9 W/m²K. The new thermal transmittance after thermal insulation with 16 cm of rock wool will be approximately 0.20 W/m²K. The heat demand for space heating was 80 kWh/(m²BGFa) before the renovation and 32 kWh/(m²BGFa) after the thermal renovation. The building's maximum area-related heating output was 80 W/m²NF before the renovation, and will be 30 W/m²NF after the thermal renovation.

Operation of the Facade-Integrated Component

The piping for the facade-integrated component activation consists of PEXX pipes with an outer diameter of 2.5 cm and a pipe spacing of 30 cm, and was laid in heating circuits ranging in length from 60 to 135 m. The pipes were installed in milled grooves, which were filled with filler and insulated with 16 cm of EPS. Prior to construction, both static two-dimensional heat flow analyses and dynamic simulations with one-dimensional equivalent models of the heat flow in the facade were conducted. The construction and commissioning will be accompanied by long-term monitoring (2 years) of the energy flows, including numerous temperature measuring points in the facade.

Current calculations, assuming a flow temperature of 40°C and an outside temperature of -10°C, promise heat flux densities in the rooms adjacent to the facade of approximately 16 watts per square meter of activated facade area, or, based on a room with a depth of 5 meters, approximately 6 watts per square meter of usable space. Regarding the effect on the room, the transmission heat flux that would have occurred without wall activation is also absorbed. In the case of an insulated wall with a U-value of approximately 0.2 W/m² at an inside temperature of 20°C and an outside temperature of -10°C, this amounts to approximately 6 watts per square meter of facade area, or approximately 2 watts per square meter of usable space. Therefore, external wall activation can be expected to contribute approximately 9 W/m² to the maximum room heating output, or approximately one-quarter of the total room heating load after renovation.

Figure 29: Heating pipes in the exterior wall, before the thermal insulation is installed. Source: IBR&I – Institute of Building Research & Innovation

These dimensions apply analogously to cooling. The system is designed for both free cooling and active cooling. The optimal operating modes will be determined during operation based on the interaction between the power consumption of the circulation pumps and the power consumption of the chiller. The system will begin cooling operation in August. The measurement results and experiences from the first year of operation are being continuously evaluated and will serve both to optimise the operation of the system in question and to derive insights for further renovations with external wall activation, which are planned as part of the ongoing accompanying research project.

Discussion of core principles, advantages and limitations – IBRI & HOB Slot System

The IBRI & HOB slot system addresses a very practical renovation problem: how existing radiator systems can remain in operation when a building is converted from high-temperature fossil heating to a low-temperature heat pump system. The façade-integrated activation provides a base heating load through the external wall and thereby reduces the required output of the existing radiators. This makes the concept particularly valuable for multi-family housing, where interventions inside occupied apartments are difficult, expensive, and socially sensitive.

The system is more modest in its claims than some of the broader façade concepts, but this is also one of its strengths. The expected heating contribution is clearly limited and is described as a partial support to the overall room heating load rather than a complete replacement of all internal heat emitters. This distinguishes it from systems such as CEPA or AktivDHKS, which aim at a more comprehensive façade-based energy concept. The main open questions concern long-term operation, cooling performance, hydraulic optimization, and the balance between pump electricity, heat pump efficiency, and useful heat transfer. The planned monitoring is therefore essential for assessing whether the calculated performance can be achieved under real operating conditions. Additionally, improvement of the slotting process is necessary to reduce manual labor, cost and occupant disturbance during the refurbishment.

2.4 Research level, innovative TABS energy storage system designs for new construction and refurbishment

The following descriptions of research efforts are based primarily on information provided by the respective academic partners. To preserve technical accuracy and reflect the different development approaches, the original structures and terminology were retained to a large extent. Consequently, the level of detail and emphasis differs between the presented systems. To ensure a scientific approach and allowing for comparison between the systems, each section ends with a discussion of the projects' core principles, advantages and disadvantages.

Thermally activated building systems that integrate hydronic piping into building mass (floors, ceilings, walls) to heat, cool and store energy in the structure — have seen renewed research interest as a low-exergy, high-inertia route to building decarbonisation, demand-side flexibility and renewable integration. Recent work emphasizes three broad directions:

- coupling TABS with thermal storage and phase-change materials to increase storage density and shift loads;
- treating the building envelope — and even bricks or façade elements — as active, controllable "skins" that combine thermal activation with sensing and control;
- pairing TABS with power-system strategies (e.g., surplus wind electricity) and district-scale low-temperature networks to exploit temporal matches between renewable supply and building thermal demand.

Reviews and recent experimental and demonstration studies synthesise these lines of work and demonstrate the energy-flexibility potential of TABS when combined with smart control and renewable sources. "PCM-boosted" TABS — i.e., embedding phase-change materials alongside or within the activated mass — has been investigated as a way to increase effective thermal capacity and to smooth peak temperatures, with both modelling and experimental studies showing promise and identifying control and integration challenges. Likewise, concepts that treat façades or modular envelope components as active thermal elements move TABS beyond slabs into walls and façades, enabling façade-level storage and local low-temperature heating/cooling.

Other innovations focus on operational strategies and system coupling. The "Wind Heating 2.0" concept demonstrates using surplus wind electricity to rapidly charge a building's thermal mass (or dedicated heat stores) so that buildings act as seasonal/long-term stores and demand-side assets for the grid. This is an approach that maps neatly onto TABS when building mass is the storage medium. Research prototypes and field tests have targeted predictive control, fast charging of activated slabs, and hybrid storage concepts. Furthermore, TABS research is expanding to district and system levels (AktivDHKS) and other district-coupling ideas, exploring how low-temperature district networks, heat pumps and activated building masses can be orchestrated for whole-neighbourhood flexibility and efficiency; recent studies quantify the electricity-market value of this flexibility. Finally, a growing body of experimental and modelling work covers novel construction forms (lightweight and brick-based activated elements), productised solutions and proprietary projects (for example, LEXU+, fronTherm, and others may represent either commercial developments or funded research prototypes).

2.4.1 Smart-Skin Salzburg Multifunctional Façade

The goal of the research project "Smart-Skin Salzburg Multifunctional Facade" was to develop a prototype for the facade of the building at Salzachtalstraße 32-34 in Hallein, see Figure 30. Together with the cooperation partners, the innovative facade was designed, planned, and implemented under scientific supervision. The prototype combines the functions of heating, insulation, and sound insulation in a single element.

Figure 30: Southwest view of the prototype at Salzachtalstraße 32/34, Hallein. Source: FH Salzburg

The research project "Smart Skin – Salzburg Multifunctional Facade" examined the interaction of wood and concrete in potential applications of building component activation. In this project, wood assumes the structural functions, while concrete serves solely the function of heat distribution and storage. This study laid the initial foundations for this combination of building materials, and in parallel, a first application in the thermal renovation of existing buildings was implemented. Together with the cooperation partners, a novel facade system was designed, planned, and implemented under scientific supervision. The developed prototype combines the functions of heating, insulation, and sound insulation in a single element and can be retrofitted into buildings, making the facade system suitable for building renovations, as depicted in Figure 31.

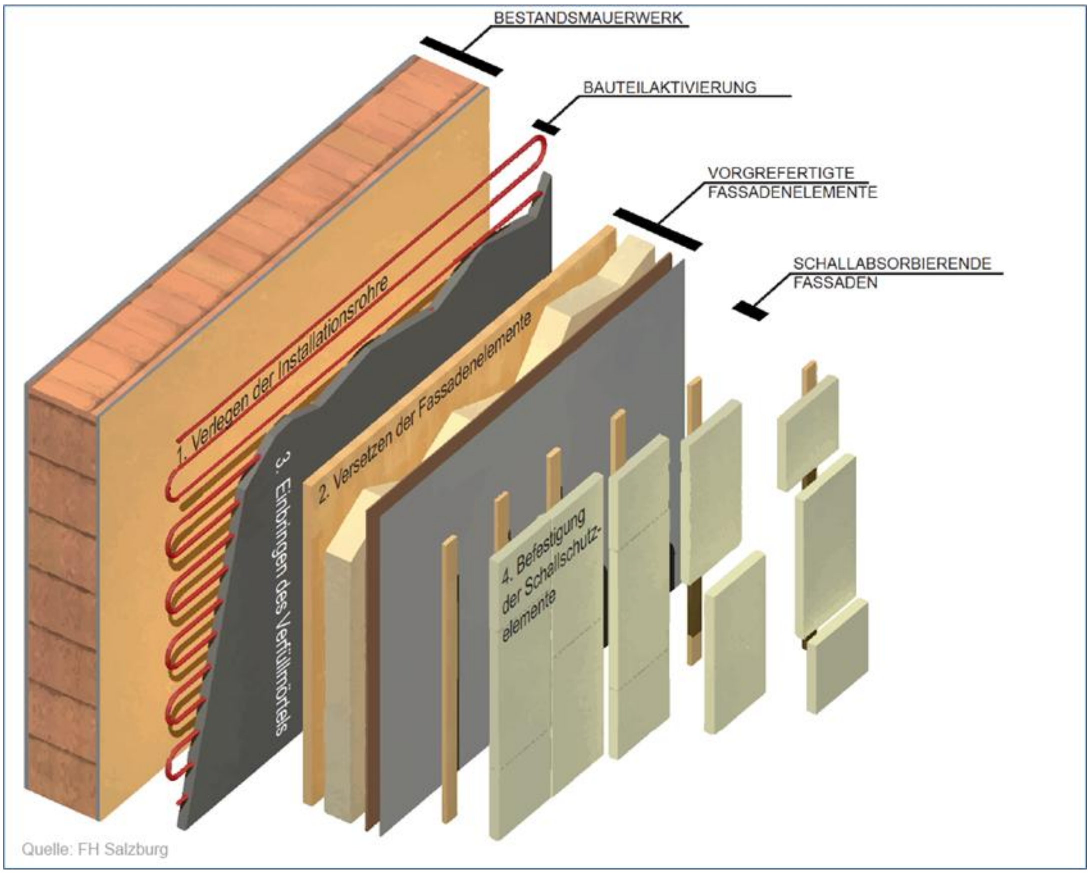


Figure 31: Developed component structure of the Smart Skin system. Source: FH Salzburg

The employees of the Salzburg University of Applied Sciences GmbH mentioned in this project were involved in all project activities and decisions during the development process, provided scientific support for the work, and were supported by the participating companies. Following the development of the facade system, a prototype was tested under real-world conditions on an existing 23.39 m² exterior wall of a residential building at Salzachtalstraße 3234 in 5400 Hallein. The prefabricated wooden components, including pipes and connections for thermal activation, were transported to the construction site and installed after the necessary work for installing the measuring sensors. Following the assembly of the elements and the installation of the measuring sensors, the cavity between the facade elements and the existing wall, in which the heating pipes were located, was backfilled with concrete. The pipes were then connected to the planned heating system, the thermal insulation was installed, and the facade cladding made of noise protection elements was installed.

Research Methodology

The properties and behaviour of the prototype were investigated under real-world conditions over a period of two months. Based on the recorded data, numerical simulations were conducted to optimize the facade system and the heating system.

The facade system underwent an acoustic analysis at the Research Department of Building Physics and Sound Insulation at the Vienna University of Technology. The sound absorption properties of the facade system were optimized by varying the layer structure, both in terms of layer thickness and by using different materials for the facade cladding. Existing noise protection products and facade cladding were mounted on different base structures and tested in a reverberation chamber. The results of the sound absorption measurements were compared to determine the optimal combination of base structure and cladding.

A wood technology evaluation of the developed facade prototype, in terms of the interaction between wood and concrete, was carried out after the data collection was completed. Before dismantling the prototype, the outermost facade layer with the noise protection element, the rear ventilation, and the insulation layer were removed. Subsequently, a sample was taken from the load-bearing wood element in contact with the backfill concrete. The sample was taken across the entire wood cross-section of the four-layer element. The wood moisture content and moisture distribution, as well as the pH value change, were determined to enable a risk assessment for the use of wood in this moisture-sensitive area – high moisture exposure during concrete pouring. Finally, a coating system for the selected facade prototype was tested for its suitability. This was done primarily with regard to the possibility of façade design in order to take aesthetic requirements into account during implementation.

Based on the results of this project and the experience gained from prototype development, the developed facade system with combined wood and concrete component activation was implemented in a thermal building renovation of a four-story residential building at Salzachtalstraße 32-34 in 5400 Hallein.

Thermal and Hygrothermal Performance

The model demonstrated sufficient thermal functionality. During the cold period (25.02–03.03.2018), with outdoor temperatures below the design value of –13.2 °C, the system maintained comfortable indoor conditions, confirming the effectiveness of the outdoor-temperature-based control. Heat transfer from the pipes through the masonry was effective due to the thermal conductivity of the mortar bond. Heat losses to the outside can be minimized by adequate insulation. With its low supply temperatures, the system is well suited for heat pumps.

The measured temperature difference between supply and return was very low (0.45 K on average) compared to floor heating systems (4–5 K). The mass flow was too high (0.69 m/s) and should be reduced below 0.50 m/s. Future optimization should aim at increasing the temperature spread and reducing flow rates, e.g., by reducing pipe spacing or slightly raising supply temperature.

A validated simulation model was developed using IDA-ICE, while WUFI Pro simulations predicted a slower drying process than measured, likely due to unmodeled air pockets in cross-laminated timber. The validation thus errs on the safe side. The model is applied in the research project *Smart City Hallein* for further development of wall heating elements and control algorithms.

Acoustic Performance

Measurements showed that façade systems with high surface roughness achieved strong sound absorption. Best results were obtained with Velox “Rille” panels, where cavity depth influenced absorption peaks in the low-frequency range. Panels with smaller cavities performed better, shifting peaks to higher, more relevant frequencies. Timber elements also performed well, mainly due to Helmholtz resonance around 600 Hz and their large surface area.

“Bark” panels achieved lower absorption than “Rille.” Contrary to initial assumptions, Velox products did not behave like porous absorbers but rather like perforated plates. The most effective variant for reducing traffic noise was “Rille” with minimum cavity depth. If non-wood surfaces are preferred, timber element constructions are a good alternative.

Moisture and pH Tests

Moisture measurements showed that inner wood layers absorbed water during concrete casting but dried within one heating season, reaching safe levels against fungal decay. The alkaline environment of the concrete further reduced risk. The initially planned coating material for façade panels did not meet expectations and will not be pursued.

Discussion of core principles, advantages and limitations – Smart-Skin Salzburg

The Smart-Skin Salzburg project demonstrates a multifunctional façade approach in which wood provides the structural function, while concrete is used mainly for heat distribution and storage. The project is particularly interesting because it combines thermal activation with insulation and acoustic performance, thereby extending the discussion beyond energy efficiency alone. In comparison with purely concrete-based systems such as CEILTEC or LEXU+, the wood-concrete combination offers a potentially resource-efficient and lightweight solution for refurbishment applications.

The project also shows clearly why façade-integrated TABS concepts require interdisciplinary evaluation. Thermal functionality was demonstrated, but the measured very low temperature spread and high mass flow indicate that hydraulic optimization is still necessary. In addition, the interaction between wet concrete and timber introduces hygrothermal and material durability questions that do not occur in the same way in mineral façade systems. Compared with CEPA or AktivDHKS, Smart-Skin is less product-standardized, but it provides valuable research knowledge on multifunctionality, acoustic integration, and material compatibility in active façade systems.

2.4.2 PCM boosted - Wall modules equipped with phase change material

The application of phase change materials (PCMs) combined with radiant cooling systems (RCS) in the building sector has attracted enormous interest in recent years owing to its thermal storage potential and feasibility for small-scale energy renovation of existing buildings. Different configurations of these systems and their performance have been experimentally tested and academically investigated.

The present study experimentally tested a newly conceived PCM-equipped modular cooling wall and evaluated the impact on thermal performance under different feed water temperatures and PCM concentrations using numerical methods. From the parametric study, we found that the feed water temperature, in comparison to the PCM concentration, is the dominant factor influencing cooling power and the final radiant surface temperature of the wall module.

During charging, these two factors impact the time constant $\tau 95$ much more than $\tau 63$. Comparing the time required for the wall surface to reach the set reference temperature of 23 ◦C during discharging, it takes 2.37 times longer in the 30% PCM scenario than in the scenario without PCM when the feed water temperature is 5 ◦C. If the feed water temperature increases to 10 and 15 ◦C, this factor changes to 1.88 and 0.59, respectively. Taken together, the results were intended to optimize the design and definition of the PCM-RCS configuration for various usage scenarios.

Description of the tested wall module configuration

The combination of thermally activated building (TABS) systems and Phase Change Materials (PCM) can enhance a building's thermal storage capacity and improve energy flexibility for space heating and cooling. By comparison, conventional radiant floor systems have limited storage capacity, as the piping is not embedded deeply enough in the concrete core. In this context, the application of PCMs combined with plaster and an integrated pipe system presents a potential solution for retrofitting old buildings, enabling the implementation of a TABS similar system.

A parametric study conducted by the Institute of Structural Mechanics and Design at the Technical University of Darmstadt investigated the thermal performance of a PCM-equipped active cooling wall module designed for application in industrial halls, considering different PCM concentrations and feed water temperatures. This wall module has a sandwich construction and consists of five layers (Figure 32). The first two plaster layers, which contain PCM and capillary tubes, serve as active cooling components, while the remaining layers, two gypsum boards with glass wool in between, function as the supporting structure. To ensure sufficient mechanical strength for supporting the tube system within the PCM-plaster layers, the PCM-to-plaster ratios are set at 10% for the inner layer and 20% for the outer layer.

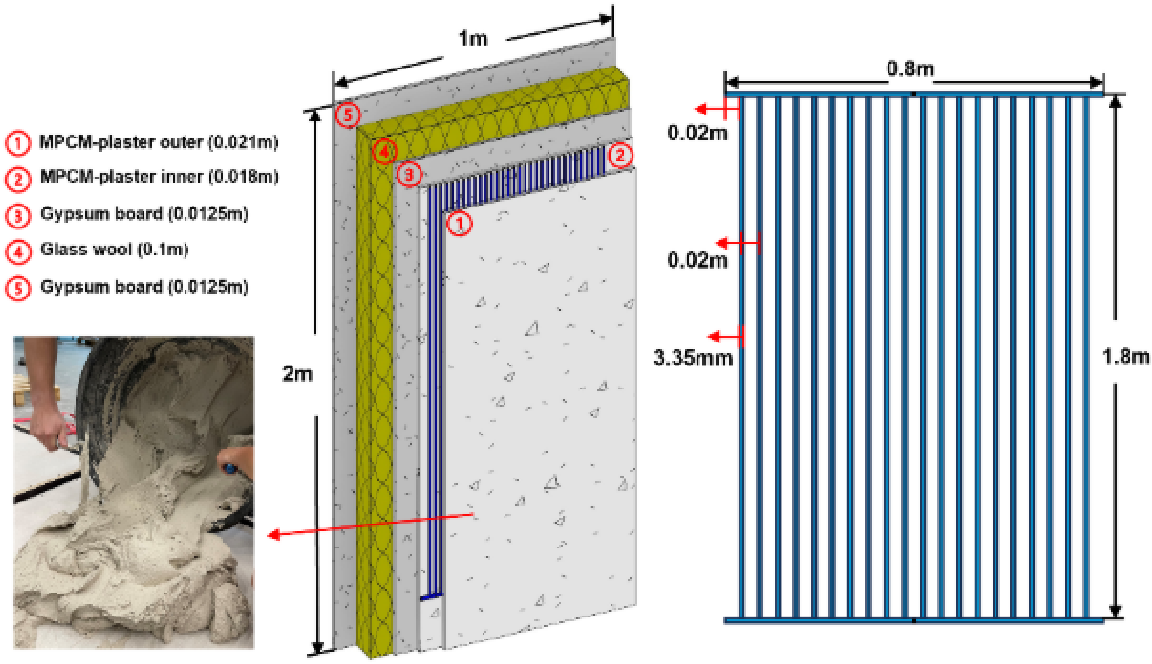


Figure 32: Wall module configuration. Source: (Y. Xue, 2024)

After constructing the wall module prototype, it was installed in a climate chamber to conduct experiments. Since the wall is designed for cooling purposes, water at 10°C was supplied continuously for 21 hours to fully cool (charge) the wall module. Then, the circulation was stopped, and the wall module was left at room temperature for 24 hours to observe the temperature changes on the surface and inside the wall (discharge). Based on experimental data, a validated numerical model is created. The simulation results indicate that the PCM amount and the feed water temperature mainly affect three key performance indicators of the wall: its cooling power, response speed, and discharge duration.

For the feed water temperatures of 5°C, 10°C, and 15°C, the wall with 30% PCM by mass showed surface temperatures 2 to 3 °C lower and cooling power approximately 24% higher compared to the wall without PCM. Using the time constants $\tau63$ and $\tau95$ to evaluate response speed (M. Krajčík, 2020), it was found that under the same water temperature, every 5% increase in PCM mass leads to an increase of approximately 3.6 minutes in $\tau63$ and 27.7 minutes in $\tau95$ (compare also Figure 33). Although applying PCM has a negative impact on the system's cooling power and response speed, it significantly increases the wall's discharge duration. Specifically, for the three water temperatures mentioned above, the time the wall surface to return to room temperature increases by an average of 105, 78, and 44 minutes, respectively, for every 5% increase in PCM mass fraction.

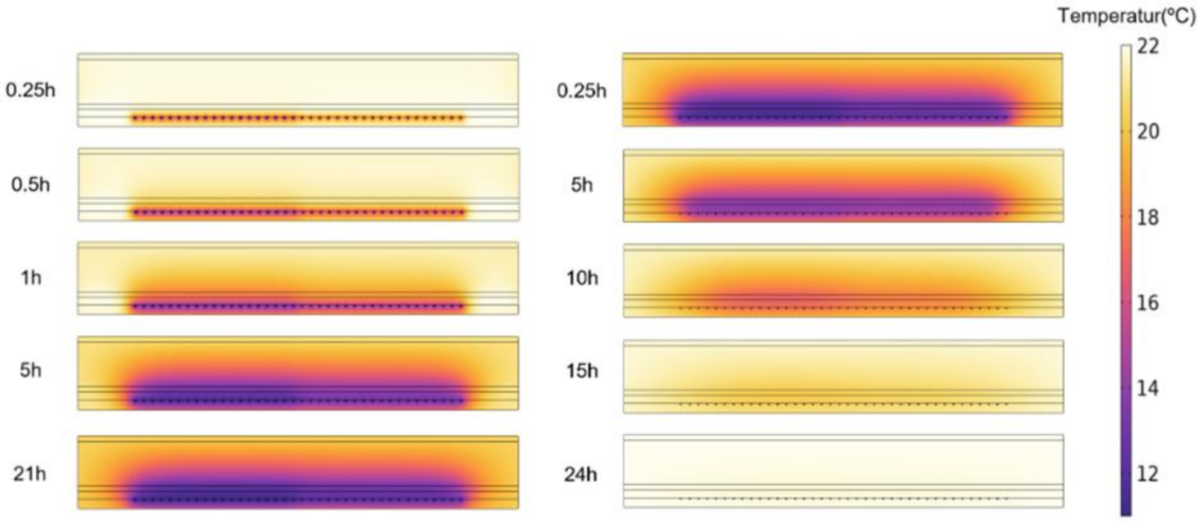


Figure 33: Temperature evolution and distribution inside the wall by charging (left) and discharging (right). Source: (Y. Xue, 2024)

According to a pre-study on used PCM, the temperature-dependent enthalpy distribution curves for the solidification and melting processes, determined through DSC are used for modelling. The major phase transitions for both processes occur between temperatures of 14 and 15 ◦C, with specific heat capacities of 62.04 and 40.56 kJ/kg, respectively, at the peak, see also Figure 34.

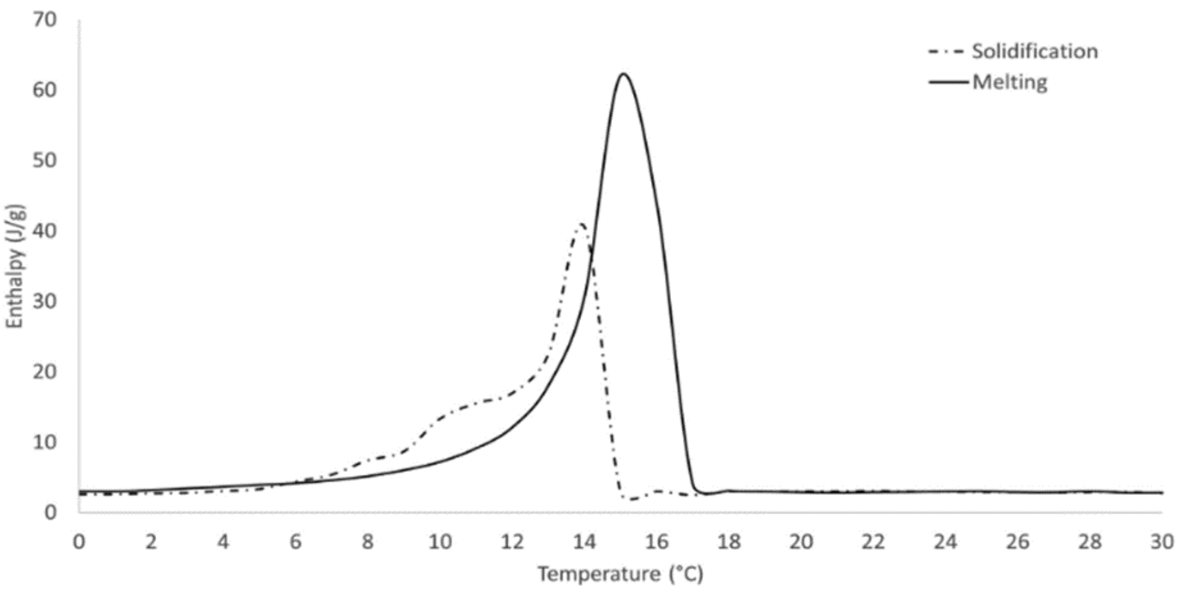


Figure 34: Temperature-dependent partial enthalpy distribution of the PCM. Source: (Y. Xue, 2024)

These results were adopted in the numerical model. The effective heat capacity of the composite is calculated and serves as a temperature-dependent function to define the active layer material. The melting and solidification curves are respectively utilized for charging and discharging process.

Conclusions

In this research, an innovative modular radiant wall with an equipped piping system and PCM-mixed plaster at the surface was developed for industrial use. The investigated active layer may also be implemented in the renovation of existing residential buildings for cooling purposes. The study discusses the impact of feed water temperature and PCM concentration on thermal response speed, cooling power, and energy flexibility. Therefore, a middle-scale experiment is conducted at the laboratory level to develop and validate a numerical model for further exploration. Throughout the experiment, temperature and humidity data from three different positions at various depths of the wall module in the cross-sectional direction is monitored. The numerical model validated with the experimental data contributes to conducting a parametric study for quantifying two impact factors on the thermal performance of the wall module.

The results provide a theoretical foundation for future designs of the wall modules and for distinguishing their intended purposes (e.g. industrial buildings, residential buildings). Future research should focus on an investigation of the wall module's long-term performance in practical applications and carry out operational optimizations. Secondly, when optimizing the configuration, consideration should be given to achieving a non-uniform distribution of PCM in the plaster by concentrating it around the capillary pipes, rather than aiming for an average distribution throughout, which can benefit and improve the use of PCM.

Discussion of core principles, advantages and limitations – PCM boosted wall modules

The PCM-boosted wall module follows a different strategy from most concrete- or masonry-based TABS systems: instead of primarily increasing sensible storage mass, it uses phase change material to increase the effective thermal storage capacity within a relatively thin modular wall element. This makes the concept especially relevant where conventional thermal mass is limited, such as lightweight construction, industrial halls, or retrofitted wall systems. The results indicate that PCM can extend discharge duration and stabilize surface temperatures, which supports cooling applications and short-term load shifting.

However, the study also shows that PCM integration is not automatically beneficial in all operating conditions. Feed water temperature appears to be more influential than PCM concentration, and increasing the PCM content can reduce response speed. This means that the PCM layer must be carefully matched to the intended operating temperature range and control strategy. Compared with CEILTEC or TermoDeck, the PCM module offers higher storage density in a compact element, but it may be less robust and more sensitive to control, material distribution, and phase-change temperature selection.

2.4.3 Wind Heating 2.0: A Sustainable Solution for Buildings

The research project Windheizung 2.0 (funded by the German Federal Ministry for Economic Affairs and Climate Action under the grand numbers 03EN6013 and 03ET1612) aims to store heat (among other storages) in a TABS (Thermally Activated Building System) to cover the buildings heat demand for 1-2 weeks. This bridging period results from the typical interval between two strong wind events (central Europe) with corresponding electricity overproduction.

Even in highly efficient buildings, a requirement of Wind Heating 2.0, a two week's energy demand requires TABS-storage temperatures too high to maintain thermal indoor comfort. The required temperature levels are about 45 °C. So, after a charging cycle the room would be too warm and later after the heat is dispersed to fast into the room, an auxiliary heating would be required to maintain minimum comfort temperature. To avoid this, the system's functions are disaggregated in the Wind Heating 2.0 storage TABS. The structurally required often heavy building material (e.g. concrete) forms the core-TABS that stores the heat and is insulated on both sides; in case of a ceiling topside the insulation typically is already provided by the impact sound insulation. Insulation levels must be designed to match the building's design heating load when the core is fully charged. So directly after charging the core-TABS the heat demand is coved by the passive discharge through the core's insulation. When the core is cooled down after a while the passive discharge heat flux is no longer sufficient to heat the building and the active discharge to a panel heating comes in operation.

New Ceilings and Walls for Wind Heating 2.0

A new type of TABS ceiling has been developed specifically for Wind Heating 2.0. These ceilings consist of a concrete core surrounded by insulation. The concrete core is designed to store heat, while the insulation helps to reduce heat losses. Heat is introduced into the ceiling through a water circuit and can be released through passive heat transfer or active discharge by circulation water between the core and the panel heating. This allows to store the heat in the building and release it as needed.

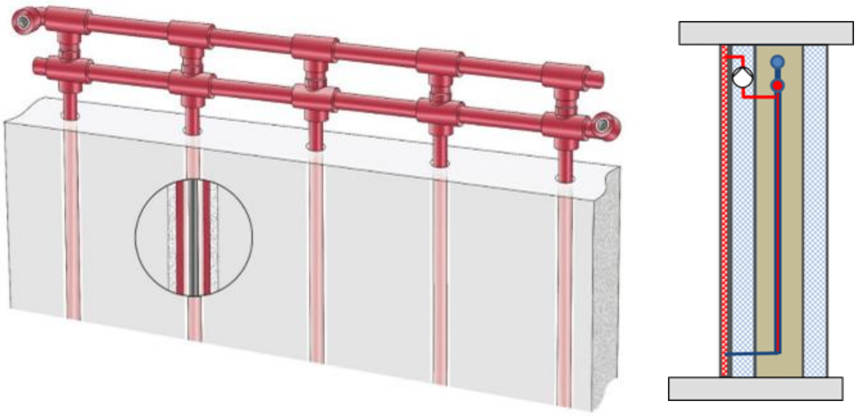


Figure 35: Left: System sketch of the KS-XK wall tempering system without the Wind Heating 2.0 typical insulation and without the outer pipe register for active heat discharge into the room air. Source: Bundesverband Kalksandsteinindustrie e.V. Right: System sketch of a Wind Heating 2.0 KS-XK wall tempering system. Source: Fraunhofer IBP

Also, a new type of TABS wall has also been developed for Wind Heating 2.0 (Figure 35). These walls consist of a lime sandstone core surrounded by insulation. The lime sandstone core is designed to store heat, while the insulation helps to reduce heat losses. The charging as well as the passive and active discharge follow the same principles as described above for the ceiling solution.

Refurbished Ceilings and Walls

It is also possible to retrofit existing ceilings and walls with TABS systems (Figure 36). This can be done to improve the energy efficiency of existing buildings together with their power grid flexibility. The TABS systems can be integrated into existing buildings, allowing for efficient heat storage and release. This can be a cost-effective way to improve the energy efficiency and grid flexibility of existing buildings.

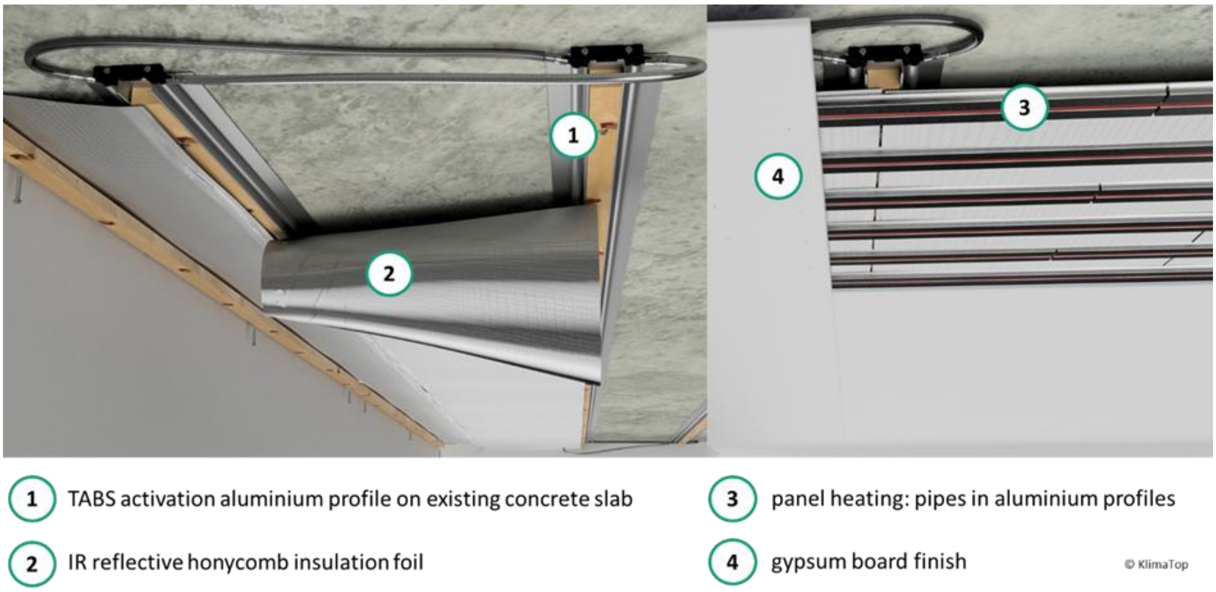


Figure 36: Schematic drawing of an existing ceiling, refurbished as thermal storage. Source: Klima-Top

It was shown that the retrofitted wall, although loaded with the same system as the retrofitted ceiling, can store about 10 % less heat. The charging capacities are also slightly reduced. This is due to the fact that the reinforced concrete of the ceiling with λ = 2.30 W/(mK) has a correspondingly higher thermal conductivity than the sand-lime brick used (ρ = 2 kg/dm^3) with λ = 1.10 W/(mK), which makes it more difficult to conduct heat into the wall component with the charging rates required for the Wind Heating 2.0 concept. The heat transfer rate and storage capacity vary, depending on the hydraulic charging system and the material of the TABS-core. The developed TABS storages show a charging rate of 260 – 450 W/m^2 during the first hour and an average of 130 - 260 W/m^2 over 9 hours. During these 9 hours 1.5 to 2.5 kWh/m^2 can be stored.

Grid-Friendliness

Wind Heating 2.0 primarily intends to improve grid stability by reducing the need for heating power in times with grid stress. The system can also improve market stability by storing heat during periods of low electricity prices. This can help to reduce the strain on the grid and improve overall energy efficiency. Different than e.g. conventional heat pump systems, Wind Heating 2.0 can stay off grid for many days to (1-2) weeks. To avoid overheating in buildings during warmer periods, a thermal demand prognosis is used to predict the building's heat demand for the upcoming 7.5 days (compare Figure 37). This prognosis is based on weather forecasts and historical consumption data. The prognosis is used to adjust the amount of heat stored in the TABS system, ensuring that the building remains at a comfortable temperature and no energy is lost by overheating. This can help to improve the energy efficiency of the building, while also reducing the need for heating.

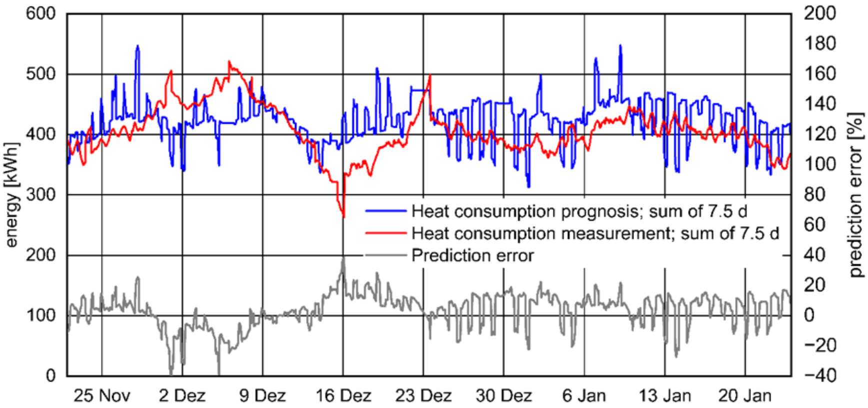


Figure 37: Thermal demand prognosis of one of the Wind Heating 2.0 demonstrators in the winter 2024/25. Source: Fraunhofer IBP

Conclusions

Wind Heating 2.0 offers several benefits, including, reduced strain on the grid / the demand of grid expansion, improved the fraction of renewables used for heating and domestic hot water and cost-effective way to improve energy efficiency of existing buildings. Wind Heating 2.0 is a promising solution for heating buildings and providing high flexibility. By utilizing wind energy excess production and storing as heat in buildings, the need for heating can be reduced during grid stress phases, minimizing the impact on the environment. The TABS system is a key component of Wind Heating 2.0, allowing for efficient heat storage and release. By improving grid stability and reducing the need for heating in times with limited energy production, Wind Heating 2.0 can help to create a more sustainable future for buildings. Future developments in Wind Heating 2.0 may include:

- Consideration of additional storage concepts, e.g. phase change material (PCM) storages
- Optimization of the control system for multifamily homes
- Consideration of Wind Heating 2.0 and similar grid friendly direct electric power-to-heat concepts in the EBPD and national building energy codes

Discussion of core principles, advantages and limitations – Wind Heating 2.0

Wind Heating 2.0 represents the most explicit grid-oriented storage concept among the described systems. Its core principle is not only to shift heating operation by several hours, but to store surplus wind electricity as heat over several days up to one or two weeks. This makes the concept fundamentally different from CEILTEC, TermoDeck, or PCM wall modules, which mainly address short-term thermal flexibility. By insulating the storage core and separating passive and active discharge, Wind Heating 2.0 directly addresses the comfort problem that would occur if large amounts of heat were stored in conventional exposed TABS.

The concept is technically ambitious and highly relevant from an energy-system perspective, but its applicability depends on very specific boundary conditions. The required storage temperatures, insulation levels, predictive control, and interaction with auxiliary heating systems make the design more complex than standard TABS operation. It is therefore less a universal building component and more a specialized flexibility concept for highly efficient buildings and electricity systems with significant renewable surplus. Compared with façade-based renovation systems, its strength lies in grid relief and long-duration storage, while its main challenge lies in comfort-safe control, construction integration, and economic justification.

2.4.4 AktivDHKS - Active Insulation Heating-Cooling System

The sustainable refurbishment of existing buildings is a key prerequisite for achieving climate neutrality in the energy sector. The Active Insulation Heating-Cooling System (AktivDHKS) introduces a new approach that combines insulation, heating, and cooling within a single solution (see Figure 38). Its goal is to accelerate renovation processes, reduce costs, and enable widespread adoption. By using renewable energy sources such as photovoltaics and geothermal systems, and by activating the thermal mass of the building envelope, AktivDHKS provides a stable and efficient supply of heating, cooling, and electricity.

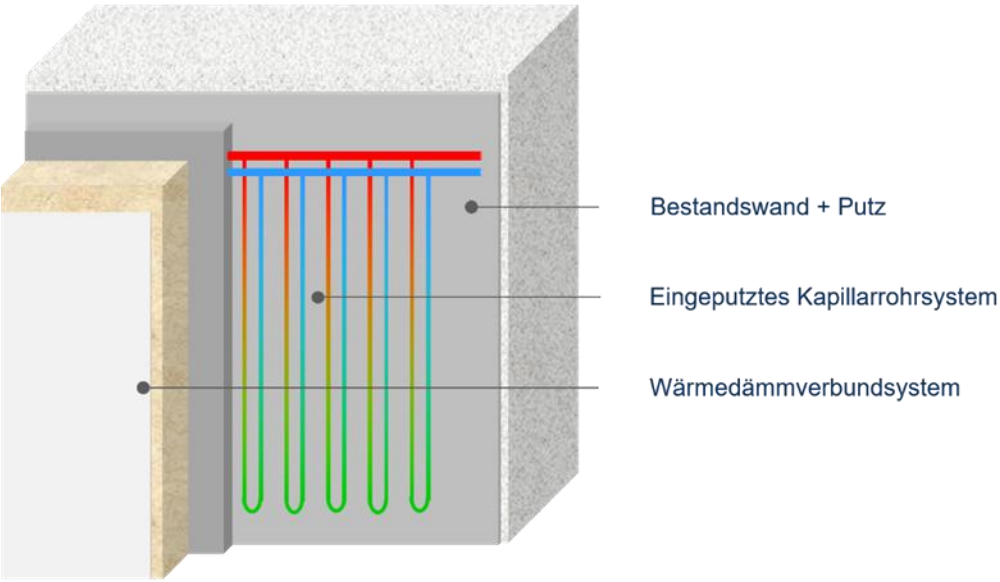


Figure 38: System design of AktivDHKS. Source: TU Dresden

System Concept and Technical Features

The AktivDHKS system is based on capillary tube mats mounted on external walls, covered with a recyclable insulation layer. A specially developed dowel-based fastening system allows mechanical attachment without adhesives and enables the installation of heavy façade elements such as photovoltaic panels or clinker cladding.

- **Minimal intervention:** Installation takes place outside, so tenants can remain in their homes.
- **Reuse of existing components:** Radiators and distribution pipes remain functional and operate at reduced flow temperatures supplied by heat pumps.
- **Passive summer cooling:** Heat can be transferred to the ground via heat exchangers, regenerating the geothermal system and reducing investment costs.
- **High efficiency:** Very low supply temperatures improve the coefficient of performance of heat pumps.
- **Durability:** Active façade temperature control prevents algae growth, condensation, frost damage, and mould, extending façade lifespan.

Contribution to Sustainable Building Operations

Unlike conventional insulation systems, AktivDHKS is recyclable and designed in line with circular economy principles. The system supports the decarbonization of heating and cooling by combining insulation with renewable energy use. At the same time, it minimizes environmental impacts by eliminating the need for chemical biocides.

On the user side, the system enhances indoor comfort, maintains affordability, and ensures resilience against climate change. Its flexibility to store and utilize self-generated energy supports grid stability while increasing overall energy efficiency.

Innovation Potential and market strategy

AktivDHKS demonstrates a high degree of innovation in several key areas:

1. **Acceleration of renovation rates** through a cost-efficient façade retrofit system.
2. **Integration of renewable energy** by combining insulation with active heating and cooling.
3. **Creation of new business models** for small and medium-sized enterprises in the construction and energy sectors.
4. **Sustainability through recyclability** of materials and reduced environmental impact.

Further innovations include passive cooling with simultaneous geothermal regeneration, advanced control strategies for renewable integration, and simulation-based planning tools. Together, these features create a scalable and cost-effective solution that can significantly transform the energy transition in the building sector.

The project partners play complementary roles in developing and commercializing AktivDHKS.

- **STO** evaluates economic feasibility, product portfolio fit, and coordinates the integration of renewable systems.
- **Clina Heiz- und Kühlelemente GmbH** expands its range of capillary tube systems for façade integration.
- **Fischer** develops and supplies the fastening technology, ensuring system stability and scalability.

The implementation strategy emphasizes **high prefabrication**, modular construction, and automated processes. This approach ensures cost efficiency, rapid installation, and smooth market entry.

Simulation and Digital Twin Approach

A core innovation is the use of digital twins and building simulation tools. Using **SIM-VICUS**, detailed models of existing and new buildings were developed in the Hosterwitz/Pillnitz district of Dresden, as seen in Figure 39. These models integrate material properties, user behaviour, climate data, and shading effects to generate **dynamic load curves** for heating, cooling, and electricity demand.

The digital twin enabled comparison of multiple refurbishment strategies under realistic conditions. This approach ensures optimal system sizing, avoids oversizing, and supports efficient integration of fluctuating renewable energy sources. It also allows precise evaluation of comfort levels, economic viability, and grid interaction, including **peak shaving** in times of PV oversupply.

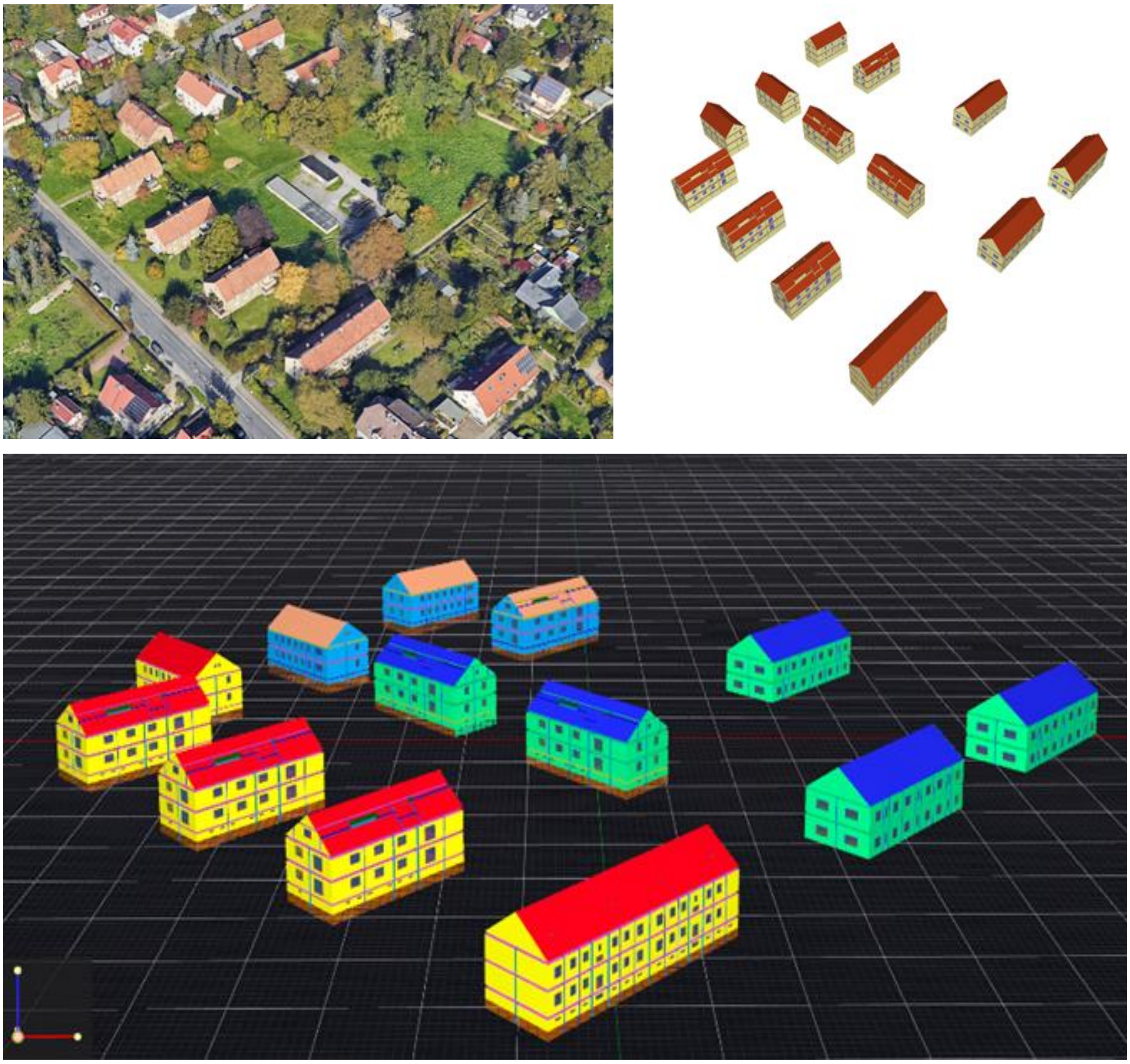


Figure 39: Aerial view of the Pillnitz/Hosterwitz district. Source: aerial view via Google Maps (top left). Simulation model of the Pillnitz/Hosterwitz district. Source: TU Dresden (top right and bottom).

Challenges and Opportunities

Refurbishment projects face technical, economic, and social barriers. Technically, it is difficult to combine energy efficiency improvements with the preservation of architectural or heritage values. Economically, high upfront costs and temporary rent reductions must be balanced against long-term benefits. Socially, tenant acceptance is critical, especially regarding affordability and comfort. Legal and regulatory aspects, such as building codes and heritage protection, add complexity. AktivDHKS addresses these challenges by offering a minimally invasive solution that allows residents to stay in place, reduces long-term costs, and improves comfort levels.

Case Study Results and conclusions

In the Dresden Hosterwitz/Pillnitz case study, AktivDHKS demonstrated its effectiveness:

- **High comfort standards** were achieved with low operating costs.
- **Renovation without displacement** of residents proved feasible.
- **Dynamic simulation results** confirmed potential for energy cost savings, improved system resilience, and significant reductions in peak loads.

Given that over 90% of Germany's building stock consists of existing buildings, energy-efficient refurbishment is essential. AktivDHKS offers a **replicable, scalable, and modular approach** that can be applied not only in suburban but also in dense urban contexts. AktivDHKS represents a model for sustainable urban development by combining technical innovation, environmental responsibility, and social acceptance. It reduces CO_2 emissions, increases energy efficiency, and enhances living comfort while ensuring recyclability and affordability. The integration of advanced digital planning tools further improves feasibility and market readiness. The Dresden case study shows that the energy transition in buildings is not only technically achievable but also economically attractive. AktivDHKS provides a blueprint for scaling up sustainable refurbishment strategies, demonstrating that with the right combination of technologies and planning methods, cities can become more livable, climate-neutral, and resilient for the future.

Discussion of core principles, advantages and limitations – AktivDHKS

AktivDHKS combines active façade insulation, low-temperature heating and cooling, renewable integration, and digital planning into a comprehensive refurbishment concept. Its main strength is the system-level approach: the façade is not treated only as an insulated boundary, but as an active interface between the building, renewable energy sources, and potentially the district energy system. This positions AktivDHKS close to CEPA and LEXU+, but with a stronger emphasis on recyclable construction, digital twins, simulation-based sizing, and urban scalability.

The broad scope of the concept is also its main challenge. Because AktivDHKS combines several functions and stakeholders, its performance depends on the quality of planning, installation, control, and long-term operation. The use of digital twins can reduce oversizing and improve system integration, but it also increases the need for reliable input data and planning expertise. Compared with the IBRI & HOB slot system, AktivDHKS appears more comprehensive and scalable, while the slot system is more focused and easier to evaluate in a specific building context. The concept is therefore promising, but its practical success will depend on whether the added complexity can be translated into robust and affordable refurbishment processes.

2.4.5 LEXU+ – Minimally Invasive Low-Exergy Renovation Concept

The LEXU+ research project builds upon the preceding projects LEXU and LEXU II. These previous projects focused on the development, study, and implementation of low-exergy external wall tempering (aWT). The aWT is a surface heating/cooling system applied between the existing wall and an external thermal insulation composite system (ETICS). The implementation of the aWT at a demonstration façade at Saarland University in Saarbrücken during LEXU II allowed for the identification of optimisation potentials for aWT applications. The aWT combines traditional trades of "heating" and "façade/ETICS/plaster," which can increase susceptibility to installation errors. Therefore, a higher degree of prefabrication was sought for the aWT to reduce errors and improve cost efficiency. From this realisation, the idea for the LEXU+ project emerged.

Key Statements

- The minimally invasive renovation concept LEXU+ combines heating system and façade renovation for existing uninsulated buildings.
- Initial ecological calculations indicate that the environmental impact of producing the sandwich façade elements is offset within just a few years thanks to the heating energy savings of the reference building analysed.
- The investment costs for the renovation are significantly higher compared to a conventional ETICS. However, this is balanced by an increase in property value, the integration of an innovative heating system, and the possibility of performing an energetic renovation — including heating system upgrade — while the building is occupied.

Project Overview

Building on insights from the previous projects, LEXU+ was developed by a consortium consisting of IZES gGmbH, RPTU Kaiserslautern-Landau, Schöck Bauteile GmbH, and KOMZET BAU BÜHL. LEXU+ focuses on the development of prefabricated sandwich façade elements for the renovation of existing buildings. These elements are capable of harvesting environmental energy, storing heat/cold, actively reducing heat losses through the renovated external wall, and additionally tempering the rooms. The component developed within LEXU+ is intended to fully perform static functions as well as energetic functions such as “energy harvesting and storage,” “tempering,” and “insulation.”

Within the project, IZES gGmbH is responsible for project coordination, thermal component development, and demand assessment. RPTU Kaiserslautern-Landau was responsible for structural component development and laboratory operation of a LEXU+ sandwich façade element on a demonstration building. Schöck Bauteile GmbH developed and applied thermal bridge-reduced connection technology based on glass fiber reinforced plastic (GFRP), while KOMZET BAU BÜHL managed the assembly and disassembly of a demonstration façade built from several parts, transfers the findings into vocational training, and conducts additional application tests. The project was supported by Otto Knecht GmbH, which manufactured the sandwich façade elements, and GEFGA Energiesystemen GmbH, which handled the design of the aWT and the absorber.

LEXU+ System Structure

The prefabricated sandwich façade element developed and studied in the LEXU+ project is a component consisting of two parallel reinforced concrete layers – the cover layer and the structural layer. These are coupled using evenly distributed rod-shaped connectors. Between these two layers lies an insulation layer, the thickness and material of which can be freely selected (see Figure 40).

The connection between the concrete layers is achieved using newly developed rod-shaped connectors made of glass-fiber-reinforced plastic (GFRP) with an undercut geometry. These connectors are suitable for use in sandwich façade elements with insulation thicknesses ranging from 60 mm to 160 mm. Both the cover layer and the structural layer can be equipped with capillary tube mats, allowing the cover layer to function as a solid mass absorber and the structural layer to serve as an external wall tempering system. A particularly slim sandwich design is targeted in order to save resources and minimise the resulting greenhouse gas emissions. Reducing the materials used also decreases weight, thereby simplifying construction processes and lowering manufacturing and installation costs. Due to the use of capillary tube mats, however, the reinforced concrete layers cannot be thinner than 70 mm in order to maintain a 20 mm concrete cover.

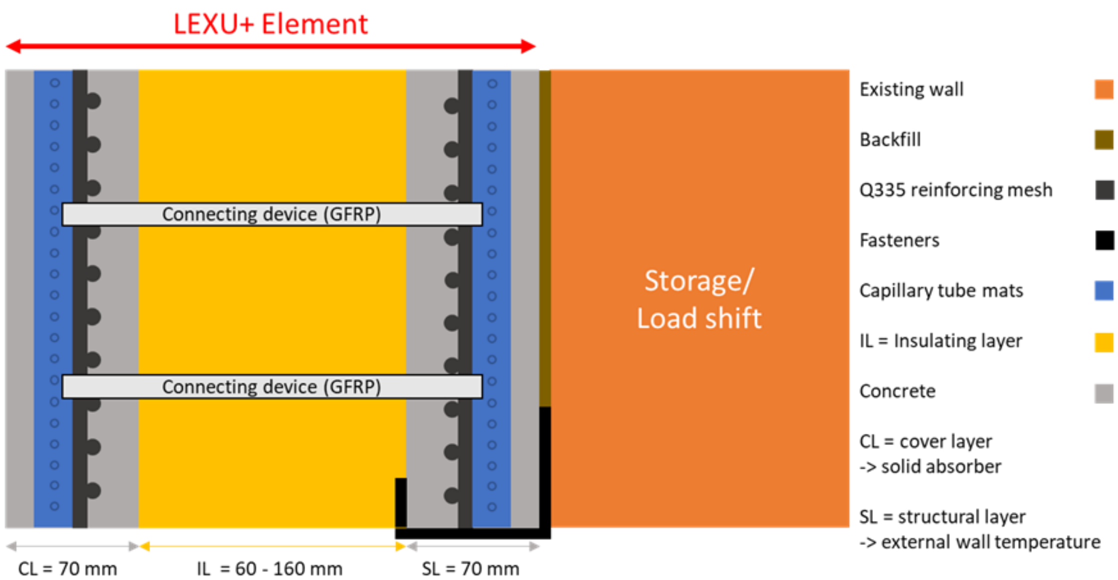


Figure 40: Cross-sectional view of the sandwich façade element implemented in LEXU+. (SL = structural layer & CL = cover layer). Source: Karsten Rauber, IZES gGmbH

When selecting the insulation material, building physics must take into account the maximum U-value of 0.24 W/(m²K) stipulated in the GEG 2020 for the initial construction, replacement, or renewal of exterior walls (Deutschland, 2024). In addition to physical, structural, and technical requirements, the system was developed so that it can be fully manufactured in a precast plant, delivered to the construction site, and installed as easily as possible. The sandwich façade element implemented in the project consists of two 70 mm reinforced concrete layers (strength class C 35/45), a core insulation of extruded polystyrene (XPS) with a thermal conductivity class (WLG) 035 and a thickness of 140 mm, as well as four glass-fiber-reinforced connectors per square meter of façade area. With this design, the sandwich façade element achieves a U-value of 0.236 W/(m²K). The connection of the developed sandwich façade elements to an existing wall is achieved using steel profiles. Standardised L-profiles with welded brackets are used for this purpose. The profiles are anchored to the existing wall with bonded anchor rods. Subsequently, the existing wall is covered with a vapor-permeable membrane, which has a negligible impact on thermal conductivity and facilitates later dismantling of the mounted sandwich façade elements that are coupled to the existing wall.

After installing the steel profiles and the vapor-permeable membrane, the structural layer of the prefabricated sandwich façade elements can be lifted into the steel profiles using a mobile crane. In a final step, the joint between the existing wall and the structural layer of the sandwich façade element is filled with flowable grouting mortar to ensure thermal coupling between the sandwich façade element and the existing wall. Figure 41 shows the described attachment process for a sandwich façade element with the maximum possible dimensions, which are limited by transportation constraints.

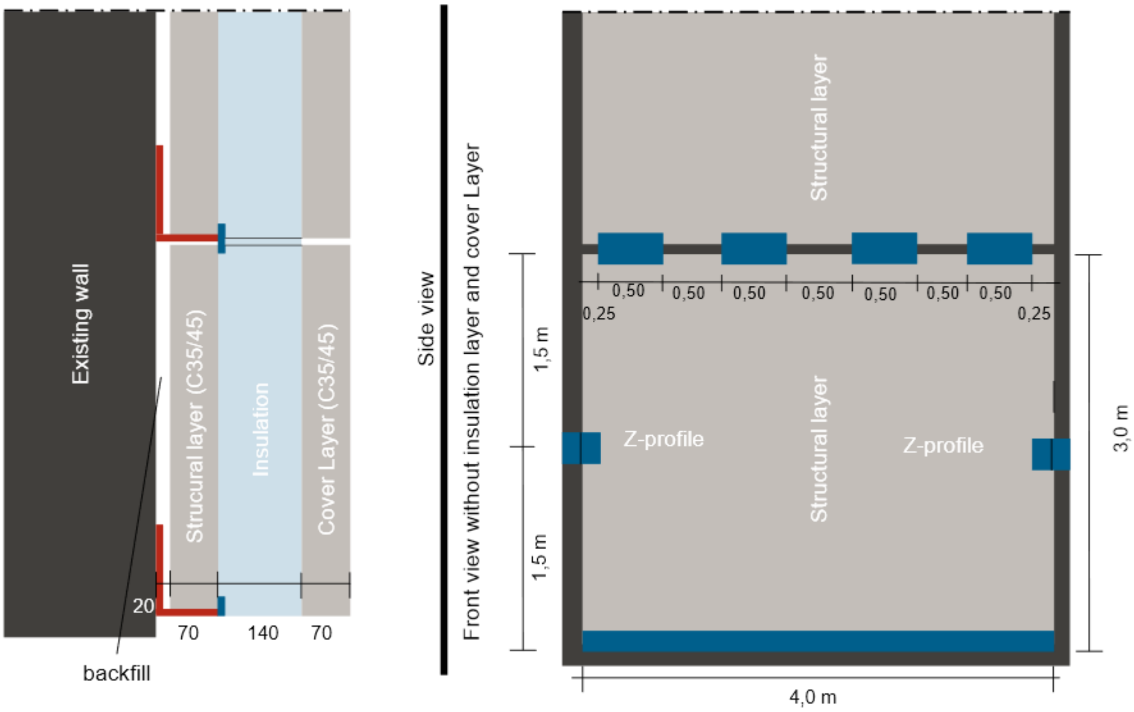


Figure 41: Installation of a sandwich façade element with maximum possible component dimensions. Source: René Basters & Matthias Pahn, RPTU

Thermal Analysis

The system structure of the developed sandwich façade element was examined within the project both through simulations and experimental testing. To illustrate the thermal function of a sandwich façade element in a simple scenario, Figure 42 shows the energy flows occurring in the element during heating operation. In the figure, the sandwich façade element is coupled with an existing wall. This coupling is represented by the thermal resistance R1, which consists of the existing wall and half of the structural layer. The thermal resistance RD consists of the insulation and half of both the structural and cover layers. The thermal resistance R2 corresponds to the remaining half of the cover layer.

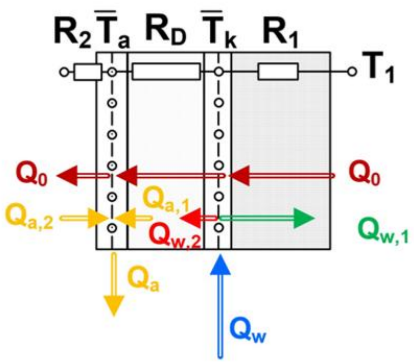


Figure 42: Energy flows within the developed sandwich façade element during heating operation. (T1 = room temperature, K = core temperature of the aWT, and a = core temperature of the absorber). Source: Christoph Schmidt, IZES gGmbH

The energy flow Q_0 shown in the figure represents the heat loss from the building interior through the wall when both the external wall tempering (aWT) and the absorber are switched off. When the aWT and absorber are in operation, new energy flows arise, as shown in Figure 42. Q_w is the energy supplied to the aWT, and Q_a is the energy extracted via the absorber. These two energy flows, along with energy flow Q_0, result in the energy balance during heating mode. Q_0 is completely eliminated, as the aWT maintains a higher temperature than the desired room temperature, preventing energy loss from the interior through the walls. $Q_{w,2}$ is the outward-directed energy flow from the aWT. The magnitudes of energy flows $Q_{w,1}$ and $Q_{w,2}$ depend on the ratio of the thermal resistances of $R_D + R_2$ to R_1. This ratio determines the theoretical efficiency of the aWT. Since the thermal resistance R_1 is much smaller than $R_D + R_2$, most energy is transported inward. The energy flows directed toward the absorber include both the external energy flow $Q_{a,2}$ and the outward-directed energy flow of the aWT $Q_{w,2}$, which subsequently becomes $Q_{a,1}$. The energy flow Q_a shown in Figure 42 serves as the source for a brine-water heat pump. This energy is then upgraded to a higher temperature level by the heat pump and supplied to the aWT (energy flow Q_w).

Structural and Constructional Analysis

The wall system, consisting of the multilayer sandwich façade elements, the existing wall, and the grouted connection joint, is subjected to a range of temporary and permanent forces. These are illustrated in Figure 43. In the final state, the following characteristic actions on the reinforced concrete layers must be considered:

- Self-weight g_k of the reinforced concrete layers according to DIN EN 1991-1-1 (V., Eurocode 1: Einwirkungen auf Tragwerke – Teil 1-1: Allgemeine Einwirkungen auf Tragwerke – Wichten, Eigengewicht und Nutzlasten im Hochbau, 2010)
- Wind loads w_k (pressure or suction) according to DIN EN 1991-1-4 (V., Eurocode 1: Einwirkungen auf Tragwerke – Teil 1-4: Allgemeine Einwirkungen – Windlasten, 2010)
- Temperature differences ΔT_k and $\Delta\vartheta_k$ according to DIBt 1995 (Utescher, 1973)
- Shrinkage of the reinforced concrete layers according to DIN EN 1992-1-1 (V., Eurocode 2: Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken – Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau, 2011)

Additionally, during the construction or installation phase, the fresh concrete pressure $\sigma_{h,k}$ according to DIN 18218 (V., Frischbetondruck auf lotrechte Schalungen, 2010) acts on both the structural layer and the existing wall due to the filling of the connection joint.

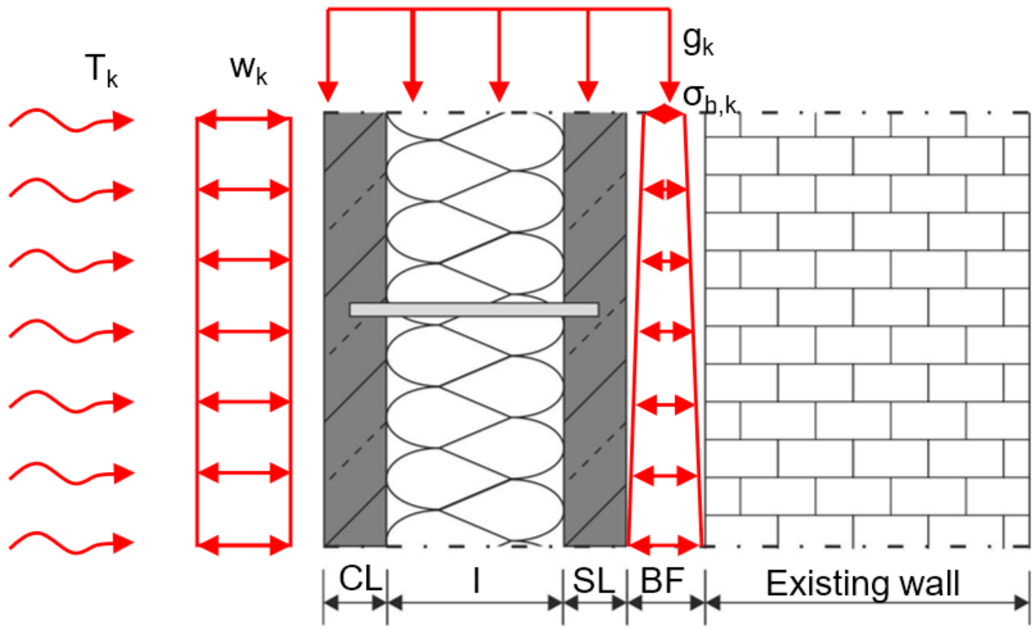


Figure 43: External actions on the sandwich façade element; CL: cover layer, I: insulation layer, SL: structural layer, BF: backfill. Source: René Basters & Matthias Pahn, RPTU

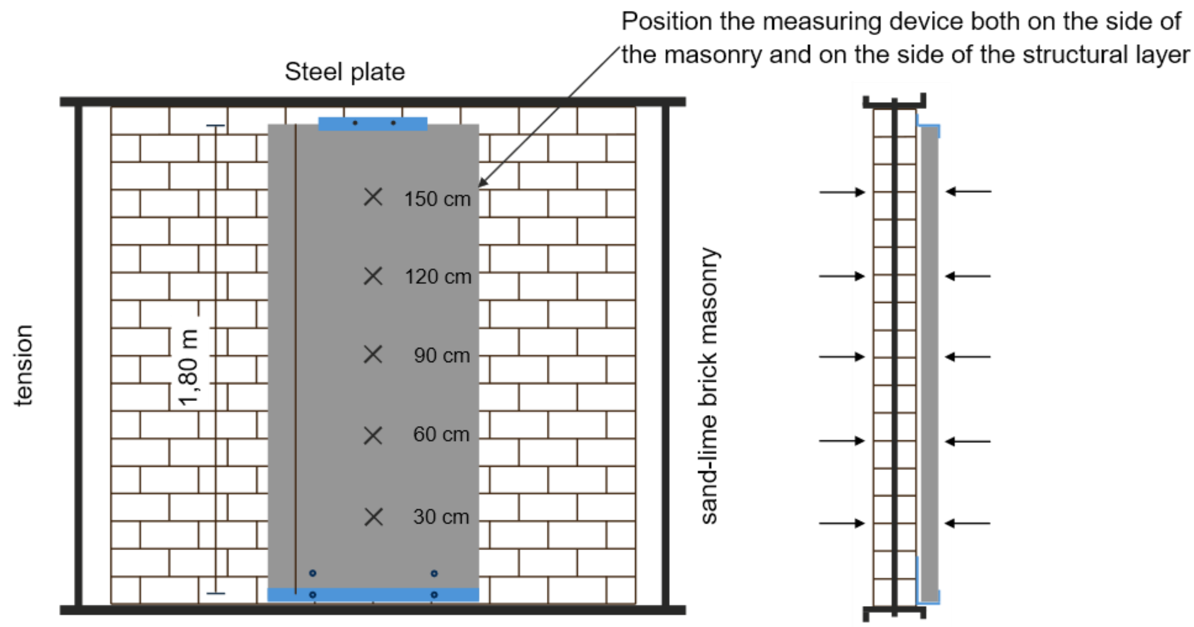


Figure 44: Test setup for the backfilling experiment. Source: René Basters & Matthias Pahn, RPTU

Because the grout, when installed in liquid form, exerts an almost hydrostatic pressure due to the fresh concrete, it is not possible to fill the entire connection joint behind the pre-installed walls in one step for structural reasons. In such a case, the shear capacity of the relatively thin structural layer would be exceeded at the lower plate bearing area, i.e., where the fresh concrete pressure is greatest. For this reason, the entire joint must be grouted in multiple stages, with each stage requiring the previously placed grout layer to set before proceeding.

To obtain detailed insights into the magnitude and especially the time development of the fresh concrete pressure between the structural layer and the existing wall, an appropriate component test with varying fill heights and mortar setting times was conducted.

The backfilling test between the sandwich façade element and the existing masonry was performed using the test setup shown in Figure 44. The calcium silicate brick masonry was prestressed using a steel frame to simulate the load from the stories above. The structural layer of the sandwich façade element was attached to the masonry using standardized steel profiles. Horizontal deformations of both the structural layer and the masonry were recorded at several measuring points with inductive displacement transducers throughout the experiment.

Manufacturing, Installation, and Dismantling of the Demonstration Façade

As part of the project, the investigated sandwich façade element was implemented in practice. For this purpose, a façade at KOMZET BAU in Bühl was selected, and the sandwich façade elements were planned using a 3D model. Figure 45 shows the initial condition on the left and the planned condition with the sandwich façade elements on the right.

Based on this 3D planning, the individual elements were detailed. The capillary tubes were hydraulically dimensioned, the number of connections was determined, and suitable fastening systems for the existing wall were selected. Subsequently, the capillary tube mats, including hydraulic connections, the insulation layer, and the structural connecting elements, were ordered or manufactured and delivered to the precast concrete plant Otto Knecht in Metzingen. There, the planned elements were produced as special components within one week (Figure 46).

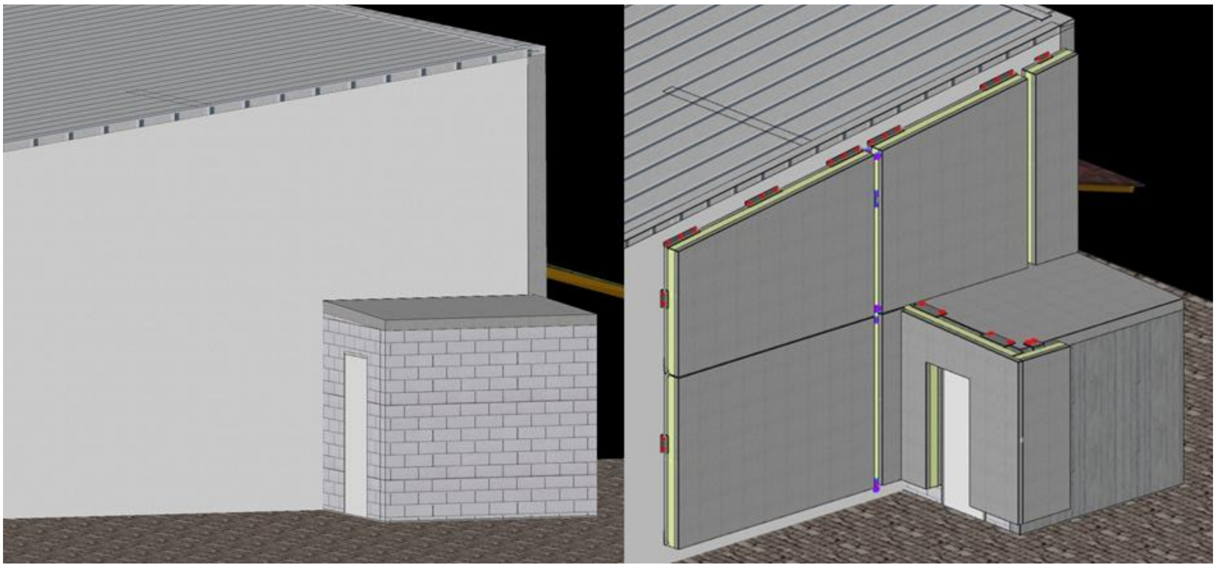


Figure 45: 3D design of the demonstration façade – initial condition (left) and renovated with sandwich façade elements (right). Source:Uwe Schneider, KOMZET BAU Bühl

Figure 46: Production of sandwich façade elements at the precast plant Otto Knecht GmbH. Source: Karsten Rauber, IZES gGmbH

The elements were then delivered to KOMZET BAU Bühl, where they were completely installed within two weeks and subsequently grouted, in the manner previously described. Figure 47 shows the façade in its raw state and after installation, including the indicated covers of the inspection shafts, which contain parts of the fastening system and the supply lines for the aWT and the absorber.

Figure 47: Implementation of the demonstration façade at KOMZET BAU in Bühl – initial condition (left) and with mounted sandwich façade elements (right). Source: Uwe Schneider, KOMZET BAU Bühl

After successful installation of the demonstration façade, the joint pattern, hydraulic connections, and thermal coupling to the existing wall were successfully verified. Subsequently, the renovation concept was examined for dismantling and recyclability (see Figure 48). All elements could be completely detached without damaging the existing wall. The dismantled sandwich façade elements could not be reused for their previous purpose, as spalling, cracks, or damage to the layers occurred during dismantling. Therefore, the condition of each sandwich façade element had to be assessed individually. It is conceivable that the elements could be repurposed for other construction tasks. After dismantling, the individual components of the sandwich elements were examined for their potential reuse. The elements were laboriously separated into their individual parts, revealing that only the concrete rubble and reinforcement steel could be reused; all other components could only be separated by destruction. More detailed information and additional images regarding installation, dismantling, and recycling can be found on the project website: www.projekt-lexu.de.

Figure 48: Dismantling (left) and recycling (right) of the sandwich façade elements. Source: Uwe Schneider, KOMZET BAU Bühl

Systematic Analysis Using a Reference Building

Within the LEXU+ project, the developed sandwich façade element was evaluated regarding its practical applicability, potential façade surface coverage, and thermal benefits using a reference building. The single-family house SFH100 from IEA SHC Task 44 (Ralf Dott, 2013), (Michel Y. Haller, 2013) served as the reference. For the analysis, the building was considered in an unrenovated state. Without any insulation, it has an annual heating energy demand of around 200 kWh/m²a.

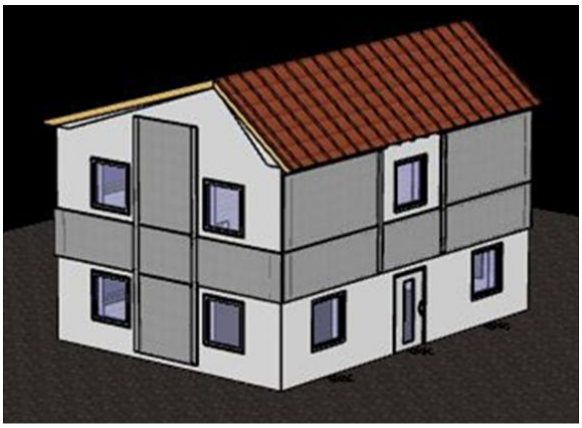


Figure 49: Renovated SFH100 using LEXU+ sandwich façade elements (dark gray) and conventional ETICS (light gray). Source: IZES gGmbH

For the renovation scenario, a combined approach was chosen: only those façade surfaces that can technically be activated — areas without windows, doors, or steep slopes — were equipped with the developed LEXU+ sandwich façade elements (see Figure 49). The remaining surfaces were renovated with a conventional ETICS of the same total thickness to ensure a uniform façade appearance and comparable building-physics properties. This approach is based on both economic and ecological considerations, since the sandwich façade elements involve higher production costs and greater CO_2 emissions due to the concrete layers. Therefore, their use is limited to areas where thermal activation can be utilized. Simulation results using TRNSYS showed that this combined renovation strategy reduced the annual heating energy demand by about 80%. The remaining heat demand can be fully covered with low supply temperatures using a combination of the activated façade elements (aWT) and existing radiators. This hybrid solution not only ensures efficient energy use but also provides uniform heat distribution and a high level of thermal comfort within the building.

Economic and Ecological Assessment

For a comprehensive evaluation of the LEXU+ project, it is necessary to conduct both an ecological and an economic assessment to fully evaluate the benefits of the chosen renovation approach. The ecological assessment — also known as Life-Cycle Analysis (LCA) — includes all phases of the life cycle of a building or renovation measure (V., Nachhaltigkeit von Bauwerken. Bewertung der umweltbezogenen Qualität von Gebäuden – Berechnungsmethode, 2012):

- the manufacturing phase of the materials used,
- the construction phase or implementation of the renovation,
- the usage phase, during which energy consumption and emissions during building operation are recorded, and
- the disposal phase at the end of the building's service life.

By considering all life cycle phases, it is possible not only to account for the emissions associated with the production of the LEXU+ sandwich façade elements but also to quantify the energy and greenhouse gas savings achieved during use. For the economic analysis, calculations were performed on the reference building. In the unrenovated state, annual costs arise exclusively from heating energy consumption, which is supplied by gas or oil heating. After renovation with LEXU+ sandwich façade elements, annual costs result from the electricity consumption of the heat pump as well as the one-time investment costs for manufacturing and installing the elements. Based on experience from the demonstration façade, the current manufacturing costs of the LEXU+ sandwich façade elements are estimated at approximately €700/m². Despite significant energy savings, the current price level for materials and energy extends the payback period to several decades. However, it must be considered that energy upgrades to the building increase its property value and can be carried out entirely from the outside, ensuring no disruption to occupants during the construction phase. From an ecological perspective, the use of LEXU+ elements is also advantageous: the CO_2 emissions generated by concrete production are offset within just a few years due to the avoidance of fossil energy consumption, meaning the measure has a positive ecological impact in the long term.

The LEXU+ research project is funded by the Federal Ministry for Economic Affairs and Energy based on a resolution of the German Bundestag under funding code 03EN1041A-D and is supervised by Project Management Jülich.

Discussion of core principles, advantages and limitations – LEXU+

LEXU+ is a highly integrated low-exergy renovation concept based on prefabricated sandwich façade elements. Its core principle is to combine insulation, external wall tempering, environmental energy harvesting, and storage in one industrially manufactured component. Compared with CEPA and AktivDHKS, LEXU+ places stronger emphasis on prefabrication, structural integration, and detailed analysis of installation, dismantling, and life-cycle impacts. This makes the project particularly valuable because it does not only describe thermal benefits, but also addresses construction feasibility, fastening, grouting, recyclability, and economic performance.

At the same time, LEXU+ illustrates the central trade-off of highly integrated façade systems. The elements can significantly reduce heating demand and enable low-temperature operation, but they are currently associated with high investment costs and higher embodied emissions due to the concrete layers. The project addresses this by limiting the use of active elements to suitable façade areas and combining them with conventional ETICS elsewhere. This hybrid approach appears technically and ecologically reasonable, but it also shows that such systems should not be applied uniformly without considering façade geometry, usable activation area, cost, and life-cycle balance.

2.4.6 fronTherm - Innovative facade heating and cooling unit for serial refurbishment

The building sector has been lagging behind its targets for achieving climate neutrality for several years. What is needed is a significant effort for refurbishment of the building stock - reduction of the heat demand (building envelope) and decarbonization of heat generation - which requires refurbishment rates that seem hardly achievable with the trade capacities available today. Furthermore, in practice, the high investments required by building owners often lead to a delay in refurbishment measures or only to the replacement of the boiler, with CO2 emissions remaining too high for the next 20 years. The use of heat pumps will play a decisive role in the transformation of the energy supply in existing buildings. However, heat pumps require low-temperature heating surfaces for efficient operation, which are usually not available in existing buildings. With regard to the heat source, problems often arise in inner-city locations, especially in multi-family houses, due to noise pollution and limited space (air heat pump) or the lack of spatial or geological conditions for ground probes.

This is where fronTherm comes in, enabling the simultaneous renovation of the building envelope and heating system. It is designed to enable the efficient use of solar and heat pump technology and can also be used without faults by semi-skilled workers. It could therefore enable strongly increased refurbishment rates in a disruptive way and thus make a significant contribution to reducing emissions in the building sector. The concept is based on façade heating and cooling units that are produced in series and applied to the outside of the façade. The modules contain a heat pump with a condenser surface for heat dissipation towards the building wall and an evaporator surface towards the ambient air and the sun (heating case). This surface is also equipped with PV modules on suitably exposed façades. In the cooling case, the condenser surface becomes the evaporator surface and vice versa. The façade heating and cooling units serve as the sole source of heating and cooling for the building. Figure 50 shows the principle of fronTherm.

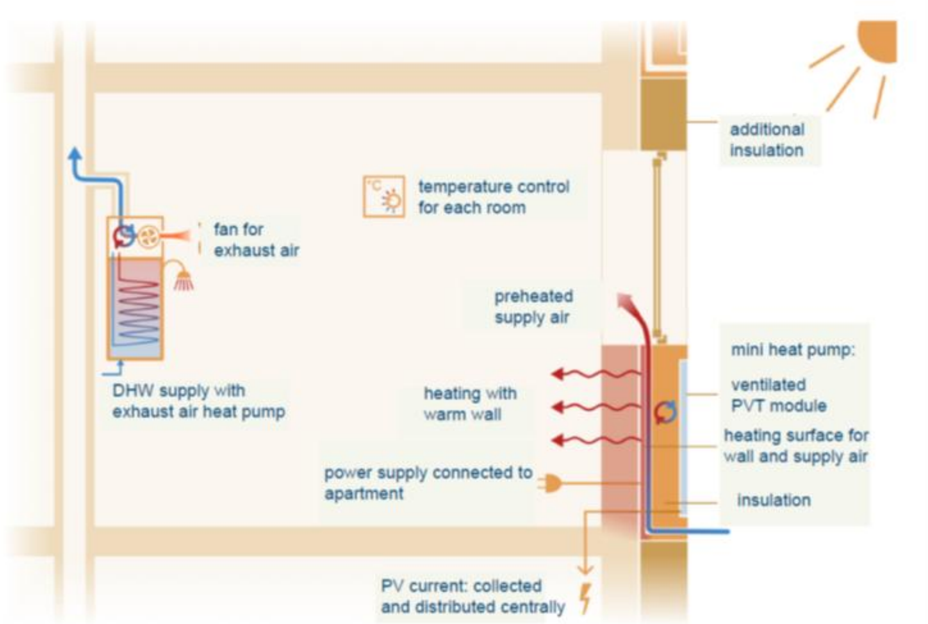


Figure 50: Principle of fronTherm. Source: Consolar Solare Energiesysteme GmbH

The project and technology development is carried out by the partners Consolar Solar Energy Systems GmbH, University of Stuttgart, Institute for Building Energetics, Thermotechnology and Energy Storage (IGTE), Karlsruhe Institute of Technology, Building Science & Technology Group (bst), ME Housing Management GmbH & Co. KG and is Funded by the Federal Republic of Germany (Federal Ministry for Economic Affairs and Energy based on a resolution of the German Bundestag).

Development of the façade module

As shown schematically in Figure 64, the façade module contains an evaporator on the outside, a compressor and an expansion valve inside the module and a condenser on the inside. These components are integrated into a housing made of closed-cell expanded polypropylene foam (EPP). EPP is characterized by a high structural strength and load-bearing capacity and has very good thermal insulation properties, so that a stable frame, free of thermal bridges, can be realized. Figure 51 shows a front view of the module - the cover of the module is only partially shown to also provide a view of the evaporator behind it.

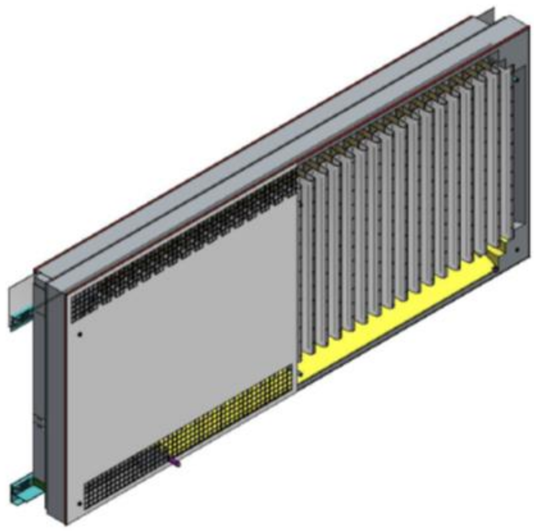


Figure 51: : Front view of the façade module: the front cover can be seen on the left (no PV module here) with the upper and lower openings for the inlet and outlet for air to flow along the evaporator; the evaporator is on the right. The compressor and expansion valve are located at the bottom left of the module behind the darker looking air inlet openings (supply air into the building). Source: Consolar Solare Energiesysteme GmbH

In front of the evaporator is a cover plate, which can be overlaid with a PV laminate or one which is color-matched with the overall appearance of the façade. It is important that a sufficiently large opening area is provided at the top and bottom, through which outside air can flow downwards behind the cover along the evaporator to extract heat from it to evaporate the refrigerant (propane). The evaporator itself consists of an aluminum heat exchanger with a large contact surface for the air. To transfer the heat generated by the heat pump to the room behind the facade module with as little loss as possible, the cold evaporator side must be thermally separated from the hot condenser side within the module. This is achieved using a thin vacuum insulation panel to minimize the depth of the façade module. At the same time, the vacuum insulation ensures a low U-value for the module. Behind the vacuum insulation - at a distance - is the condenser as the rear cover of the module, which establishes contact with the wall using a slotted aluminum sheet. The slots give the entire sheet a certain flexibility, which is intended to compensate for unevenness in the existing (plastered) outer wall surface in order to achieve good wall contact.

As can be seen from Figure 50, in addition to heat conduction from the condenser through the solid exterior wall, some of the heat is transported into the room via the supply air that flows through the façade module from outside. This requires a supply air duct from the front of the module (recognizable by the air inlet opening at the bottom left of the module, which appears darker in Figure 65) past the hot compressor behind it and through a recess in the thermal insulation to the rear, where the air is guided along the condenser for further heating. At the top of the module there is an air duct that connects directly to the outer wall. From there, the air enters the building interior through exterior wall vents with integrated fans. Figure 52 shows the rear of the module with the slotted condenser plate and the air duct.

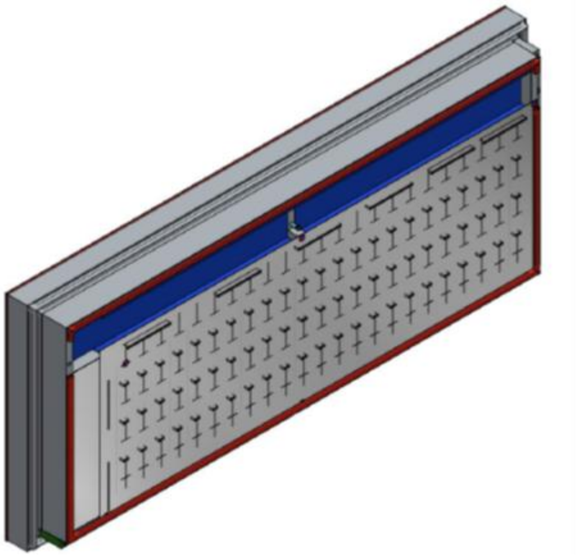


Figure 52: Rear view of the façade module with slotted condenser plate and air duct. Source: Consolar Solare Energiesysteme GmbH

In principle, it is intended that the façade module can also extract heat from the room behind it in reverse mode - reversible heat pump operation. However, the development of the fronTherm system is currently concentrating on the heating function.

Development of the overall façade system

In addition to optimizing the performance of the new façade module, questions regarding integration into an overall façade must also be addressed - taking into account architectural design, structural design and building physics aspects in order to arrive at architecturally appealing and permanently functional solutions. From an architectural point of view, it must be clarified which façade systems are most compatible with the fronTherm module and which types of apartment building are basically suitable for renovation with the fronTherm system. This also results in a module size that is suitable for as many façade geometries as possible - with both horizontal and vertical formats.

From a building physics point of view, in addition to thermal (thermal bridges, average U-value of the overall façade) and moisture-related (condensation in the façade element and at connection points, tightness of the façade and driving rain resistance) issues, the main focus is on fire protection requirements (material selection, cable routing). Particular attention must be paid to the connections of fronTherm modules to conventional façade components. Finally, attention must be paid to the revision of fronTherm modules (e.g. in the event of a heat pump failure).

Although external thermal insulation composite systems are still the preferred choice for energy-efficient refurbishments for cost reasons, curtain wall systems are also being considered as an option for fronTherm. On the one hand for design reasons due to the modularity of the fronTherm elements, which is more compatible with the façade appearance of a curtain wall, and on the other hand due to the increasing demand for life cycle considerations and circularity in the construction industry, where the external thermal insulation composite system still has clear disadvantages at the moment and may lose its cost advantages in the future.

External thermal insulation composite system (ETICS)

The integration into an ETICS is shown in Figure 53 - in this case with a PV module as a cover - which can also be designed as a conventional panel. Essential for this integration is the tight connection of the fronTherm modules to the ETICS system or windows in order to prevent moisture damage. This is achieved using specially formed additions which are parts of the fronTherm module. In order to be able to establish this connection securely, the fronTherm modules are first attached to wall rails (the lower one also serving as a cable duct) during façade installation. In the next step, the thermal insulation of the remaining wall surfaces is installed together with the plaster base. The wall surface is then plastered - a clean plaster connection to the fronTherm modules is achieved using plastering angles. Fire barriers formed by non-combustible insulation material in the ETICS prevent fire spreading to the next storey. For fire protection reasons, the vertical cable routing (connection of PV modules to a central point in the house connection room) must be designed as a surface-mounted system. Drains located on the lower edge of the fronTherm modules ensure that condensation drains from the modules and prevents it from running down the façade surface.

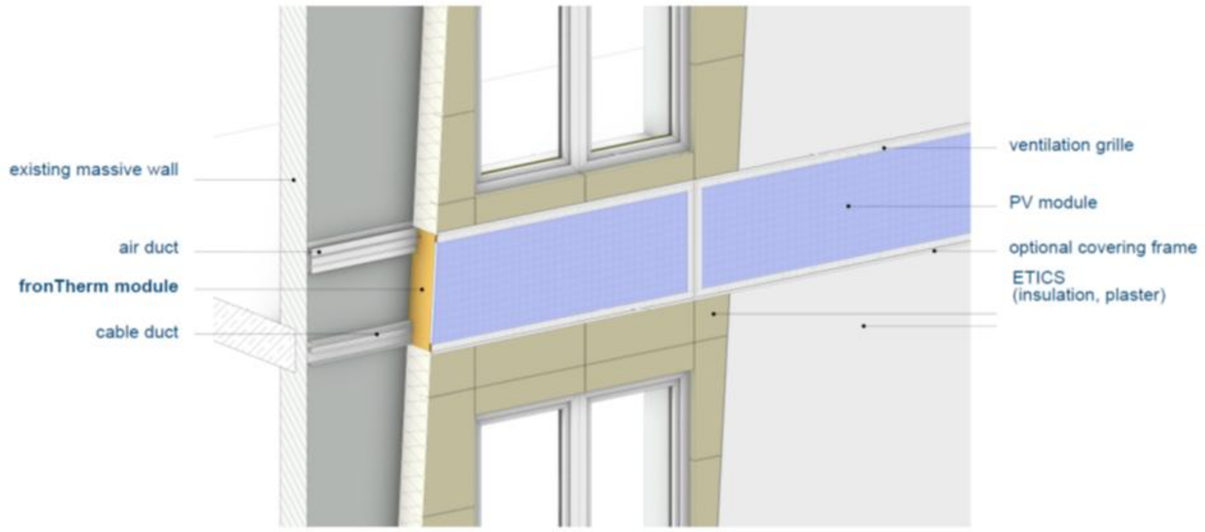


Figure 53: Integration of fronTherm modules in a thermal insulation composite system. Source: Karlsruhe Institute of Technology, Building Science & Technology Group

When installing the curtain wall (CW) (see Figure 54), the fronTherm modules are also first attached to the wall rails (same profiles as for ETICS). In the next step, the insulation of the remaining wall surfaces is also realized with a tight connection to the specially formed additions of the fronTherm modules. At the same time, brackets are attached to the wall, to which the horizontal rails for attaching the ventilation grilles, the PV modules and the rest of the façade claddings are then attached. A façade membrane protects the thermal insulation from moisture ingress. The fire barrier, which in this case is designed as a metal bracket, prevents the fire from spreading to the next storey through the separating air space behind the façade cladding.

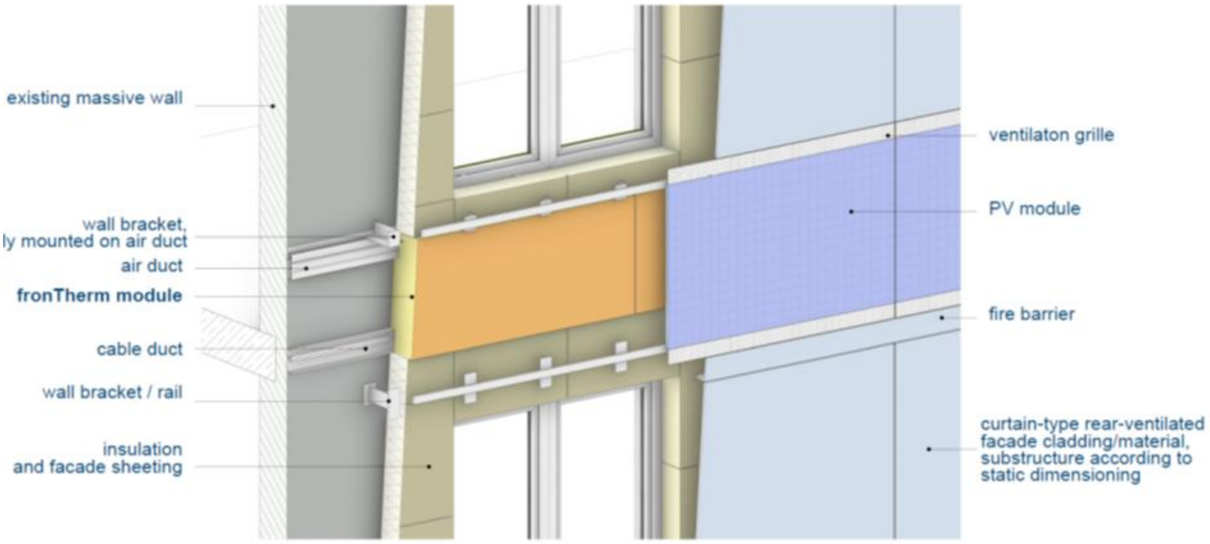


Figure 54: Integration of fronTherm modules in a curtain wall. Source: Karlsruhe Institute of Technology, Building Science & Technology Group

On the basis of preliminary investigations with regard to suitable types of multi-family house (building age classes, external wall characteristics, geometric façade features), a module size of 2.10 m x 0.90 m has emerged, which is suitable for both horizontal and vertical modules. An important point for the façade construction is the revision of fronTherm modules in the event of component failure. As costly revision work on the façade is to be avoided, both façade designs were developed so that individual fronTherm modules can be replaced with just a few steps for disassembly and reassembly.

Overall thermal system

For the rough dimensioning of the fronTherm module, calculations were first made for the heating output of a fronTherm module. With the envisaged size (and therefore output) of the compressor and a module area of approx. 2 m², this results in a heating output of 300 W.

Furthermore, a comparative calculation was made of the heating demand resulting from a conventional refurbishment of an apartment building and from a refurbishment of the building with the fronTherm system. The results are shown in Figure 55. It can be seen that the specific heating load for the building under consideration can be reduced by 65% from 73 to 25 W/m² in both cases, but the heat transfer shows clear differences: in the fronTherm system, just under 18% of the heat is transferred to the room via conduction to the inside of the exterior wall in a stationary view and 79% via the supply air heated in the module (38% of which is used to heat the air from 20 to 40°C). The dynamic simulations planned for the next step will take a closer look at the properties and effect of the outer wall as a heat store, which is particularly important for controlling the heat input to a specific target temperature.

For the optimization of the heat transfer mechanisms within the module - free convection at the evaporator for heat extraction from the outside air, forced convection at the condenser for heating up the supply air, heat conduction and radiation during heat transfer from the condenser to the exterior wall - both analytical considerations and CFD simulations are being carried out; this work has also not yet been completed. If the residential units are heated decentrally via façade elements, domestic hot water must also be provided decentrally at apartment level. In order to use a technology that can function in a climate-neutral way in the medium term, an exhaust air heat pump is envisaged. This uses the heat from indoor air of the apartment and, in addition to DHW heating, can also be used to supply heat to radiators in indoor bathrooms and toilets (see Figure 50).

A significant proportion of the heating energy from the fronTherm modules is provided by the supply air. In combination with the exhaust air heat pump, which generates a negative pressure in the apartment during operation and thus enforces an air flow to its air inlet, normal vents in the external wall could be used which are connected to the air duct of the fronTherm modules. The number of vents depends on the number and size of the rooms in a residential unit.

	unreno-vated	convent. reno-vated	fronTherm 261 modules 26% wall	
Heat losses	**227**	**78**	**37,4**	**kW**
- transmitted through wall	176	36	33,1	kW
- ventilation/infiltration	51	42	4,3	kW
Heat delivered	**227**	**78**	**78,4**	**kW**
- to room via radiator / wall	227	78	13,8	kW
- preheated supply air (to room)	-	-	61,9 (23,6)*	kW
- Heat losses at evaporator	-	-	2,7	kW
Specific heat load	**73**	**25**	**25**	**W/m²**

building age group
1958 – 1968

net floor area
3129 m²

4 floors
32 apartments

* 23,6 kW for preheating air from 20 to 40 °C

Figure 55: Comparison of the heating demand required for a conventional refurbishment of an apartment building and for a refurbishment of the building with the fronTherm system. Source: IGTE, University of Stuttgart

In this configuration, the respective supply air flow in the individual rooms would depend on the operation of the exhaust air heat pump and the respective pressure difference built up by the heat pump fan. This can vary depending on the flow resistance on the air flow paths through the façade modules and the individual rooms, which influences the respective air volume flows. This would make it difficult to exactly control the heating demand required per room; at the same time, the nominal volume flow required per room for hygienic reasons must also be ensured. For these reasons, an active supply air supply is provided in the rooms with supply air fans in the vents so that the required air volume flow can be set precisely for each room. These active supply air elements (vents) are installed in core drill holes through the exterior wall with a direct (sealed) connection to the outside air duct of the fronTherm façade elements. This would make it possible to inspect the fans and also to replace air filters located behind the fans on the room side.

Project status and outlook

A first functional model of the fronTherm module has been in existence since April 2025 (see Figure 56) and as of October 2025, essential work on façade integration has been completed. Work on the fronTherm module has progressed so far that in December 2025, an optimized test sample - with regard to the heat transfer mechanisms and the design of the individual components - will be installed in a climate chamber at the IGTE of the University of Stuttgart, where its performance will be measured under different boundary conditions. One focus of the investigations will be the dynamic behavior of the system in connection with the wall as a heat storage. The next major step will then be the implementation of the fronTherm system in a demonstration building in the fall of 2026, where the functionality and performance will be tested under real boundary conditions (inhabited unit).

Figure 56: Functional model of the fronTherm module on the façade of Consolar's production hall in Lörrach. Source: Karlsruhe Institute of Technology, Building Science & Technology Group

Discussion of core principles, advantages and limitations - fronTherm

fronTherm differs from the other systems because it does not primarily activate existing mass through a central hydronic system, but integrates decentralized heat pump modules directly into the façade. The façade element acts simultaneously as heat generator, heat transfer unit, ventilation-related component, and potential PV surface. This makes the concept especially relevant for serial refurbishment of multi-family buildings where central heat sources, ground probes, or conventional outdoor air heat pumps are difficult to implement due to space, noise, or urban constraints.

The concept is innovative, but also still at an early development stage compared with market-ready solutions such as TermoDeck or CEILTEC. Several critical issues are correctly identified within the project itself, including moisture safety, fire protection, façade integration, module replacement, air volume control, and the dynamic behaviour of the exterior wall as thermal storage. Compared with CEPA, AktivDHKS, or LEXU+, fronTherm reduces the need for a central low-temperature distribution system, but introduces more decentralized technical components in the façade. Its success will therefore depend strongly on reliability, maintenance accessibility, acoustic behaviour, control of supply air flows, and demonstrated performance under real occupied conditions.

2.5 Strategies for zoning

Zoning is one of the most critical yet frequently underestimated design parameters in Thermally Activated Building Systems (TABS). Because TABS are structurally integrated technologies — with pipes embedded directly into load-bearing slabs or walls — spatial subdivision decisions made during design are extremely difficult to modify after construction. Unlike conventional HVAC systems, where ductwork or terminal units can be adapted or extended relatively easily, the thermal zoning of TABS is largely fixed once the concrete has been cast. This makes early planning decisions particularly consequential.

In principle, from a thermal comfort and flexibility perspective, it would be ideal to design zones as small as possible. Smaller zones allow more precise temperature control, better adaptation to heterogeneous occupancy patterns, and improved responsiveness to local thermal loads. However, such fine-grained zoning quickly becomes impractical. Each additional zone increases hydraulic complexity, requires additional control valves and sensors, and contributes to higher pressure losses within the system. As a result, pumping energy demand increases, installation costs rise, and commissioning complexity grows. Beyond a certain point, the marginal benefit of smaller zones is outweighed by system inefficiency and economic burden. A compromise must therefore be found between control granularity and system feasibility.

Different implementation strategies illustrate how industry addresses this trade-off. Companies such as Innogration GmbH, for example, utilize prefabricated activated elements that represent their smallest modular thermal zones (see section 2.3.1). These modules can be hydraulically coupled to form larger zones where appropriate. This modular approach provides a degree of flexibility while maintaining manageable hydraulic design, see Figure 57.

Figure 57: Design of the prefabricated panels of Innogration GmbH, utilizing individual slabs that are connected via pipes to form thermal zones that are individual controlled by a classic floor heating manifold (bottom left). Source: Innogration GmbH

Similarly, companies like TOWERN 3000 define zones along building façades in retrofit applications for their CEPA product. Their approach foresees collection ducts where individual façade segments are grouped and connected to central heating and cooling systems, as well as supplying individual flats with their own circuits, see .

Figure 58: Schematic of CEPA zoning for TABS retrofit in a multi-family house. Individual colors represent individual hydraulic zones in the building envelope that correspond to the living units in the billing, ensuring flat wise energy supply as basis for billing. Source: Towern3000, presentation at the 35th ES TCP On-Seminar, 16.10.2025

The importance of proper zoning becomes evident when considering practical examples of poorly defined thermal zones. A typical failure case occurs when meeting rooms and office spaces are grouped into a single zone. Meeting rooms often experience high internal gains due to occupancy density and equipment usage, resulting in increased cooling demand. Adjacent office spaces, with lower and more stable occupancy, may simultaneously require heating. If both areas are controlled within one hydraulic zone, one of two undesirable outcomes occurs: either the meeting room overheats, or the offices become uncomfortably cold. In both cases, thermal comfort is compromised because the zoning structure cannot accommodate differing demand profiles. Another illustrative example involves large office complexes with extensive glazed façades. In the morning hours, the east and south façades may experience strong solar gains and require cooling, while the north façade may still require heating. Without façade-oriented zoning, simultaneous heating and cooling demands cannot be addressed independently. The result is either thermal discomfort or inefficient system operation.

Zoning also has implications beyond comfort and energy efficiency. In residential buildings, billing per apartment requires clear hydraulic separation between units. If TABS zones do not correspond to individual flats, transparent and fair energy accounting becomes difficult. Retrofitting proper billing zones after construction is particularly challenging due to the embedded nature of the system.

In theory, adaptive zoning concepts could offer a solution. For example, hydraulically controllable switches could connect or disconnect sub-zones, allowing dynamic aggregation or subdivision of thermal areas. However, such approaches increase system complexity and have not yet been widely studied or implemented in real-world projects. Further research is needed to evaluate their technical and economic feasibility. Interestingly, zoning considerations are often underrepresented in research projects. Many experimental studies focus on small-scale prototypes or single-zone demonstrators. While this allows detailed investigation of control strategies or storage dynamics, it neglects the systemic implications of zoning in real buildings. As a result, the practical challenges of hydraulic balancing, zone interaction, and spatial heterogeneity are sometimes underestimated. In conclusion, zoning in TABS design represents a fundamental structural decision with long-term consequences for comfort, flexibility, and economic viability. It must balance precision and practicality, control granularity and hydraulic simplicity. Because post-construction modification is extremely difficult, zoning strategies must be carefully aligned with occupancy patterns, façade orientation, billing requirements, and anticipated flexibility use cases during the earliest stages of design.

3 Subtask B – System integration and control

Led by: Dr. Daniel Muschich, BEST – Bioenergy and Sustainable Technologies, Austria

Designing and operating buildings with thermally activated components poses challenges distinct from other heating and cooling solutions; on the other hand, the technology also provides different benefits and even opens business models.

In subtask B, the tools and approaches to handle the difficulties and profit from new opportunities are investigated. First, mathematical models and available simulation tools are presented based on a survey among experts in the field. Modelling and simulation allow to experiment with new configurations and concepts and can be used to verify that prospective buildings behave as expected. From detailed temperature and humidity propagation in the components, over validating heating and cooling system and control concepts, to estimating the storage capacities for demand shifting applications, simulation tools of varying complexity exist and help the component engineer, the building or HVAC planner, or the district energy provider.

Based on multiple reports of successful implementations of thermally activated buildings, but also based on recent research and possible new ideas, the subsequent section 3.2 investigates system concepts incorporating activated building components. These concepts go beyond stabilizing the room temperature with large thermal mass and involve both active and passive management of the thermal masses.

Each concept requires its own individual control strategy to get the best performance out of it while maintaining satisfactory user comfort levels. Section 3.3 proposes different approaches, ranging from simple, but effective control strategies for temperature control to predictive strategies considering weather forecasts, varying energy prices and dynamic comfort models to actively manage the thermal mass.

More advanced control strategies require more information and depend on external data sources such as weather forecasts or price signals to perform best. This enters the field of data safety and security since personal behaviour patterns can be potentially derived from spatially and temporally localized data, leading to privacy issues, while external tampering with price signals can lead to worsened performance or even device failure. This is briefly addressed in section 3.4.

3.1 Simulation Models and Tools

Mathematical modelling and simulation of (thermally activated) building components fulfil many tasks. For the component producer and designer, these models enable the detailed analysis of temperature and humidity propagation within building materials, accounting for key parameters such as layer thickness, pipe depth, and spacing. By simulating the dynamic thermal and hygric behaviour of TABS, these tools provide valuable insights into heat transfer, energy efficiency, possible dangers of condensation, and indoor climate regulation. The use of advanced simulation tools ensures that design decisions are informed by accurate predictions. This is especially of interest when considering new materials and mixes of materials, such as activating wood or clay, or when integrating phase change materials (PCM). The modelling of conduction and diffusion processes rely on detailed knowledge of material properties, often incorporated in the form of material libraries based on extensive research and experiments. The simulations can be performed dynamically or deliver steady state solutions, resulting in a wide range of computing power requirements. Therefore, some simulation tools are restricted and can only perform 1D simulations, while others provide 2D and even 3D simulation capabilities.

For modelling the interaction of multiple components, or activated components with other elements of the building, the precision is often reduced, and the setup becomes more involved, the user having to provide 2D and 3D geometries and placement information. These simulations are then used to detect thermal bridges or identify possible regions where condensation – and thus mould – can appear. Even less precise simulations can be used to simulate thermal zones and buildings, typically to estimate thermal losses, heating and cooling demand, and investigate thermal comfort due to draughts, heat radiation (or lack thereof) and HVAC control strategies.

A large variety of simulation models and tools to cover these various aspects is available on the market and described in scientific literature. Within the subtask, a questionnaire was formulated to assess both the most widely used tools and those tools that are developed by the Task members themselves. The list cannot be assumed to be exhaustive. The list here focuses on tools which either are specifically useful for the investigation of thermally activated components or explicitly consider thermally activated components. However, such a specialization on TABS is rare; therefore, some more generalist simulation tools such as Modelica and TRNSYS, which are quite commonly used and allow to consider TABS in a straightforward way, are also included.

In the following, the table of tools reported back is presented first, followed by a more detailed description of some of them. Finally, in section 3.1.3, a short summary and recommendation for choosing the appropriate tool is given.

3.1.1 Summary of obtained model factsheets

The questionnaire asking for simulation model factsheets was returned by eleven participants of the Task and external experts, with some overlap in the reported tools, and sometimes multiple nominations per expert. The following Table 10 summarizes the main use cases and suitability of different simulation tools and models that were reported back for the study of Thermally Activated Building Systems (TABS). The classification ranges from component-level hygrothermal analysis to large-scale building and city-quarter energy system validation. It also indicates whether tools are specifically suited for TABS or are general-purpose tools that can also be applied to TABS modelling.

Table 10: Simulation tools and their main applications

Tool / Model	Main Use Case / Scale	Special Suitability for TABS
IDA ICE	Whole building & neighborhood simulation; HVAC & control validation; refurbishment studies	General building simulation tool with TABS support (Koschenz & Lehmann method)
TRNSYS (Types 56, 653, 993)	Building/system performance analysis; control integration; MPC studies using co-simulation	General-purpose; several TABS types exist (trade-off between accuracy and speed)
Modelica Buildings Library	Detailed multi-domain modeling of HVAC, TABS, and energy systems; flexible for control	Very suitable for TABS (dedicated RadiantSlab / TABS components), coupling with EnergyPlus envelope model possible
EnergyPlus / OpenStudio / GenSim	Widely used in practice for building energy performance; accepted in engineering / architecture	none

WUFI (Pro, 2D)	Transient hygrothermal 1D/2D component simulations (heat & moisture transfer)	Not specialized for TABS, but possible with expertise
Physibel VOLTRA	2D/3D FEM modeling of components; thermal bridges and heat storage	Pipes in concrete can be modeled dynamically
DELPHIN (TU Dresden)	Coupled heat-moisture transport in porous materials; hygrothermal analysis	Strong at component-level; TABS can be represented through linking boundary conditions between inlets and outlets of individual pipes
HTFlux	Component-level FEM (steady-state & transient)	Good for studies of surface temperature and risk of condensation.

3.1.2 Selected models in detail

The following sections introduce some of the tools in more detail, starting from the most detailed simulation models for individual components, up to simulation tools sufficiently abstract to model whole buildings together with their HVAC systems, and even city quarters.

WUFI

WUFI (German "Wärme Und Feuchte Instationär", meaning "heat and humidity non-stationary"), developed by the Fraunhofer Institute for Building Physics, is a suite of tools for simulating transient heat and moisture transport in building components. It is extensively validated and provides a user-friendly interface. There are different tools from the WUFI suite, each tailored to a different application:

WUFI 1D is best for straightforward simulations of layered building assemblies (e.g., walls or roofs). It is efficient and widely used in design and research for one-dimensional problems.

WUFI 2D is suited for complex, two-dimensional scenarios like thermal bridges, corner details, and joint systems where moisture transport in multiple directions is critical.

WUFI Plus enables whole-building hygrothermal simulations, accounting for interactions between building systems and the indoor climate.

WUFI Bio adds a layer for assessing mold growth risks based on hygrothermal conditions, particularly useful in high-humidity environments.

WUFI's intuitive interface and extensive material database make it accessible to both engineers and researchers without specialized programming knowledge. Comprehensive experimental validations ensure accuracy, making it reliable for critical design decisions. WUFI also supports a variety of boundary conditions, including custom climatic data, enabling location-specific modeling. However, while user-friendly for standard applications, detailed customization requires a deeper understanding of hygrothermal dynamics.

The software is commercial, and advanced versions may not be accessible to small firms or students without institutional support.

DELPHIN

DELPHIN is a hygro-thermal and hygro-physical simulation tool developed at the Institute of Building Climatology (IBK) – TU Dresden (Germany) together with the company Bauklimatik Dresden Software GmbH. It solves the coupled transport of heat, moisture (liquid + vapour) and additional constituents (for example salts or matter transport) in porous, capillary materials, building components or soils.

The modelling framework allows 1D, 2D, and in recent versions 3D geometries, and supports detailed representations of boundary conditions (climate data, solar radiation, convection, etc.). A comprehensive validation of the solver implementation has been documented demonstrating its numerical correctness for standard benchmark problems (e.g., HAMSTAD benchmarks & EN 15026) for hygro-thermal transport.

The software allows coupling (co-simulation) with other simulation tools via a Functional Mock-up Interface (FMI) or FMU workflow. Typical application fields have included building envelope hygro-thermal performance (walls, roofs, internal insulation, ventilated facades), but also more recently ground/soil energy systems (ground collectors, shallow geothermal) and active building systems.

In the context of TABS - i.e., systems where building structures (floors, ceilings, walls, slabs) or building elements serve both as heat/cold distribution and some thermal storage or exchange medium - several features of DELPHIN are particularly relevant:

- Coupled heat and mass transport / storage effects
- Ground/soil coupling for subterranean storage or floor-slab coupling
- 2D/3D geometry capability
- Co-simulation / integration with system models
- Validation and reliability

DELPHIN is relatively detailed at the component level: This means modelling complexity (geometry, discretisation, detailed material properties) and computational effort may be high. For whole-building or network models one might need to simplify the model or use co-simulation. If, e.g., moisture transport models are less relevant in some TABS cases (unless the activation system interacts with humidity), one may choose to deactivate or simplify moisture modelling to reduce complexity.

Detailed models require input data of high quality to leverage their full potential: For TABS, correct material thermal properties, pipe network geometry/heat transfer coefficients, boundary conditions (fluid temperatures, flow rates) need to be provided. Also, the coupling to fluid/hydronic network and room/building loads must be handled carefully. DELPHIN models the structural mass and boundary interactions, but the building energy and HVAC side may be modelled separately (thus requiring coupling).

To demonstrate the capabilities of DELPHIN for the simulation of TABS, a retirement home located in the centre of a German city within a moderate climate zone was selected (Figure 59), modelled and simulated with three different heating systems (radiator, floor heating, ceiling heating with a TABS).

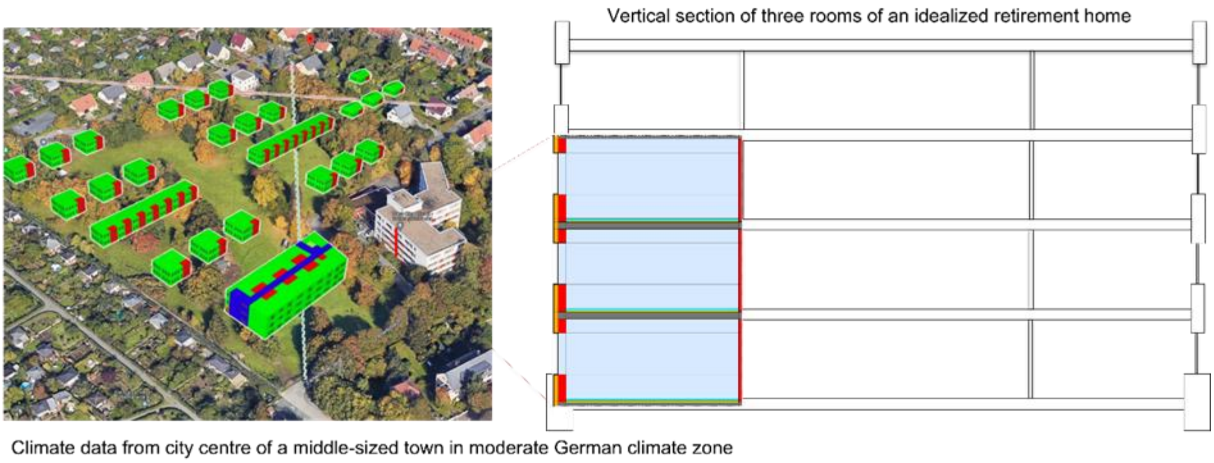


Figure 59: Location of a retirement home building (left) and schematic drawing of the construction with selected rooms for the TABS simulation study (right). Source: TU Dresden

To represent this climate zone, Test Reference Year (TRY) data from the German Meteorological Service (DWD) station in Essen are used. The four-story building with a basement was constructed in the 2000s. It consists of a reinforced concrete structure with solid intermediate floors and pre-fabricated façade elements. It can be assumed that the building complies with the energy performance standards that were in effect about 20 years ago.

For demonstration purposes, it is not necessary to model the entire building. Instead, three rooms arranged vertically above one another were selected (Figure 59). Care was taken to ensure that additional rooms exist both above and below the modelled section, which justifies the use of adiabatic boundaries at the internal interfaces. The exterior wall boundary condition corresponds to a south-facing façade exposed to the typical climate of Central Germany.

To develop the simulation model, the building structure was idealized, omitting details irrelevant to the thermal analysis. The intermediate concrete floors and the insulated exterior wall, however, were included. Each room has a depth of 5 m and a clear height of 2.32 m. The exterior walls are 36 cm thick, and the intermediate floors, including 5 cm impact sound insulation and 5 cm screed, have a total thickness of 30 cm.

To illustrate DELPHIN's ability to evaluate TABS effectiveness, underfloor and ceiling heating systems were compared with a standard radiator. Three DELPHIN models were created for this purpose (Figure 60). The radiator is located beneath the window on the exterior wall. The underfloor heating is embedded in the screed and consists of two circuits with ten pipes each, spaced 20 cm apart. The ceiling heating follows the same configuration but is positioned closer to the surface of the building component.

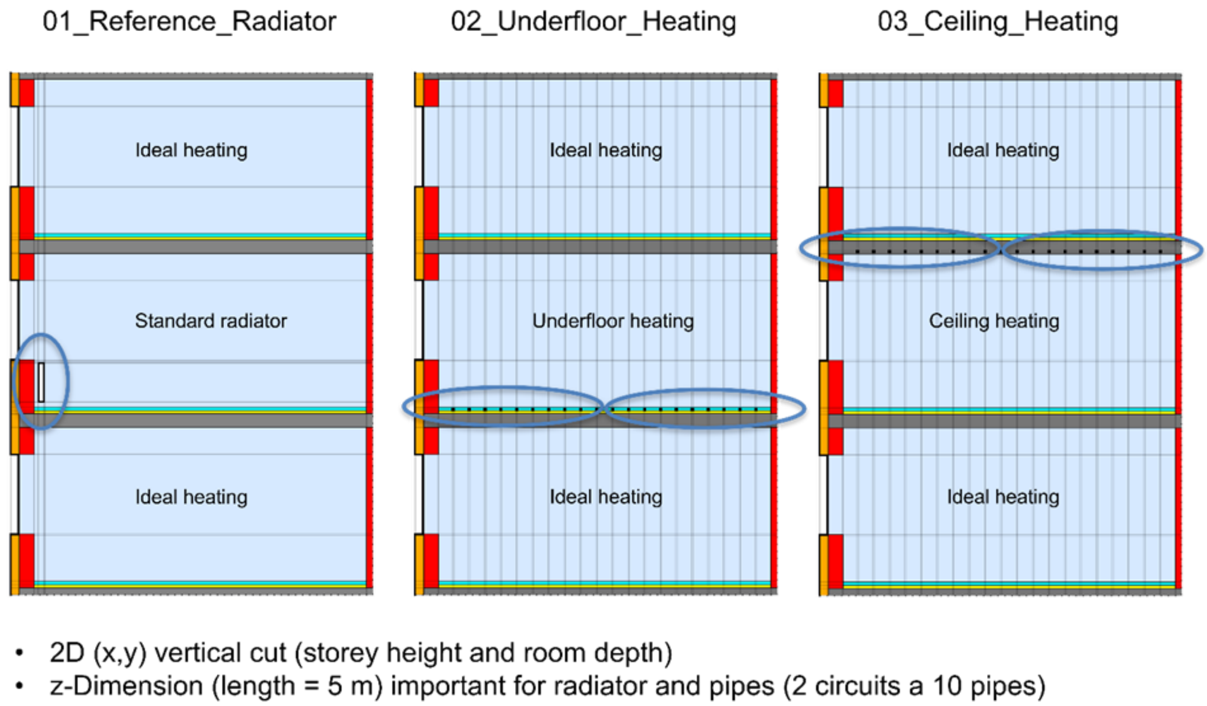


Figure 60: Visualization of the three DELPHIN models for simulating TABS (left: standard radiator, middle: underfloor heating, right: ceiling heating). Source: TU Dresden

To ensure a realistic usage scenario, an air infiltration rate of 0.1 h^{-1} was assumed for all rooms. There is no mechanical ventilation system; natural ventilation is represented by infiltration.

An ideal heating system was implemented for the upper and lower rooms (Figure 61). This system does not model the detailed heat transfer mechanisms within the room but rather supplies sufficient heat to maintain the target temperature within an acceptable tolerance. The same idealized heating approach was applied across all variants to ensure consistent boundary conditions for the middle room. A reference case (00_Reference_NoHeating) without active heating in the middle room was also considered.

In DELPHIN, all boundary and field conditions can be linked to schedules, allowing the automatic activation or deactivation of specific conditions. In this case, the heating system is switched off during summer according to the defined schedule. The heating schedule distinguishes between a heating season and a non-heating period. Heating operates from January 1 to June 19 and from September 18 to December 31, resulting in a one-year simulation period. During summer, no heating or cooling is provided, assuming the absence of an air-conditioning system.

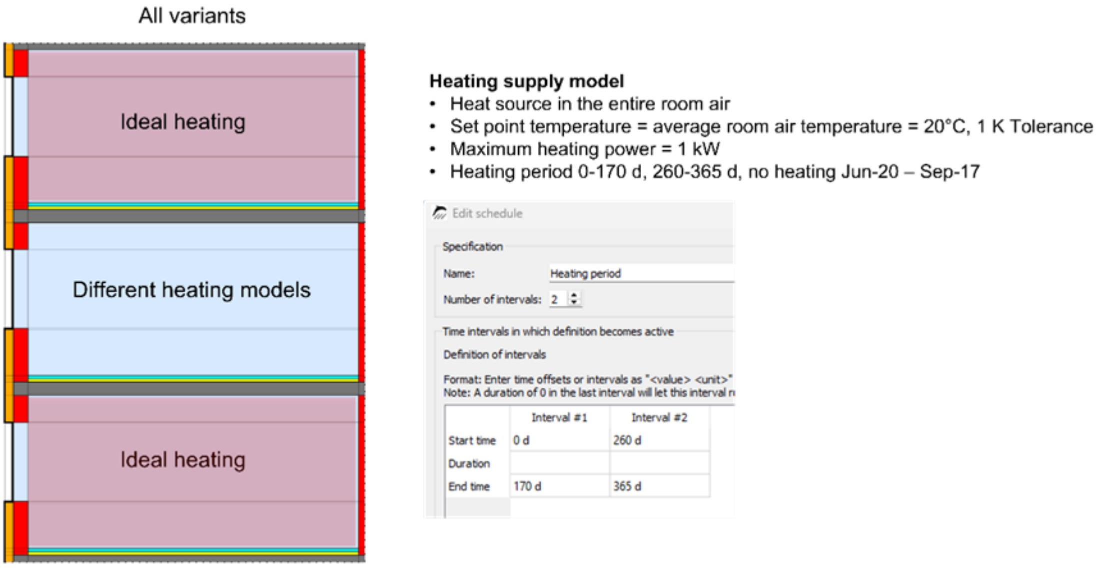


Figure 61: Assignment of heating supply models to the upper and lower rooms and specification of the heating schedule (right). The same heating schedule is applied for all heating systems of this study. Source: TU Dresden

Next, the desired output quantities were defined and assigned to the model geometry (Figure 62). All quantities are time-dependent and can be output either as spatial fields, averages, or integrated values. Specifically, the temperature field of the whole domain, average air temperature of the middle room, and radiant surface temperatures of the exterior wall, ceiling, interior wall, and floor were recorded. In addition, the heating power input (kW) and the total heat energy (MWh) in the middle room were calculated specifically according to the assumed heating variants.

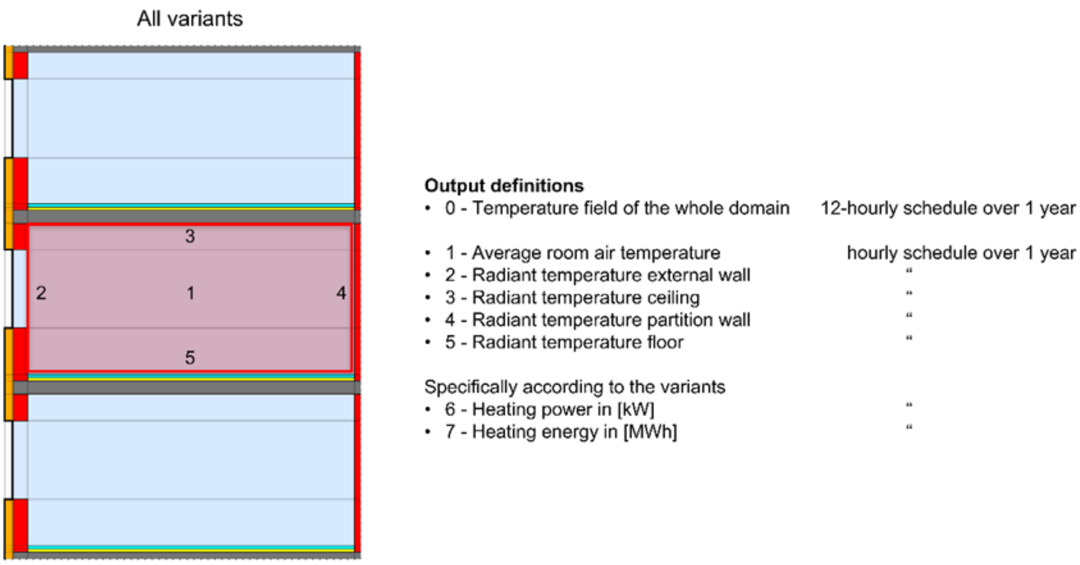


Figure 62: Definition and assignment of the outputs to the geometry of the simulation models; each quantity can be output as a field (individual values) or as an average or sum of a range. Source: TU Dresden

The heating systems were modelled using internal boundary conditions along the edges of cavities created by removing material assignments. Each internal edge was assigned a fluid supply temperature, enabling convective heat transfer to the surrounding material. The supply temperatures were pre-calculated on an hourly basis, based on the ambient air temperature from DWD data and a heating curve specific to each system. This approach is illustrated in Figure 63 - Figure 65 for the three heating systems under consideration.

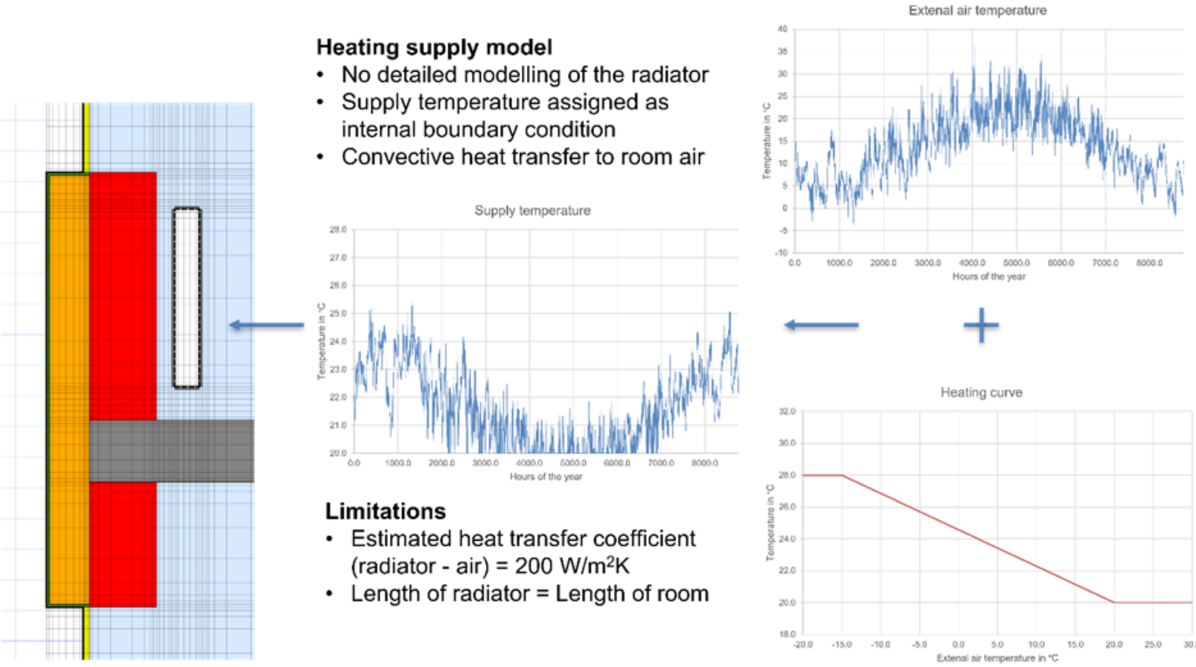


Figure 63: Detailed modelling of the standard radiator via an internal boundary condition with supply temperature. Source: TU Dresden

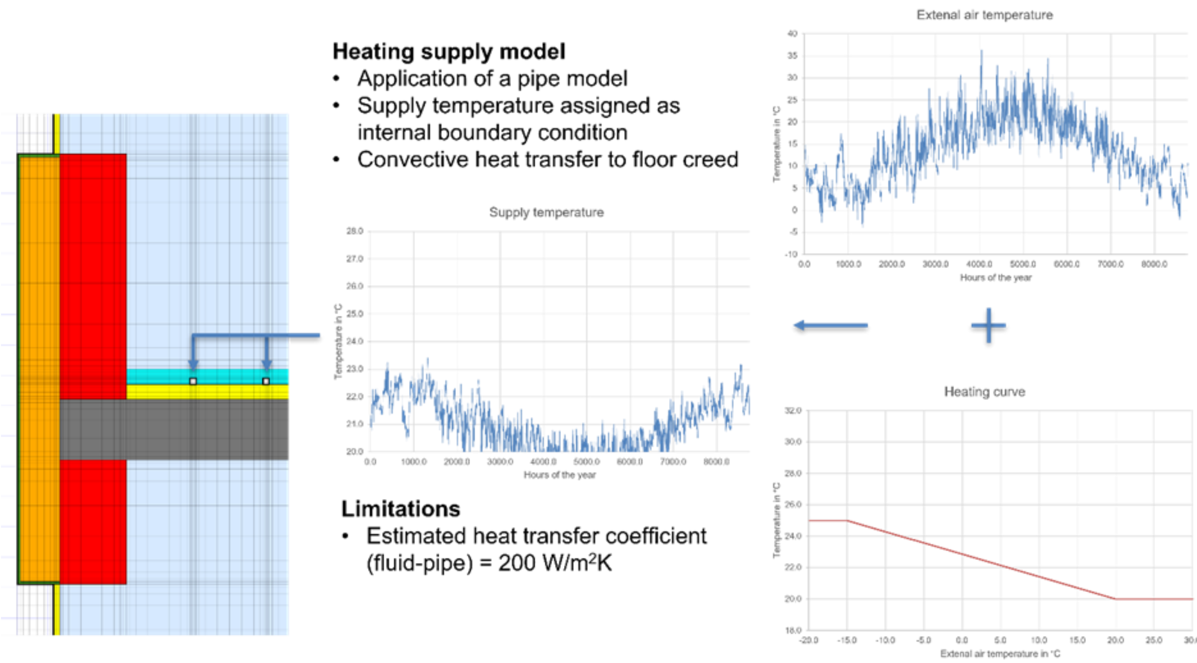


Figure 64: Detailed modelling of the floor heating system via an internal boundary condition with supply temperature. Source: TU Dresden

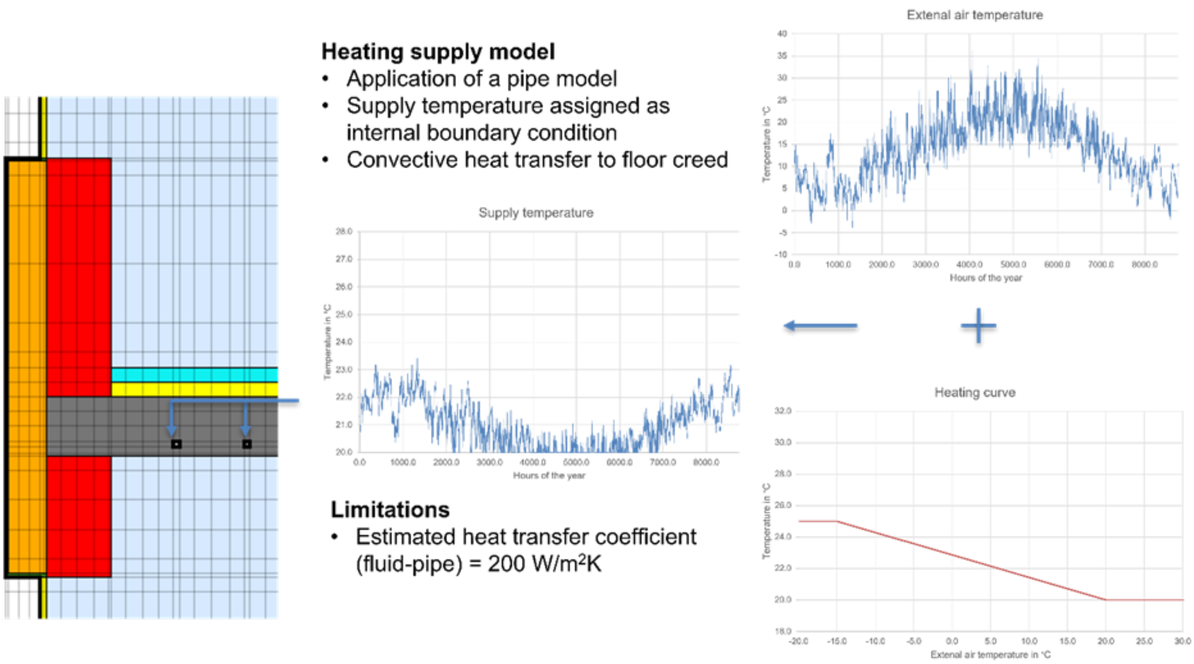


Figure 65: Detailed modelling of the ceiling heating system via an internal boundary condition with supply temperature. Source: TU Dresden

For the standard radiator, heat is transferred to the room air via the time-dependent flow temperature and convective heat transfer. Since the width of the radiator in the z-direction corresponds to the room depth, it may be slightly oversized. In practice, the radiator would be sized according to the width of the window. However, in this model, the window also has the width of the room depth.

The underfloor and ceiling heating systems are more complex: in practice, heating circuits are arranged to ensure uniform surface heat distribution. This requires interconnected pipe loops, where the return temperature from one pipe becomes the inlet temperature of the next. While the mass flow rate may vary over time, it remains constant along each connected circuit.

For these systems, the total heat transfer must be calculated as an integral over the pipe length and circumference, based on the temperature difference between the fluid and the surrounding material and a convective heat transfer coefficient. The fluid temperature along the pipe length follows an exponential decay function, derived from the differential equation for steady-state flow. The temperature of the surrounding material is determined for each individual pipe by discretizing the area around the cavity. This approach, for example, captures the increased heat transfer from a pipe to the side with the higher thermal conductivity when the pipe is located between an insulating layer and a highly conductive layer.

Since DELPHIN has a powerful numerical solution system, the simulation of the variants can be run on a standard notebook in just a few minutes. The results are evaluated using a program called POSTPROC. It is a scientific post-processing tool developed by Bauklimatik Dresden GmbH for analysing and visualizing simulation results, especially from DELPHIN.

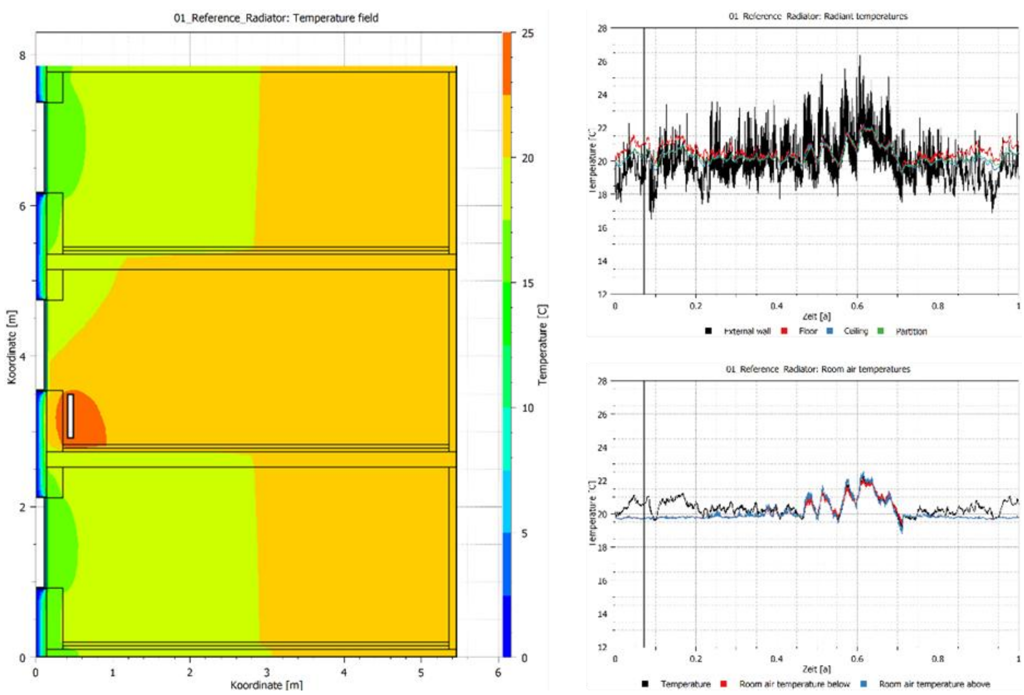


Figure 66: Temperature field in wintertime (17th of January, left), annual radiant temperatures of the surfaces (top right) and annual room temperatures (bottom right) of the reference using a radiator (01_Reference_Radiator). Source: TU Dresden

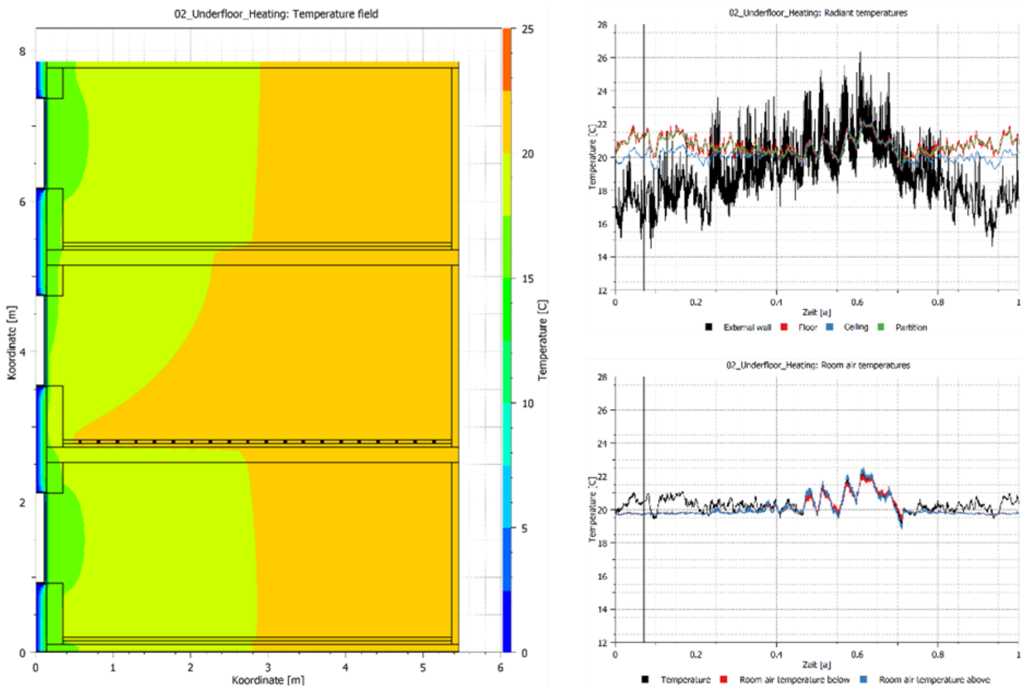


Figure 67: Temperature field in wintertime (17th of January, left), annual radiant temperatures of the surfaces (top right) and annual room temperatures (bottom right) of the variant using underfloor heating (02_Underfloor_Heating). Source: TU Dresden

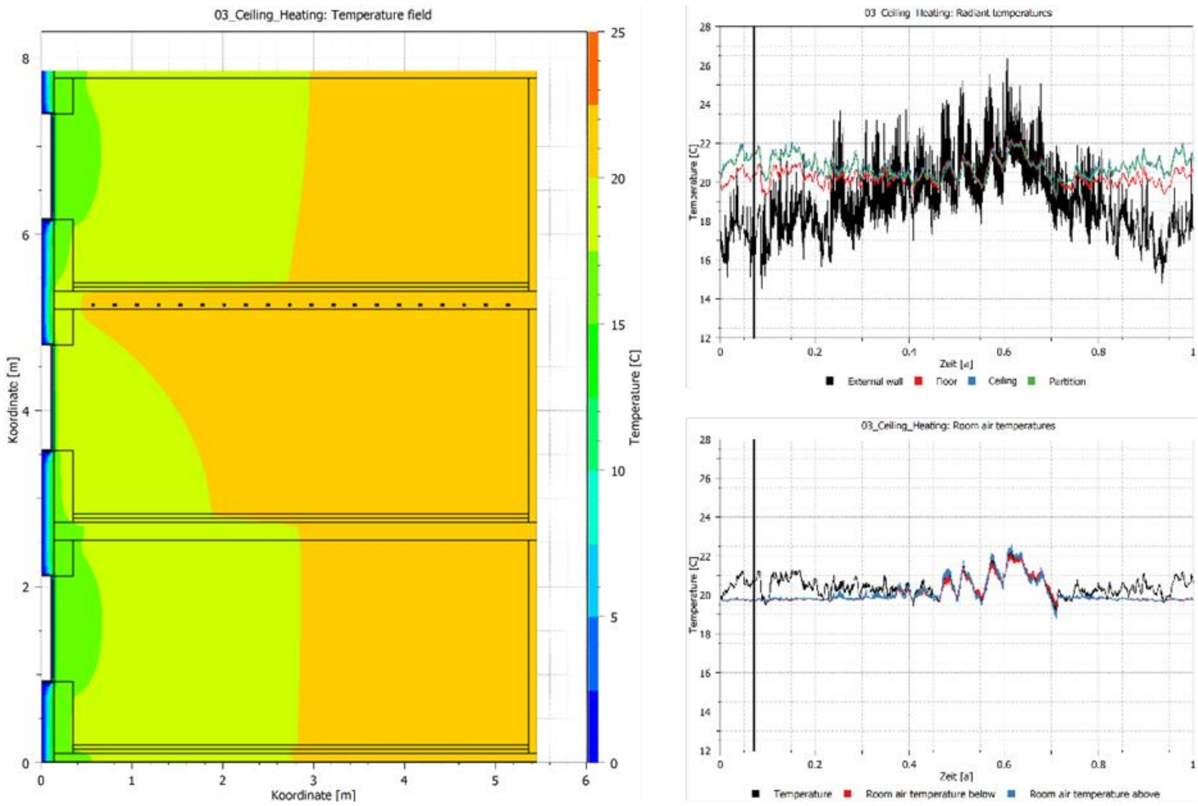


Figure 68: Temperature field in wintertime (17th of January, left), annual radiant temperatures of the surfaces (top right) and annual room temperatures (bottom right) of the variant with ceiling heating (03_Ceiling_Heating). Source: TU Dresden

The results of the different variants, evaluated using POSTPROC, are shown in Figure 66 - Figure 68.

On the left, temperature fields for the coldest time in winter are shown. On the right, the annual temperature profiles are given in hourly resolution for the whole year starting at January 1st 0:00 and ending at December 31th 24:00. The time at which the temperature field is plotted is indicated by a vertical line in the annual profile curves.

The difference between the temperatures of the ideally heated rooms (top, bottom) and the middle room is clearly visible. It is also noticeable that the ideal heating system maintains room temperatures very precisely at 20°C during the heating season, as a tolerance of only 1 K was specified. In summer, however, room temperatures exceed 20°C in all rooms, which is to be expected since no air conditioning is used.

Comparing the annual temperature profiles in the rooms, it is noticeable that the control system in the middle room allows for larger deviations from the target temperature for all variants than the ideal heating system. This is primarily due to the fact that the radiator model does not include a mass flow rate, while the pipe model assumes a constant mass flow rate. This would imply that the residents do not use the radiator's thermostat. This is not a limitation of the model and can certainly be modelled differently if necessary. For example, the radiator could also be modelled using a pipe model in the z-direction, and the mass flow rates could be specified as time-dependent.

The radiant temperatures shown in the upper temperature plots are defined as wall surface temperatures. In the DELPHIN model, these are output as the average temperature in the first 10 mm of the structure. For the exterior wall, the surface temperature of the window was also included. Comparing these values across the different variants reveals differences. With a radiator, the radiant temperature in winter is closer to that of the other wall surfaces, suggesting that the colder window is compensated for by the placement of the radiator below it.

HTFlux

HTFlux, developed by HTflux Engineering GmbH in Austria, is a commercial software that simulates heat and moisture transport in 2D by employing numerical methods, particularly the finite element analysis (FEA). HTFlux is validated according to standards such as EN ISO 10211 and EN ISO 10077, ensuring its reliability for building physics applications. It provides access to a database of diverse materials such as wood, concrete, hybrid composites and various window frames and glass compositions. See Figure 69 for an example of using HTFlux to investigate the thermal properties of wooden materials as a replacement for concrete in TABS applications. There are tutorials available both as web pages (HTFlux, 2026) and as videos on YouTube.

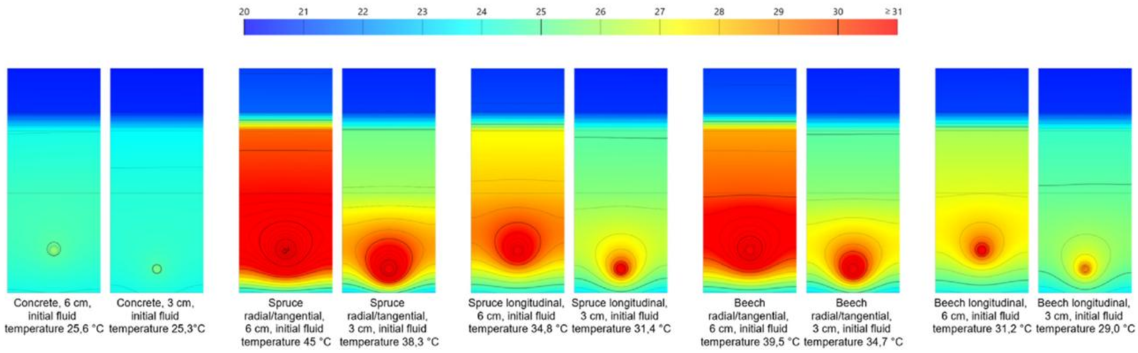


Figure 69: HTFlux simulations of initial temperature distribution of a thermally activated component made of different materials. Source: (Heidenthaler, Leeb, Schnabel, & Huber, 2021).

HTFlux is specialized on steady-state simulations and visualizing temperature distribution, heat flux, and implements a 2D variant of the Glaser method to calculate condensation. Dynamic simulations are also possible, but are based on periodic, pre-defined boundary conditions. It is not possible to couple it to external tools in a co-simulation manner. Instead, the software produces informative plots and reports.

The workflow consists of specifying a geometry, either by loading a CAD file (.dxf) or drawing it with the internal tools. Then the user applies materials, defines boundary conditions and can perform steady-state simulations. Based on the steady-state simulation results, which specify the spatial resolution, dynamic simulations or the Glaser simulations for the estimation of condensate quantities can be performed.

Physibel Program Suite

The Belgium-based company Physibel offers a suite of programs based on the Finite Element Method with individual strengths for different applications. BISCO and BISTRA are 2D simulation tools and together are comparable to HTFlux, with BISCO offering steady-state analysis and BISTRA transient simulations. Their main application is the thermal study of windows, doors, and curtain walls. They can be used for thermal bridge and surface condensation analysis. They also offer the capability to handle detailed infrared radiation and thus model thermal comfort using the RADCON module, which is especially interesting in the context of TABS. A speciality of BISTRA lies in its consideration of temperature-dependent component properties, making it possible to investigate thermal stress in glass and detect glass fracture, perform fire simulations, and to consider phase change materials (PCM).

TABS systems can be approximated by simulating multiple slices along the z-axis (the direction of the pipes). Alternatively, the 3D equivalents to BISCO and BISTRA are TRISCO and VOLTRA. These are limited to rectangular shapes, while SOLIDO also allows to have arbitrary geometries.

VOLTRA is maybe the best suited for evaluating thermal comfort when using TABS. Its ability to perform transient heat transfer simulations makes it ideal for dynamic evaluations of TABS under varying conditions, such as changes in water temperature, flow rate, and material properties. Its detailed modelling of supply and return water temperatures, as well as transient surface temperature distributions, allows engineers to optimize TABS designs for both energy efficiency and occupant comfort. The ability to model TABS incorporating PCM or other advanced materials like graphite/PCM concrete, accounting for latent heat storage and providing accurate predictions of heat storage and dissipation during phase transitions, makes it useful to also investigate the effects of different operational strategies. However, as with HTFlux, there is no option to perform co-simulations, so a coupling between a control algorithm and the simulation is not straightforward.

Modelica and the Modelica Buildings Library

Modelica is a declarative, equation-based, object-oriented language for modeling multi-domain physical systems. Its main frontends are the commercial software *Dymola* (Modelica, 2026) by Dassault Systems and the open version *OpenModelica*. Instead of specifying an input-to-output signal flow as in causal simulation software such as *Simulink*, physical equations can be specified directly; the solver figures out causality at compile time and integrates the resulting differential-algebraic equation (DAE) system. This allows the definition of acausal connectors and automatic energy and mass conservation: Components connect through physical ports (fluid, thermal, electrical, …) that correspond to equations conserving the equivalents of both pressure and flow, allowing the solver to determine causality during compilation.

Modelica is a general simulation language. As such, it is inherently multi-domain, enabling the integrated simulation of thermal, electrical, hydraulic, and control systems within a single environment. The availability of standardized open component libraries, such as the *Modelica Buildings Library* (Library, 2026) and *AixLib*, both based on the jointly developed *IBPSA* Modelica models, provides access to well-documented models while allowing researchers and practitioners to adapt and extend the underlying models. These features make Modelica particularly suitable for applications where strong interactions between building physics, thermal energy systems, and external signals (such as dynamic tariffs or balancing energy markets) must be represented in a unified model.

In Modelica, thermal components are typically represented using one-dimensional conduction models for walls and slabs, coupled with radiative and convective heat exchange at the surface. Alternatively, predefined simplified or detailed models such as the Buildings.ThermalZones.Detailed.MixedAir model can be used, or external simulation tools can be linked via functional mockup units (FMU). For example, the building and control simulation engine Spawn of EnergyPlus (Energy Plus 1. , 2026) links EnergyPlus (Energy Plus 2. , 2026) envelope models with the Modelica model representing HVAC component simulation and control logic. Hydronic distribution systems are modeled through fluid ports that account for mass flow, pressure, and enthalpy exchange. Control logic can be integrated at different levels of complexity, from proportional–integral (PI) loops to model predictive control (MPC) using co-simulation interfaces such as FMI/FMU.

The Buildings.Fluid.HeatExchangers.RadiantSlabs package of the the Modelica Buildings Library provides parameterized models specifically designed for hydronically activated slabs and floors. The library includes models for single- and multi-circuit slabs, which can be adapted to different geometries and hydraulic layouts. Parameters include slab thickness and material properties, number and length of circuits, pipe spacing, and depth of embedding. The library also provides connectors for coupling slab surfaces to room models, ensuring a physically consistent representation of radiant and convective heat exchange. Integration with hydronic components (pumps, valves, sensors) facilitates the inclusion of radiant slabs into larger HVAC and energy system models.

Without linking to external tools, TABS are modeled in Modelica by combining three key elements:

- Slab conduction model: Heat conduction through the concrete slab is represented by a multi-layer discretization that captures the thermal time constants of several hours to days.
- Pipe–concrete coupling: Hydronic circuits embedded in the slab are modelled as fluid volumes exchanging heat with the surrounding solid material. Parameters such as pipe diameter, spacing, burial depth, and flow rate define the effective heat transfer.
- Surface coupling to zones: Heat fluxes at the slab surface are split into convective and radiative components, allowing interaction with the room air and other surfaces for accurate comfort assessment.

Through these elements, TABS models in Modelica capture both the slow response dynamics of the slab and the interaction with room-level conditions. This enables the assessment of control strategies such as supply temperature reset, pre-heating or pre-cooling, and predictive charging in response to external signals.

Many libraries are based on models developed in the *IBPSA* (IBPSA, 2026) project, which in turn was part of IEA EBC Annex 60. Its main objective was to provide standardized and open software that builds the basis of next generation computing tools for the design and operation of building and district energy and control systems. Of special note is also the BOPTEST (BOPTEST, 2026) initiative which provides a framework for testing the performance of building control systems. It is also based on Modelica and provides a RESTful HTTP API that is used to start a building emulator, set up tests, control the virtual systems, access data, and report KPIs.

IDA ICE

IDA ICE (EQUA, 2026) (Indoor Climate and Energy) is a commercial, whole-year detailed and dynamic 3D multi-zone simulation application for the study of thermal indoor climate as well as the energy consumption of the entire building. As such, it models heating and cooling, including components such as heat pumps, thermal storage, pumps, and HVAC, as well as electrical aspects such as yield from photovoltaic cells and batteries.

Like Modelica, it uses equation-based models and handles acausal connections in its solver. However, since it is specialized for the simulation of buildings and not an all-purpose simulation engine, its user interface is more streamlined, and it is more commonly used outside of the researcher community for this specific use case.

IDA ICE does not officially support co-simulation, which makes integrating more complicated control strategies such as model-predictive control difficult.

With the BIM import extension, building data can be imported by the open and neutral IFC (Industry Foundation Classes) format commonly used in Building Information Modeling (BIM). It includes geometry (walls, roofs, walls, windows and doors), spaces (to create zones), and sets of properties (for walls, windows and materials) and can be exported by all leading CAD tools such as ArchiCAD, AutoCAD Architecture, Autodesk Revit, Bentley Architecture, DDS CAD, MagiCAD, Plancal Nova and many more.

The boreholes extension provides the prediction of the performance of large fields of interacting boreholes, which together with heat pumps can be an excellent choice for the provision of heating and cooling via TABS.

Thermally activated building components are modelled using a model by Koschenz and Lehmann, see (Koschenz & Lehmann, 2000) and in accordance with the European standard EN 15377-1. This model assumes a fictive layer in the material through which heat or cold is introduced. The 3D transient heat conduction is approximated with a small error to 1D heat conduction. The pipe's influence is approximated through equivalent thermal resistances, such that a sufficiently accurate connection between the supply temperature and the mean material temperature is obtained (Nageler, et al., 2018).

TRNSYS

TRNSYS , (Klein, 2017), short for TraNsient SYstem Simulation and pronounced 'tran-sis', is a complete and extensible environment for the transient simulation of a wide variety of systems, including multi-zone buildings and thermal and electrical energy systems (wind, solar, photovoltaic, hydrogen systems) (TRNSYS, 2026). Individual components are represented as so-called "Types" that exchange information with each other, and a performant solver written in FORTRAN solves the resulting equations to convergence. The results are plotted or output to a file.

The basic software includes "Type 56" representing a multi-zone building model. It can model zone temperatures, air exchange and humidity, and has a wide variety of window types it can handle. A specialized program called TRNBuild is used to pre-process a building description that is then encoded in special files read in by Type 56 in the main TRNSYS). It is possible to import building information from different sources, mainly in the form of an .idf file. However, since there is no real standard, this seems to lead to problems sometimes, and the preferred way is to generate models in the SketchUp plugin TRNSYS3D.

The walls can be represented by multiple layers, and there is the option to define an "active layer" to couple fluid mass flow with the building dynamics and thus model TABS. The user needs to provide the inlet temperature and the mass flow rate as inputs, e.g., from a controller and other types modelling the energy hub, and obtains the outlet temperature as an output. The TABS configuration is limited to the diameter of the pipes, their spacing (center to center), thickness, and the pipe wall conductivity; the pipe layout cannot be considered. The heat transfer through the slab is based on an efficient approximation of heat transmittance in the x-y plane (the cross section orthogonal to the direction of the pipe) and the mean temperature of the fluid in the pipe along the z-axis, resulting in a good approximation of the core and surface temperature. The approach is described in detail in section 6.4.4 of the TRNSYS 16 documentation, Volume 6 on Multizone Building modeling with Type56 and TRNBuild (Solar Energy Laboratory, Univ. of Wisconsin-Madison, 2007).

TRNSYS has an extensive library of components, with more detailed and professional models available via the TESS library (TESS, 2026). This also includes other types to model TABS, from Type 653 for a simple floor heating system (an even simpler version than the active layer in Type 56) to Type 993 modelling parallel horizontal pipes in a slab. TRNSYS can also be extended by linking it with customized DLLs, and there are links to Python (CFFI (CFFI, 2026)), the Building Controls Virtual Testbed (BCVTB) middleware via Type 666 (limited to 100 variables), among others. As such, it is ideal to simulate building control, heat provision via central heating, solar thermal collectors or heat pumps, et cetera. This allows for very efficient simulations of single buildings; for multiple buildings and districts, simplified types need to be used: There can only be one instance of Type 56 in a simulation.

TRNSYS is a mature software with a somewhat outdated user interface. It is still widely used in academia due to its extensibility and broad area of applications and computation speed.

3.1.3 Conclusion and Recommendations

There is a wide variety of simulation tools, and an even wider variety of specialized tools (1D-HAM, ESP-r, …) available. For checking thermal conduction, hygrothermal effects and the possibility of condensate forming, 2D simulations based on finite element modelling (FEM) such as HTFlux, BISCO and WUFI 2D might be the most straightforward and easy to use. If temperature-dependent material properties, e.g., for the consideration of phase-change materials is required, transient simulations such as VOLTRA or DELPHIN must be considered.

For the combined modelling of the building envelope and heating and cooling, IDA ICE is probably a good contender with a modern user interface and an easy representation of larger buildings. More experienced users can try to use TRNSYS and Modelica; however, the large variety of available models and the lack of a unified or modern user interface make this more difficult to handle. On the other hand, if co-simulation for the testing of advanced control algorithms is a goal, the FMU capabilities of Modelica and DELPHIN stand out; TRNSYS can also be easily incorporated using various coupling types.

From the perspective of correct TABS representation, finite-element method-based simulations (HTFlux, BISCO, WUFI 2D, DELPHIN) should be relied on for the spacing of the pipes and avoiding the risk of condensation, esp. in the case of ceiling cooling, and to answer questions related to thermal comfort. For larger-scale simulations of rooms and buildings, the simplified models used in TRNSYS, Modelica and IDA ICE, if correctly parametrized, are sufficiently accurate to capture the dynamic implications on indoor climate.

3.2 System Concepts

In this section, TABS are not seen as individual technology, but as being a part of a whole. The systemic viewpoint must consider aspects from architecture over statics to energy provision, using the storage capabilities for local optimization or even business models considering the connection to the electrical grid or thermal network.

3.2.1 General strategy of system design

Designing systems with thermally activated building components (TABS) involves a holistic, interdisciplinary planning process that links architecture, building physics, structural engineering, and energy systems. The following is a summary from design guidelines issued by the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK) (Friembichler, Handler, Krec, & Kuster, 2017), enhanced with considerations deduced from the case studies and current research in the area of TABS.

Integration into Building Design

The integration of TABS must begin early in the design process. Because the system becomes a part of the structural building components, decisions regarding TABS affect the architectural layout, the structural dimensions (particularly ceiling thickness and reinforcement), and the coordination of technical systems. A key requirement is a high-performance building envelope that minimizes thermal losses. Only when the transmission and ventilation heat losses are sufficiently low can TABS cover heating and cooling loads reliably and without the need for auxiliary systems.

For this reason, TABS are most suitable for buildings that meet or exceed low-energy or passive house standards. Heat loss should ideally not exceed 25 W/m^2 of treated floor area, allowing the entire thermal demand to be met via the ceiling. High levels of insulation, airtight construction, heat-recovery ventilation, and solar shading are all essential prerequisites. These design criteria not only reduce the required heating power but also enhance the cooling effectiveness in summer, when limiting solar gains becomes equally important.

Comfort and Control Strategy

TABS systems function primarily through radiant heat transfer, minimizing convective currents and allowing for extremely uniform room temperatures. Comfort is maximized when the temperature of the activated surfaces does not differ from room setpoint temperatures by more than 4 K. Thanks to the large surface areas and moderate temperature gradients, TABS systems exhibit a “self-regulating” behavior: as room and surface temperatures converge, the heat output naturally declines. This simplifies the control strategy, allowing room temperatures to be regulated using just a few core sensors, without the need for high-precision modulation. Note that this is no longer the case if the thermal mass is actively used as storage; then more care must be taken such that the surface temperatures do not diverge too far from the room temperature (both for reasons of comfort and, in the case of cooling, to avoid condensation).

Thermal comfort is further enhanced by the even distribution of surface temperatures, which avoids hot or cold spots, drafts, or noise. Because TABS operate at low heating and high cooling temperatures, they are particularly compatible with renewable energy sources and efficient heat generators such as heat pumps.

Energy Supply Strategy

The synergy between TABS and renewable energy technologies is central to the system design. TABS are ideal for use with heat pumps, which can operate at very high coefficients of performance (COP) when delivering low-temperature heat. Solar thermal energy and photovoltaics can also be effectively integrated, with energy converted and stored in the building's concrete mass during periods of surplus. For instance, solar thermal collectors can charge the system during daytime, while the stored heat is released gradually over many hours, smoothing peak loads and reducing the need for on-demand generation.

Similarly, photovoltaic systems coupled with heat pumps enable flexible energy management. Excess PV electricity can be used to run the heat pump during off-peak hours or periods of low electricity prices, transferring energy into the building mass. This approach not only increases the self-consumption of PV power but also stabilizes the local electricity grid by providing demand-side flexibility. TABS can even act as thermal batteries, storing energy when wind or solar production is high and releasing it later, without noticeable comfort disruptions.

Where available, connection to a district heating network can also be considered. Although conventional district heating systems operate at temperatures higher than needed for TABS, proper integration via mixing circuits or secondary loops can enable efficient operation. However, district heating is generally less suited for cooling applications unless supplemented with reversible systems or local heat rejection infrastructure.

Passive and Active Cooling Potential

In addition to heating, TABS provide a passive and energy-efficient method for cooling. Passive cooling uses the natural thermal gradient between the building and its environment, often exploiting ground-coupled heat exchangers or groundwater sources, with only minor electricity consumption for circulation pumps. Active cooling via reversible heat pumps enables further temperature control when passive means are insufficient. Both strategies benefit from the thermal mass of the concrete structure, which can absorb heat during the day and release it at night, especially if complemented by night-time ventilation and effective solar shading.

3.2.2 Difference to floor heating

Floor heating and thermally activated building systems (TABS) are two low-temperature heat emission systems commonly used in buildings. While both leverage the thermal mass of building components, they differ fundamentally in their design, energy flexibility potential, and effectiveness in heating and cooling applications.

Construction and Thermal Coupling

Floor heating typically consists of water-bearing pipes embedded in the floor structure (usually screed). It provides radiant heating from the bottom upwards and is primarily optimized for heating. Due to the positioning in the floor slab, it only partially exploits the building's thermal mass. In contrast, TABS integrate heating and cooling circuits directly into the load-bearing concrete structure, most commonly in ceilings or walls. This direct coupling with high-mass components allows TABS to utilize a significantly larger proportion of the building's thermal storage capacity.

Thermal Inertia and Energy Flexibility

The increased thermal mass connected to TABS gives them a distinct advantage in energy flexibility. In a study comparing cost saving potential for a city district, TABS achieved the highest cost reduction potential (up to 21.3%) when operated with a variable temperature setpoint driven by dynamic electricity prices (Heidenthaler, Leeb, Moltinger, & Bednar, 2023). This is due to their ability to store thermal energy during low-price periods and release it during high-price periods with minimal losses. Floor heating systems also provide load shifting potential, but to a lesser extent, because of their smaller thermal mass engagement.

If actively used for storage to provide flexibility, TABS can exhibit higher peak loads compared to floor heating and radiators. Due to a slower propagation of the feed temperature to the surface, feed temperatures can be chosen much higher or lower and for longer times than for floor heating applications. This allows for a wider power range for charging and discharging.

Suitability for Cooling

A key advantage of TABS lies in their bidirectional use. Unlike floor heating, which is mainly designed for heating and has limited cooling capability due to comfort and condensation constraints, TABS are well-suited for passive or active cooling. Their large surface area and slow response characteristics make them ideal for maintaining stable indoor temperatures, especially in high-performance buildings with significant internal and solar gains.

Operational and Comfort Aspects

From a control perspective, both systems require careful tuning to avoid overheating or undercooling due to their inertia. TABS, due to their slower response time, are more dependent on predictive control strategies. Floor heating reacts somewhat faster but still lags behind convective systems like radiators. Occupant comfort is generally high with both systems, especially due to their silent operation and even temperature distribution, but cooling with TABS may require additional dehumidification systems.

3.2.3 Local system design

Local system design focuses on two main aspects: Thermal comfort based on near-ambient temperature sources for heating and cooling and, if available, the efficient use of local, fluctuating renewable energy sources. In contrast, operation can also be designed to positively interact with the electricity or heat networks; see section 3.2.4 for more information about this.

There are two opposing approaches for TABS-based system design: Without fluctuating energy sources, the thermal inertia of TABS can be used to reduce the modulating requirements of the heat source, e.g., a heat pump, leading to very constant operation and low peak power demands, thus leading to low connection power ratings and costs. Operating temperatures will be only slightly different from desired room temperatures. If, however, fluctuating renewable energy sources are available, the thermal mass can be used to store surplus energy for later times. In both cases, the large surfaces allow the use of low temperature sources for heating and even passive cooling in summer using ground water (“free cooling”). The main difference is the power requirements for the energy hub and whether active charging and discharging of the building mass is a goal or not.

Another design criterion is whether TABS is implemented in a new building or whether it is added to an existing building as a refurbishment. Here, the goal often is to interfere as little as possible with existing infrastructure and the residents, and the strategy is to attach pipes to the outside of an existing building envelope and add an insulation layer to the façade.

For both cases, pre-fabrication of slabs or façade elements can have positive impact on the economic and ecological aspects.

In the following, the different system designs are investigated, their advantages and disadvantages are outlined, and the main applications are discussed. A summarizing table can be found in Table 11.

Concrete Core Activation (Ceiling/Floor TABS)

Thermally activated building systems (TABS) embedded in concrete slabs involve hydronic piping cast directly into ceilings—or occasionally floors—leveraging the concrete's thermal mass to serve as both radiant emitter and sensible heat reservoir. By circulating hot or cool water through these circuits, indoor temperatures are regulated through radiant exchange and the slab buffers diurnal temperature swings.

The piping can be integrated into slabs cast *in situ*, or pre-fabricated slabs can be used. This variation uses factory-made precast floor elements featuring either hollow-core structures or layered (sandwich) composition. Hydronic piping is placed near the underside of the slab, with manifolds decentralized to facilitate individual-room control. In contrast to solid concrete slabs, sandwich and hollow-core constructions require less CO_2-intensive concrete while providing similar static stability. From the point of view of heating and cooling, this insinuates that less thermal mass is available as storage. If only the lower shell is available for installing the pipe registers, an arrangement of the pipes close to the surface can increase thermal output significantly (70 W/m^2 for cooling and approximately 50 W/m^2 for heating) and increase responsiveness. On the other hand, a sandwich construction can also allow to operate the upper layer as an energy storage due to the insulating effect of the cavity separating the layers.

Benefits:

- Excellent integration into the building structure yields high thermal storage and uniform comfort. Prefabrication additionally enhances construction quality and cleanliness; its lower concrete volume reduces embodied carbon.
- Low-exergy operation aligns well with heat pump systems, reducing energy use.
- Noise-free radiant transfer enhances occupant comfort.

Drawbacks:

- Response times are slow due to the large heat capacity, limiting use in situations requiring rapid set-point adjustment. Faster response times can be achieved with a layer composition and pipe registers inserted closer to the surface. However, storage capacity is then less than that of massive slabs, reducing effectiveness for diurnal shifting.
- Retrofitting into existing structures is challenging, requiring significant work.
- Control complexity increases due to thermal lag and potential overshoot.

Limitations:

- Best suited for newly built projects with predictable loading patterns.
- Zoning must be coarse; perimeter or peak-load demands may require supplemental systems. For prefabricated slabs, however, decentralized manifolding supports effective thermal zoning. On the other hand, interfaces between prefabricated elements require careful detailing and more elaborate plumbing logistics.

Opportunities:

- Combining with forecasting strategies (weather or occupancy) and fast-response supplemental technologies can address peaks.
- Using low-carbon or alternative concrete can reduce embedded emissions while retaining mass benefits.

Retrofit Façade Activation

If a building already exists, a common renovation procedure is to add external insulation and change the existing heating system from a fossil fuel-based boiler to a heat pump. In order to be minimally invasive, one of the goals is to keep existing radiators, even though their surface is often too small to provide the required heating power when operated at low temperatures of about 40°C. Adding a heating or cooling pipe layer between the existing wall and the external insulation acts in a similar way to concrete core activation. Proposed solutions include thin capillary mat systems, creating grooves in the existing masonry and inserting the pipes there, or pressing entire concrete sandwich slab modules onto the walls.

When operated at close to room temperature, such setups can reduce the losses through the wall to almost nothing; with higher operating temperatures, interior heating can be omitted entirely. In summer, cold ground water can be used for free cooling, or a chiller can be used for active cooling.

The main challenges are ensuring thermal conductivity between the pipes and the wall, avoiding problems with moisture and heat bridges while guaranteeing structural integrity, especially if the external elements are heavy. Another main concern is recyclability and the CO_2 footprint of the façade elements. Additional considerations are external noise dampening and optics.

Benefits:

- Interior disruption is minimal—ideal for occupied retrofits. Leverages existing radiator and hydronic systems at reduced supply temperatures.
- Low-exergy operation improves façade hygrothermal performance and reduces risk of condensation, frost, or microbial growth.
- Exterior mounting favors integration with PV, geothermal, or grid-responsive systems. Circularly designed materials further support sustainability.
- Flexibility in finishing—potential to include PV panels or green façade layers.

Drawbacks:

- Additional layers of façade detailing are required, raising complexity for moisture and wind load resistance. Integration may create thermal bridging if not carefully managed. Grooving for better heat transfer requires structural checks in load-bearing elements. Milling generates noise and particulate—site logistics must manage this.
- Hydraulic design must carefully address long loops, insulation continuity, ventilation cavity integration, and moisture barriers.
- Complexity in coordinating acoustic, ventilation and thermal performance.

Limitations:

- Performance is limited by façade surface area; more suited to base-load conditions than dynamic peak loads.
- Not a standalone solution for colder climates or peak loads; supplementary heating is often required.
- Capital-intensive for full façade replacement projects.
- Requires meticulous detailing at junctions and openings.

Opportunities:

- Ideal for deep retrofit or renovation programs. Strong potential for scalable retrofit strategies has been supported by building digital twins and district-scale modeling.
- Refinement of standardized installation workflows could accelerate roll-out in multi-unit buildings.
- Offers potential to integrate active façade components (e.g., shading, solar PV, acoustic panels) in façade assemblies.

Insulated-Core TABS for Long-Duration Storage

Concrete core activation and façade activation both rely on passive discharging of the activated element, meaning that heat is conducted from the internal pipes via the concrete or wall material towards the surface and then radiated into the room. This severely limits the way such systems can be operated in terms of acceptable feed temperatures. A difference of more than a few degrees Kelvin from the desired room temperature can result in reduced comfort. As a result, the storage capabilities of such systems are rather limited, both in terms of capacity and in terms of duration the storage remains charged.

An alternative approach separates thermal storage (heavy core) from emission by insulating both sides of a dense thermal core (e.g., concrete or sand-lime brick). The core is charged to higher temperatures (~45 °C) during renewable energy surplus, then discharges heat passively and slowly through the insulation, or actively by pumping water from the core to an active register closer to the surface.

An extreme example uses the insulated foundation slab of a building as thermal storage for heat from solar collectors.

Benefits:

- Can maintain heating for 1–2 weeks, enabling charging aligned, e.g., to typical cycles in wind power output.
- Ceiling installations (e.g., with $\lambda \approx 2.3$ W/mK concrete) have higher charging/discharging capabilities than wall solutions.

Drawbacks:

- Requires added insulation bulk, increasing envelope thickness.
- Control strategies are complex to avoid overheating.

Limitations:

- Best fit for highly efficient buildings integrated with renewable supply.

Opportunities:

- Excellent platform for price-responsive energy markets and sector coupling.
- Further research should optimize insulation thickness for passive loss vs. useful heat flux.

PCM-Enhanced Active Wall Systems

Another way to influence the charging/discharging behavior of activated components is the integration of phase-change materials (PCMs). Like water at the freezing or boiling point, changing the phase of the PCMs requires large amounts of heat; the temperature only increases or decreases further when the phase change process is finished. This addition of latent heat to the sensible heat stored in the walls greatly increases thermal capacity. By using materials with a phase change temperature close to the desired room temperature, PCMs naturally lead to more comfortable room temperatures since the wall temperatures cannot increase or decrease as quickly as without PCMs.

Implementations use wall modules that are constructed using plaster or gypsum layers enriched with PCMs, embedding hydronic tubing for charging or discharging. Designed for active cooling and peak-shaving, these systems store and discharge cooling over extended periods.

Benefits:

- Extended discharge times—peak cooling shifts into off-peak hours.
- Tests show 2–3 K lower surface temperatures and ~24 % higher cooling power with 30 % PCM versus non-PCM walls.

Drawbacks:

- Incorporating PCM slows down response (higher τ_{63}/τ_{95}), potentially hindering responsiveness.
- Material compatibility and long-term stability of PCM in the plaster matrix require verification.

Limitations:

- Better suited to short, frequent peaks rather than continuous high loads.

Opportunities:

- Targeted application near piping may enhance discharge efficiency.
- Ideal for energy-flex buildings aiming to shift peaks and offer demand-response capabilities.

Comparison Table

Table 11: Different system concepts for TABS.

System Family	Typical Output (W/m²)	Storage Capacity	Response Speed	Invasiveness	Best Use Cases
Slab-embedded (cast-in-situ)	~40–60 (heating), ~40–60 (cooling)	Very high (multi-day diurnal)	Very slow (>6 h)	Only in new buildings	Offices, schools, predictable occupancy
Prefabricated slabs	~50 heating, ~70 cooling	Medium	Moderate (1–3 h)	New buildings, modular	Prefab housing, modular offices
Façade retrofit – Capillary mats/ETICS	~10–20	Low–medium	Fast (<1 h)	Low interior disruption	Mass retrofit, continuous occupancy
Façade retrofit – Slot-groove	~16 façade + 6 transmission W/m²	Low	Moderate	Moderate disruption outside	Housing blocks, boiler to heat-pump conversions
Façade retrofit – Prefab panels	~20–30	Medium	Moderate	Exterior work only, heavy logistics	Deep retrofits,

					institutional buildings
Insulated core	Depends on charging regime	Very high (1–2 weeks)	Slow (days)	Requires insulation + core modifications	Renewable-driven grids, passive houses
PCM-enhanced active walls	~30–45 W/m² cooling, ~20–40 W/m² heating (depending on PCM fraction and supply temperature)	Medium (latent storage enhances duration rather than peak)	Slow to moderate (extended discharge)	Only in new buildings	Peak cooling, variable load spaces

3.2.4 Interaction with grids: Electricity grid and heat networks

The high thermal capacity of thermally activated components, and their corresponding ability to act as thermal storage, can also be leveraged by external grids. This will become increasingly relevant as the share of renewable energy sources in the electrical grid increases and the electrification of transport, but also heating and cooling progresses. Already, heat pumps and thermal storage are seen by grid operators as potential providers of flexibility, and pooling solutions are developed and marketed. Adding the additional thermal capacity of the building itself would further increase the flexibility potential, especially when also considering cooling in summer when power surplus from photovoltaics (PV) production becomes a problem to grid stability.

Buildings not only can be used to balance the diurnal yield from PV, but also to balance loads in the electrical grid due to excessive wind power. Contrary to power from PV, this is especially relevant during winter where heating demands are highest. For example, the project "Windheizung 2.0" of Fraunhofer IBP aimed at integrating building thermal mass and other, high-temperature heat storage technologies to manage surplus electricity from renewable sources, especially wind energy in wintertime. Here, fluctuations have a period of one to two weeks, requiring the ability to store heat for a longer time than default TABS with their continuous passive discharging. The project integrates renewable power into buildings through a power-to-heat strategy, where excess electricity is converted into heat and stored in the thermal mass of buildings or specialized storage systems. Surplus electricity drives electric heating elements, which raise the temperature of materials such as concrete in walls and floors, effectively storing the heat within the building structure. This stored heat is only gradually released to maintain indoor thermal comfort, reducing the reliance on external energy sources. High-efficiency buildings, such as passive houses, are particularly suitable for this system because their superior insulation and low heat loss extend the effective storage duration.

The project also incorporated advanced storage solutions, such as high-temperature stone storage (HTSS) and building-integrated thermal storage (TABS). The HTSS is designed for compact, centralized heat storage, capable of holding sufficient energy to cover heating and hot water needs for one to two weeks during periods of low wind generation. In contrast, the TABS approach integrates heat storage directly into building elements like floors and walls, providing distributed storage capacity and reducing the need for separate systems. Both methods emphasize maintaining high storage efficiency while minimizing passive heat loss through added insulation.

The flexibility potential identified in the project is significant. Simulations revealed that high-efficiency buildings could cover up to 100% of their heating demand using surplus electricity during periods of strong wind generation. Additionally, the system demonstrated a reduction in CO_2 emissions of 7 to 16 kilograms per square meter annually, emphasizing its environmental benefits. By shifting energy use to align with surplus electricity availability, the approach also reduces wind energy curtailment and lowers strain on the electrical grid. This capability enables buildings to act as grid-supporting assets, stabilizing electricity demand and accommodating the variable nature of renewable energy.

To achieve these outcomes, sophisticated control strategies were developed. Predictive algorithms and real-time adjustments allow heating schedules to match grid conditions, using surplus electricity during periods of low demand and reducing consumption when the grid is under strain. This dynamic operation ensures not only energy cost optimization but also the system's contribution to grid reliability and efficiency. Furthermore, the flexibility of this system makes it suitable for participation in dynamic electricity markets, where it can take advantage of pricing signals to further enhance economic viability.

3.3 Control Strategies

TABS are controlled by varying the temperature and mass flow of the fluid flowing through its pipes or capillaries. Their thermal properties can vary considerably based on the total thickness of the slabs, the insertion depth and spacing of the pipes, and the existence of insulation between the slab and the conditioned room. Depending on the thermal properties and the corresponding different system concepts and applications, different control approaches may be required. The classification of these approaches is described in the following section, and the individual approaches are investigated in the corresponding sections.

3.3.1 Classification of Approaches

We will distinguish between three degrees of complexity for the control of TABS. For the default application of simply heating and cooling rooms, the required complexity depends on the thermal properties of the TABS. For a shallow lining of pipes, the systems more closely resemble floor heating systems and, while not reacting as quickly as those, direct control of mass flow through the pipes, depending on room air temperature measurements, is often sufficient. These ad-hoc strategies are explained first in section 3.3.2.

As the thermal inertia increases, temperature control will increasingly benefit from predictive elements. While higher inertia in general helps maintain a constant temperature, foreseeable changes in internal or external disturbances (e.g., increases in internal load due to a meeting in a room, solar irradiation through facades made from glass) may be countered by sufficiently early actions. These predictive control strategies are explained in section 3.3.3.

Finally, TABS provide the possibility to actively charge or discharge them. If they are sufficiently insulated, such as activated foundation slabs, they can act similar to water-based storage; this case is not investigated here. If, however, passive discharge has an influence on the room climate, this needs to be considered one way or another. This is investigated in section 3.3.4.

3.3.2 Ad-hoc strategies based on current measurements

The standard way to control temperature in buildings using TABS is to use a heating curve considering the outdoor temperature, the desired indoor climate and the thermal capacity of the structure to determine the feed temperature. This feed temperature is often identical for all supplied zones, while the mass flow is adjusted for individual zones to account for differences in solar insolation, different temperature requirements, or regulated using a motorized valve to actively consider indoor temperature sensors and provide optimal comfort.

Because of the high thermal inertia, temperature sensors inside of the rooms are often a poor choice and can lead to overshoot if the controller is parametrized too aggressively. Sensors inside of the slab, but close to the surface can be used to avoid overheating or -cooling by detecting high or low temperatures early on. These sensors can also help to control both the air temperature and the radiant surface temperature, the latter playing a significant role in the perceived occupant comfort.

Slow control of TABS can also be combined in hybrid systems with HVAC or home ventilation. Faster control loops adjust the ventilation temperature or flow rate and thus allow a quicker adaption to changes in occupancy patterns, internal loads or desired temperatures.

Irrespective of the application and control method, active control of shading is a prerequisite to lower energy consumption and higher comfort; modern, well-isolated buildings often have a significant share of glass facades and are very difficult to cool if the sun is unimpeded.

3.3.3 Predictive strategies based on forecasts

These control strategies utilize forecasts of the weather conditions and possible models of the building to judge the effect of control actions on the building conditions such as temperature and humidity.

Building models can be categorized into three main paradigms: white-box, grey-box and black-box, see (Drgoňa, et al., 2020). While **white-box models** allow for detail, they typically require the most knowledge. For large buildings this results in considerable modelling effort. Typically, a white-box modelling approach cannot be automated, which makes this approach not well suited for large buildings. **Grey-box models**, on the other hand, describe physical phenomena, but often in a simplified way, and their parameters are estimated from data. Typically, resistor-capacitor (RC) based models are used for this. These capture the dominant time constants and thermal conductivity of the walls within the building envelope. **Black-box** models in general use no prior knowledge about the system at hand. However, they require large amounts of training data to be able to extract and model statistical patterns in the data. Models include autoregressive models, regression models, artificial neural networks, and many other non-parametric models.

In the context of TABS, RC-based grey-box models are used most frequently. These types of models include thermal capacitances for all major thermal masses of the building, e.g. floor, wall, internal structures and the active element. Thermal resistance between these captures the structure of the building. Additionally, internal loads and solar radiation can be considered.

A RC-based grey-box model of 3rd order for a single thermal zone, for example, can be stated as follows:

Equation 4:

$$\begin{aligned}
\frac{\mathrm{d}T_{\mathrm{zone}}}{\mathrm{d}t} &= k_{\mathrm{wall,zone}}(T_{\mathrm{wall}} - T_{\mathrm{zone}}) + k_{\mathrm{floor,z}}(T_{\mathrm{floor}} - T_{\mathrm{zone}}) + \boldsymbol{k}_{\mathrm{sol}}^{T}\boldsymbol{I}_{\mathrm{g}} + d \\
\frac{\mathrm{d}T_{\mathrm{wall}}}{\mathrm{d}t} &= k_{\mathrm{z,floor}}(T_{\mathrm{zone}} - T_{\mathrm{wall}}) + k_{\mathrm{amb,wall}}(T_{\mathrm{amb}} - T_{\mathrm{wall}}) \\
\frac{\mathrm{d}T_{\mathrm{active}}}{\mathrm{d}t} &= k_{\mathrm{zone,active}}(T_{\mathrm{zone}} - T_{\mathrm{active}}) + k_{\mathrm{h}}(T_{\mathrm{feed}} - T_{\mathrm{active}})u_{\mathrm{h}}
\end{aligned}$$

where T_{zone}, T_{wall} and T_{active} are the temperatures of the zone, the wall and the active element, respectively. The ambient temperature T_{amb}, solar radiation $\boldsymbol{I}_{\mathrm{g}}$ and internal loads d are considered as external influences. The control of the zones can be modelled via the feed temperature T_{feed} and the valve position u_h. Other influencing factors include the solar radiation $\boldsymbol{I}_{\mathrm{g}}$ and the internal gains d.

This is a simplified, linearized model that only approximately captures the true behaviour of the system. However, through its simple structure, it is easy to integrate into mathematical optimization problems that allow predictive control methods to consider the thermal zone in their reasoning.

Predictive control strategies, particularly Model Predictive Control (MPC), have emerged as a powerful approach in building energy management, offering the ability to optimize energy use while maintaining occupant comfort. MPC operates by predicting future energy demands and system behavior using mathematical models, which typically describe building dynamics while considering weather predictions and occupancy schedules. They can also consider other elements in the energy supply, such as thermal storage, heat pump efficiency, or active room ventilation. By solving an optimization problem at each control interval, MPC determines the optimal control inputs to minimize energy consumption or costs while adhering to operational constraints, such as thermal comfort and equipment limitations. The anticipatory nature of MPC allows it to respond proactively to external factors like fluctuating electricity prices and varying weather conditions, making it especially effective in integrating renewable energy sources, managing HVAC systems, and coordinating energy storage. This strategy offers significant potential for reducing energy costs and carbon footprints in smart buildings, aligning with sustainability and efficiency goals.

Model predictive control (MPC) is one of the most widely used non-linear control approaches. It is suitable for handling constraints, incorporate forecasts and it easily handles large time constants and dead times – something that is very challenging with traditional control approaches. These benefits make MPC perfectly suited for BEMS in the context of TABS. However, for MPC a descriptive objective function, constraints and state estimation are needed.

The objective function in Model Predictive Control (MPC) for building energy management systems (BEMS) typically incorporates multiple components, with energy costs being a primary factor. However, achieving an optimal balance requires consideration of occupant comfort, which is often defined in terms of maintaining indoor environmental parameters, such as temperature, within specified ranges. These objectives are inherently conflicting, as minimizing energy costs may compromise comfort, and vice versa. Therefore, the tuning of cost coefficients in the objective function is a critical step in ensuring that the trade-off between these competing goals aligns with the specific priorities and operational requirements of the building.

As a model-based control strategy, MPC relies on an accurate representation of the system's current state to make informed decisions about future control actions. In the context of BEMS, this means that the controller must have precise and up-to-date information about key variables, such as the temperatures of thermal zones, walls, and active building elements like HVAC systems or TABS. These state variables serve as inputs to the predictive model, enabling the MPC to estimate the system's future behavior under various control scenarios. Ensuring the accuracy and availability of these state measurements is essential for the effective implementation of MPC, as any discrepancies can lead to suboptimal performance or failure to meet operational objectives.

State and Parameter Estimation

State estimation is a fundamental aspect of any predictive control strategy, as it provides the controller with the necessary information about the system's current state, which serves as the foundation for predicting future system behavior. Accurate state estimates ensure that the model used by the predictive controller reflects the actual conditions of the system, thereby enabling reliable and effective decision-making. One widely employed technique for state estimation is the Kalman filter, which is particularly suited for systems with stochastic noise and uncertainties. This method iteratively refines state estimates by combining model predictions with real-time measurement data, effectively mitigating the impact of noise and inaccuracies in either source.

In addition to state estimation, parameter estimation is another crucial process, as it involves identifying or updating the parameters of the model to ensure its continued accuracy over time. Optimization-based methods are commonly used for parameter estimation, leveraging techniques like least-squares fitting or gradient-based approaches to minimize discrepancies between model predictions and observed data. However, Kalman filtering can also be adapted for parameter estimation, particularly when dealing with time-varying parameters, by treating them as additional states in an augmented state-space formulation. Regardless of the chosen method, the availability of sufficient and high-quality measurement data is vital. Without adequate data, both state and parameter estimation processes risk inaccuracies that could compromise the predictive controller's performance, underscoring the importance of robust sensing and data acquisition in predictive control applications.

3.3.4 Active management of building mass as storage

In contrast to concentrating on occupant comfort alone, the goal of actively managing the building thermal mass is to utilize the inherent flexibility of the building mass as an energy storage. TABS are especially suitable for this, as their storage capacity is typically higher than other surface heating and cooling systems. The low required feed temperatures allow the efficient usage of heat pumps or other low-temperature sources such as waste heat, thus opening the possibility of using the thermal mass as an alternative to an electric battery to, e.g., increase own consumption from photovoltaics, or act as added flexibility for the electrical grid (as seen in, e.g., the Windheizung 2.0 project mentioned in section 3.2.4).

Active pre-heating or pre-cooling requires the controller to choose or combine two different strategies: Either increasing or decreasing the feed temperature, or simply increasing or decreasing the mass flow. The first must consider limitations; while not as sensitive as in floor heating applications, where changes in the feed temperature quickly result in high or low surface temperatures and thus discomfort, the radiant surface temperature must nevertheless be guaranteed to stay within certain bounds. Otherwise, either comfort is deteriorated, or, more critically, condensation can appear and mold formation may occur. The latter strategy, namely varying the mass flow, can limit the heat capacity available as storage.

Active management adds a second objective to the control task apart from temperature control. This objective represents the desired shift in demand and can have very different reasons. Typically, this involves the energy distribution hub, e.g., the heat pump and predicted yield from photovoltaics or varying electricity prices. Incorporating this hub into predictive control models for building energy management introduces significant complexity. These models must now account for both binary decisions—such as activating or deactivating heat pumps and boilers—and continuous decisions, such as adjusting feed temperatures or valve positions. Mathematically, this combination leads to nonlinear mixed-integer problems (MINLP) problems, which are challenging to solve due to their computational intensity and the intricacies of integrating discrete and continuous variables.

One common approach to mitigate this complexity is linearization, where nonlinear models are approximated around a specific operating point or trajectories. This simplification transforms the problem into a mixed-integer linear programming (MILP) problem, which is more tractable for existing solvers. For instance, linearizing the thermal dynamics of a building's HVAC system can facilitate the application of MILP-based energy management strategies.

Another technique involves approximating thermal systems using simplified models that represent the system as a collection of mass flows at constant temperatures, see (Muschick, Zlabinger, Moser, Lichtenegger, & Gölles, 2022). This method reduces the complexity of the thermal storage representation, enabling the formulation of MILP problems suitable for energy management systems. An example of this approach is the multi-layer model of stratified thermal storage, which has been applied in MILP-based energy management systems to enhance computational efficiency while maintaining model accuracy.

These strategies aim to balance model fidelity with computational feasibility, ensuring that predictive control approaches remain practical for real-time application in complex building energy systems.

The control task is basically the same as for the predictive controller. However, due to the more complex system model, incorporating discrete decisions, solving the MPC optimization problem in real time becomes an issue.

3.4 Digital Interfaces and Privacy

In modern building management systems, predictive control techniques have become state-of-the-art for optimizing HVAC (heating, ventilation, and air conditioning) performance while leveraging building thermal mass as a resource for grid flexibility. However, these advancements come with critical challenges. Firstly, predictive control relies on vast amounts of data, including occupant behavior, energy usage, and indoor conditions, which raises significant privacy concerns. Secondly, the reliance on external data sources such as weather forecasts, energy price trends, and grid signals introduces vulnerabilities to cyberattacks and system manipulations. The interplay between optimizing building performance and ensuring data privacy and system security is a crucial issue that requires innovative solutions to make these systems both efficient and resilient in the face of evolving threats.

The use of building mass as a flexibility option for the electrical grid requires the secure, reliable, and privacy-compliant exchange of information between grid operators, energy markets, and buildings. Relevant data includes network-specific signals such as dynamic electricity prices or balancing energy instructions, as well as building-specific data such as photovoltaic (PV) surplus, battery state of charge, and indoor climate conditions (temperature, humidity, CO_2 concentration). The combination of critical infrastructure data with personal or occupant-related information makes data communication a central concern in such systems. The following section discusses the essential aspects of secure and reliable communication for this application. Subsequent sections

3.4.1 Essential aspects of secure and reliable communication

Data Integrity and Cybersecurity

Grid-related signals such as dynamic tariffs, demand response calls, or balancing energy control signals must be transmitted without manipulation. Incorrect data—such as artificially lowered price signals—may lead to unintended heating or cooling activation, causing increased system costs or even stressing the electricity grid.

Key measures to ensure integrity and cybersecurity include:

- Encryption of communication channels (TLS, VPN) to prevent interception.
- Authentication and authorization of communication partners to ensure trusted sources.
- Digital signatures or checksums to guarantee data integrity.
- Continuous monitoring for anomaly detection and intrusion prevention.

Particularly in the context of smart buildings, where numerous devices may be connected, endpoint security and secure firmware updates are also essential.

Operational Safety and Resilience

Data communication failures or corrupted information can lead to unsafe or inefficient building operation. For example, the loss of forecast data may prevent predictive heating control, while delayed balancing signals could result in non-compliance with grid support obligations.

To mitigate these risks, the following strategies are recommended:

- Redundant communication paths for critical signals.
- Fallback strategies such as default operation modes (e.g., maintain comfort temperature when signals are unavailable).
- Data validation and plausibility checks (e.g., comparing tariff signals against known limits).
- Time-stamping of signals to avoid the use of outdated information.

Personal Data Protection

Unlike industrial processes, buildings contain highly sensitive information about their occupants. Indoor temperature, humidity, CO_2 concentration, and detailed load profiles can reveal occupancy patterns and behavior. The protection of personal data is therefore a fundamental requirement, especially under regulations such as the EU General Data Protection Regulation (GDPR).

Privacy protection measures include:

- Data minimization: transmit only the information strictly required for grid interaction (e.g., flexibility range rather than raw sensor data).
- Pseudonymization or aggregation of data to prevent identification of individuals.
- Local processing of sensitive data within the building, sharing only aggregated flexibility values externally.
- Transparency and user consent, ensuring that occupants are informed about what data is collected and how it is used.

Reliability and Availability

Because flexibility services are often time-critical, communication systems must guarantee adequate levels of reliability, availability, and latency. This is particularly important when buildings participate in balancing markets. Recommended technical measures include:

- Quality-of-Service (QoS) guarantees in communication infrastructure.
- Buffering and synchronization mechanisms for forecast and measurement data.
- Automated recovery in case of connection loss.

Interoperability and Communication Protocols

Building-based flexibility relies on interaction between heterogeneous systems: grid operators, aggregators, building automation systems, and end-user devices. Interoperability and standardized protocols are therefore essential.

Commonly used communication standards in building automation include:

- BACnet (Building Automation and Control Network): Widely used in HVAC systems; supports standardized object models and, with BACnet/SC (Secure Connect), enhanced security features.
- KNX: A common standard in European building automation, covering lighting, HVAC, and shading; KNX Secure provides encryption and authentication.
- Modbus: A simple and widespread industrial protocol, often used for connecting heat pumps, boilers, or PV inverters, though traditionally lacking built-in security.

- OPC UA (Open Platform Communications Unified Architecture): A flexible, secure, and platform-independent standard, increasingly applied in energy and building contexts.

All protocols without specific encryption and authentication options should only be used in a separate network inaccessible from the outside world, e.g., by using a gateway with two separate network interfaces.

For external communication between buildings and aggregators or grid operators, higher-level protocols such as IEC 61850 (substation automation and DER integration) or IEC 62351 (security for energy applications) are also relevant.

Ensuring interoperability not only reduces integration costs but also increases transparency, simplifies audits, and reduces the attack surface associated with proprietary interfaces. If systems using different protocols need to be combined, hardware converters are one option, but easily programmable solutions such as Node-RED gain increased attention, especially for protocols based on Ethernet.

4 Subtask C – Non-technical challenges

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4.1 Regional boundary conditions

The study "Activating the electrical energy flexibility of residential thermal systems: An analysis of non-technical barriers in six countries" (Ritter D. R., 2026) investigates the institutional and regulatory conditions that determine how residential buildings equipped with technologies such as heat pumps (HPs) and Thermally Activated Building Systems (TABS) can contribute to electrical energy flexibility. Based on forty-one expert interviews conducted within the framework of the IEA Energy Storage TCP Task 43, Subtask C, the study systematically compares findings from Austria, Belgium, Canada, Denmark, Germany, and Spain. The following text summarizes the key results of this research, focusing on regional boundary conditions and legislation affecting flexibility, grounded in the data reported in the study.

4.1.1 Legislation affecting flex in general

The expert interviews revealed that legislation is the most decisive non-technical factor influencing the realization of residential thermal flexibility. Although HPs and TABS are technically mature and widely available, the supporting legal and regulatory frameworks remain incomplete, fragmented, or misaligned with market needs. Across all six countries, more than 85 % of stakeholders identified the absence of an explicit legal definition of flexibility as a central institutional barrier. Current Energy Performance Certificates (EPCs) and building codes were criticized for evaluating energy performance on an annual basis, ignoring temporal dynamics and the storage potential embedded in building structures. Consequently, even buildings equipped with advanced control systems and flexible components receive no additional credit in national certification schemes or energy assessments.

Among the six countries studied, Denmark was repeatedly cited as the most advanced in integrating flexibility into its legislative and market framework. The Danish Electricity Supply Act and executive orders from the Danish Energy Agency formally recognize flexibility as a grid service and allow aggregators to trade aggregated household loads at both the transmission and distribution levels. Denmark's regulatory model also mandates the provision of hourly variable electricity tariffs to all customers with smart meters, achieving more than 98 % national coverage. Experts considered this combination of clear legal definitions, dynamic tariffs, and full metering penetration to be a model of best practice that other countries could emulate. However, even in Denmark, the study found that building codes and electricity regulations are still only partially integrated, leaving administrative and data-sharing gaps that restrict full-scale deployment.

In Germany and Austria, flexibility has become a frequent topic in policy discussions but has yet to be incorporated into binding law. In Germany, Section 14a of the Energy Industry Act (EnWG) allows distribution system operators (DSOs) to curtail HP operation during grid congestion. However, the administrative complexity and lack of clear remuneration have discouraged participation—fewer than 2 % of German residential HPs were registered under this scheme in 2024. Similarly, the Renewable Expansion Act (EAG 2021) in Austria supports collective self-consumption but does not include mechanisms for flexibility aggregation or thermal storage, limiting opportunities for aggregators to enter the market. In both countries, the legal ambiguity surrounding aggregator rights and responsibilities continues to be a barrier to broader participation in flexibility markets.

Belgium and Spain have partially transposed elements of the EU Clean Energy Package (2019), which defines the rights of consumers and aggregators to engage in demand response. However, the secondary legislation needed to implement these directives—such as rules on aggregator participation, verification, and compensation—remains incomplete. As a result, these countries lack coherent procedures for flexible markets. Smart-meter penetration in Belgium stands at around 55 %, and in Austria around 60 %, with neither country having a binding national mandate for deployment. Spain has legally mandated time-of-use (ToU) tariffs for all consumers, yet these remain static, disconnected from real-time price signals, and therefore provide limited incentives for flexible operation.

In Canada, energy regulation is decentralized and managed at the provincial level, resulting in a fragmented legal landscape. Only Ontario and Alberta operate liberalized electricity markets that enable participation in demand-response programs. Ontario's Independent Electricity System Operator (IESO) Demand Response Auction includes aggregators, but residential consumers represent less than 5 % of enrolled capacity due to strict metering and verification requirements. In other provinces, vertically integrated monopolies and the lack of enabling legislation effectively exclude third-party aggregators, preventing market-based flexibility services from emerging.

A recurring issue identified across all six countries was data governance and privacy. Approximately 78 % of interviewees regarded data-protection laws as major obstacles to operationalizing flexibility. The EU General Data Protection Regulation (GDPR) and Canada's Personal Information Protection and Electronic Documents Act (PIPEDA) restrict real-time data exchange between households, DSOs, and aggregators. In countries such as Germany and Belgium, every data transaction typically requires individual user consent, making automated control and real-time optimization economically unviable. While experts agreed on the necessity of robust consumer protection, they emphasized that overly rigid interpretations of these laws impede the efficient operation of smart systems that rely on continuous, secure data flows.

Comparing legislative maturity across countries, Denmark leads with a near-complete integration of energy, digitalization, and flexibility frameworks. Germany and Austria occupy an intermediate position with comprehensive but slow-moving legislation, while Belgium and Spain are still finalizing national transpositions of EU directives. Canada's provincial fragmentation remains the most significant structural obstacle to nationwide flexibility. Experts agreed that only a small fraction of the technical flexibility potential of residential heat pumps and TABS is currently being utilised across the six countries analysed. Exposure to time-varying electricity prices also remains uneven and largely country-dependent—ranging from mandatory dynamic pricing in Denmark, to limited or uncommon exposure in Belgium and Canada, with intermediate situations such as time-of-use tariffs in Spain and the ongoing rollout of dynamic tariffs in Germany.

The findings of the study demonstrate that the barriers to residential flexibility are institutional rather than technological. While the technical potential for flexibility through HPs and TABS is well understood, legislative and regulatory systems have not yet adapted to the requirements of dynamic operation. The experts emphasized that enabling flexibility requires a new legal paradigm—one that replaces static efficiency targets with adaptive frameworks supporting interoperability, data exchange, and market participation. Flexibility, the study concludes, cannot thrive in a regulatory vacuum. It depends on predictable remuneration, transparent data governance, and coordinated policymaking across the energy and building sectors. Only when legislation evolves to become as dynamic as the systems it governs can the full potential of residential thermal flexibility be realized.

4.1.2 Regional boundary conditions — Denmark

Denmark provides one of Europe's most advanced environments for implementing demand management in thermal networks. Around 67% of electricity generation in 2023 came from renewables, creating a strong need for flexibility. On the demand side, heating electrification is widespread, with approximately 22% of buildings using heat pumps and more than 90% of new heating systems based on this technology. Nearly all households are equipped with smart meters, and suppliers are legally required to offer hourly variable tariffs, enabling dynamic adjustment to real-time energy prices. District heating covers over half of all households, positioning Denmark as a frontrunner in large-scale thermal demand response.

Research summarized in IEA EBC Annex 84 2025 (Marsza-Pomianowska, 2025) shows that Danish households generally support participation in demand response programs when comfort and user control are maintained. Transparent communication and simple digital interfaces improve acceptance, while unclear pricing or complex control schemes can reduce engagement. District heating utilities recognize the value of demand-side flexibility but still face barriers related to regulation and limited knowledge sharing. Field studies conducted in Denmark demonstrate energy savings of up to 20% through advanced control strategies and peak-load reductions reaching 48% when electric booster systems are applied. Most projects operate at technology readiness level seven, confirming near-market maturity. To accelerate progress, modernization of substations, wider use of digital monitoring, and harmonized data standards are needed. The Danish experience illustrates that technological readiness must be matched by clear policies, user engagement, and well-designed market incentives to realize the full flexibility potential of buildings connected to district heating networks.

4.1.3 Regional boundary conditions — Germany

Germany combines a rapidly growing need for flexibility with comparatively weak enabling conditions on the residential side (non-residential buildings not considered in source study). On the supply side, variable renewable electricity already accounts for a large and increasing share of power generation, which amplifies the value of demand-side flexibility from electrified heating. At the same time, heat pump penetration in the existing building stock is still relatively low compared with several peer countries, even though annual sales and the share of heat pumps in new heating installations have increased markedly in recent years. In this context, flexibility from heat pumps and building thermal mass (including thermally activated building systems, TABS) is particularly relevant for heating and cooling operation, where peak management and distribution grid congestion become key drivers for controlled load shifting and thermal storage utilization.

A central constraint is digital infrastructure. Compared with other European frontrunners, Germany's smart-meter rollout has historically been slow, and limited coverage reduces the scalability of automated, verifiable flexibility provision in the residential sector. Also, the power grid status / stress is currently not available digitally for all grid levels. This matters because most flexibility activation mechanisms—dynamic tariffs, aggregation, settlement, and measurement/verification for grid or market services—depend on widespread metering, secure data exchange, and standardized interfaces. The regulatory direction is evolving toward broader smart-meter deployment, which is expected to improve the technical preconditions for residential flexibility, but the pace of implementation remains an important boundary condition for near-term deployment.

From a regulatory and market-design perspective, Germany stands out for having a comparatively strong grid-driven instrument, but still a fragmented pathway for small actors to participate in markets. A mature lever is regulated direct load control under the national framework that allows distribution system operators to limit controllable loads (including heat pumps above defined thresholds) under specified conditions to prevent local congestion. This approach can be effective because it is triggered when grid constraints occur; however, this mechanism is intended as an emergency fallback and its successful use depends on transparent rules, adequate user protection, and credible remuneration structures. If end-users perceive interventions as unpredictable or unfair, acceptance and willingness to connect controllable loads can decline.

In parallel, price-based signals are becoming more relevant. Mandatory availability of dynamic electricity tariffs and grid fees improves general conditions for load shifting and for aligning heat pump operation with lower-price (and often lower-emission) hours. Yet, participation through aggregators and flexibility markets can still be constrained by transaction costs, administrative requirements, and the practical complexity of contracting, verification, and settlement—especially for small residential assets. In addition, a persistent structural issue is that building-integrated thermal storage and TABS-enabled flexibility are not always explicitly recognized in common building performance frameworks and incentive logic, meaning that the value of controllability and thermal storage behaviour can remain invisible in planning, procurement, and financing decisions.

4.1.4 Regional boundary conditions — Austria

Austria offers a comparatively strong technical foundation for activating thermal flexibility in buildings, but the enabling framework remains uneven across flexibility use cases. From an energy-system perspective, the growing share of variable renewable electricity increases the value of shifting demand in time, while the ongoing electrification of heating expands the pool of controllable assets. Heat pumps are becoming increasingly common in both new installations and, gradually, in retrofits, which strengthens the potential for demand-side flexibility—especially when combined with thermal storage and the use of building thermal mass (including thermally activated building systems, TABS). Given Austria's long heating season and cold to moderate climate conditions, flexibility value is particularly pronounced in winter, where peak load management and congestion relief in local distribution grids become relevant objectives.

Austria's digital infrastructure constitutes an important enabler. Smart-meter deployment has progressed significantly, providing a basis for more granular monitoring, time-dependent tariffs, and the measurement and verification needed for automated control and aggregated flexibility. This lowers practical barriers for implementing load shifting strategies at scale and supports the rollout of price-based incentives that can steer heat pump operation toward periods with lower system stress or higher renewable availability. However, digital readiness alone does not guarantee flexibility activation; the market and regulatory pathways must also be simple enough for households, installers, and aggregators to participate without excessive transaction costs.

From a regulatory and market-design perspective, Austria has been characterized by a relatively strong emphasis on “local optimisation” approaches—especially through energy sharing and community-based arrangements that encourage local balancing of generation and consumption. Such frameworks can be particularly effective when heat pumps are operated in coordination with onsite or community PV generation, supporting self-consumption and reducing net grid exchange. While this can deliver tangible local benefits, it does not automatically translate into broader system services such as standardized flexibility procurement by DSOs/TSOs unless participation routes, contracting models, and settlement procedures are clearly established and widely accessible.

For TABS, Austria benefits from targeted diffusion drivers in specific locations and building segments (e.g., strong municipal requirements that can accelerate adoption in parts of the non-residential stock). Nevertheless, a key boundary condition is that the system value of thermal mass and TABS-driven flexibility is still not consistently visible in conventional energy performance assessment methods or in incentive structures. In practice, this means that the controllability and storage behavior of the building may remain undervalued in project decisions compared with more easily quantifiable efficiency measures, even though thermal mass can provide robust flexibility with limited comfort impact when properly designed and controlled.

Stakeholder and operational realities shape what is feasible. Distribution system operators may be cautious about relying on decentralized flexibility at low-voltage level unless interoperability, data exchange, and operational interfaces are streamlined and trusted. In addition, end-user acceptance remains critical: flexibility schemes must be transparent, protect comfort, and offer credible economic value; otherwise, uptake will remain limited regardless of technical potential.

4.1.5 Regional boundary conditions — Spain

Spain presents a heterogeneous set of regional boundary conditions that strongly influence the potential for activating electrical flexibility through thermal systems. Climatically, Spain encompasses a wide range of zones—from ASHRAE classifications 3A and 3B to 4A and 4C—reflecting its geographic diversity from arid southern regions to more temperate northern areas. Spain has made significant progress in integrating renewable energy sources into its electricity generation mix, with renewables—particularly solar and wind—accounting for more than 50% of total electricity production in recent years (Red Eléctrica. 2025). This strong renewable presence has increased the variability of generation within the Spanish power system, thereby intensifying the need for flexibility solutions such as heat pumps and TABS. Consequently, heat pumps in Spain are typically used for both heating and cooling, with a pronounced focus on cooling during extended summer periods. This dual function aligns well with the growing relevance of Thermally Activated Building Systems (TABS), which offer an efficient means of balancing thermal demand while complementing photovoltaic (PV) self-consumption patterns, as peak cooling demand coincides with solar generation.

From a regulatory perspective, Spain exhibits limited maturity in flexibility markets. Time-of-use tariffs are well established but not yet synchronized with real-time renewable generation patterns. In the electricity market, the Iberian market operator (OMIE) plays a central role in incorporating renewable generation into daily and intraday markets, yet mechanisms for fully integrating distributed renewable assets and demand-side flexibility remain underdeveloped. The same organization OMIE, has initiated pilot projects to test local flexibility markets, yet comprehensive frameworks for decentralized participation remain under development. Independent aggregators, which would enable smaller assets such as buildings to provide grid services, are still unregulated and are not expected to be formally in the upcoming months. Moreover, existing mechanisms such as the national balancing service (Servicio de Respuesta Activa de la Demanda) require a minimum participation threshold of 1 MW, excluding most building-level systems.

Regarding structural challenges, Spanish construction practice is characterized by a lack of coordination between architects and engineers, and awareness of TABS technology remains low among both professionals and the general public. Financial incentives and subsidies exist but are inconsistently linked to advanced energy-flexibility technologies. Despite these limitations, Spain's high penetration of smart meters and its favourable climatic alignment with solar energy create promising preconditions for the expansion of TABS and other thermal flexibility solutions, provided that regulatory and institutional frameworks evolve to support them.

4.1.6 Regional boundary conditions — Belgium

Belgium presents a paradoxical context for decentralized thermal flexibility. On the one hand, Belgium has ambitious climate and electrification objectives, increasing PV deployment, and a rapidly evolving smart-meter rollout. On the other hand, heat pump penetration remains among the lowest in Europe, and the regulatory environment for flexibility is fragmented across regions (Flanders, Wallonia, and Brussels). These structural conditions limit the enabling environment for residential flexibility in general and TABS-based flexibility in particular.

Belgium's building and energy regulation is governed regionally, resulting in three separate EPB/PEB frameworks and heterogeneous implementation of smart meters and renovation incentives. Expert interviews emphasize that no region currently provides a clear regulatory pathway for recognizing TABS as an energy storage technology or as a flexibility resource for grid operators. TABS may indirectly improve EPB scores, but they are not explicitly valued in renovation subsidy schemes or design guidelines (Ritter D. R., 2026).

Dynamic tariffs, capacity tariffs, and flexible grid charges are emerging, especially in Flanders, yet they remain voluntary and are not systematically linked to building-integrated flexibility technologies. As Lieve Helsen notes, Belgium offers no obligation, no guaranteed remuneration, and no dedicated scheme for tapping the flexibility potential of TABS or heat-pump-driven thermal storage. Belgium's regulatory landscape therefore stands in contrast with countries like Denmark or Germany, where direct load control or mandatory smart-meter–enabled tariffs provide more structured frameworks for residential DR (Helsen, 2025).

All Belgian experts interviewed converge on a single central barrier: lack of awareness and familiarity with TABS among architects, HVAC designers, contractors, and even building owners. As reported in the stakeholder interviews, architects frequently reject TABS due to perceived design risks, unfamiliarity with control strategies, or fear of long thermal response times. This results in a conservative preference for traditional systems such as radiators or floor heating, even in projects where TABS would deliver superior efficiency and flexibility (Helsen, 2025).

The construction sector's fragmentation amplifies this challenge. TABS requires genuine integrated design between structure, HVAC, control, acoustics, and energy systems. Belgium's project delivery culture, still largely sequential, does not easily support this level of cross-disciplinary coordination.

Coordination efforts add cost and uncertainty, further discouraging ado integration among structure, HVAC, and control options. ad hoc integration among structural integration among structure, HVAC, controls

light high upfront investment, long payback periods, and lack of dedicated incentives as persistent barriers in Belgium. Even when life-cycle costs are favorable, decision-makers, especially in public institutions, prioritize short-term visible needs over long-term operational optimisation. Universities, for example, face tight budgets and difficulty justifying TABS when financial cycles operate on short horizons (Ritter K. e., 2025).

Commercial real estate markets are further constrained by split incentives: owners carry the investment cost while tenants capture the operational savings. This dynamic is well-documented across the six Task 43 countries and is especially pronounced in Belgium's rental-dominated office sector. Belgian occupants and facility managers tend to prefer systems with fast response times and visible controllability. The slow dynamics of TABS are often misunderstood as a disadvantage, despite offering superior comfort, stability, and lower operating costs. Interviews reveal a widespread fear that TABS reduce user autonomy, even though advanced predictive controls (e.g., MPC as commercialized by Belgian spin-offs such as Buildwise/Building Twins) mitigate these concerns. Noise and acoustics are sometimes mentioned as issues in commercial buildings, although experts agree these are solvable and not actual barriers when TABS are properly designed.

Despite low adoption, Belgium's potential for TABS-based flexibility is significant. Several Belgian research groups (KU Leuven, UGent, ULiège) have demonstrated strong preconditions:

- Growing PV penetration and increasing coincidence between summer cooling demand and solar production
- Introduction of capacity tariffs that financially reward peak shaving
- Pilot-tested model predictive control solutions enabling both daily loads shifting and, when combined with ground-coupled heat pumps, seasonal storage (geotabs)
- Large commercial buildings with constant occupancy profiles, favourable for flexibility demonstrations

The Belgian case study in De Coninck & Helsen (De Coninck, 2016) shows that buildings in Brussels can provide significant flexibility but at non-zero cost, and that flexibility varies strongly depending on weather, schedules, and comfort constraints, reinforcing the need for advanced controls and clear market signals

Belgium's potential for TABS-based flexibility is significant, yet its adoption is hindered by a consistent set of non-technical barriers. The regulatory framework remains fragmented across regions, with no explicit recognition of TABS as a flexibility or storage technology and limited incentives supporting their integration. Market uptake is weakened by low awareness among architects, designers, and contractors, who often reject TABS due to unfamiliarity with control strategies and perceived risks, while the construction sector's fragmented delivery processes amplify coordination burdens. Financial constraints, including high upfront costs, long payback periods, and the absence of targeted subsidies, discourage investors, and split incentives further limit uptake in commercial buildings. Behavioral resistance persists as users prefer fast-acting conventional systems over slow-response radiant mass, despite proven comfort and efficiency benefits. Although Belgium is increasingly adopting dynamic tariffs and smart meters, these instruments do not yet generate stable, attractive revenue streams for flexible buildings. Together, these factors confirm the broader Task 43 finding that insufficient awareness, incomplete regulation, and weak economic incentives remain the dominant barriers to deploying residential thermal flexibility in Belgium.

4.1.7 Regional boundary conditions — EU wide

Across Europe, residential heat pumps are expected to become a central pillar of demand-side flexibility as countries increase the share of variable renewable energy and electrify heating. However, despite the technical readiness of heat pumps and TABS, their actual contribution to flexibility remains far below potential because of persistent non-technical barriers documented in recent cross-country studies. The Task 43 Subtask C analysis highlights that the EU lacks a unified, coherent enabling framework for decentralised thermal flexibility, and that most countries address only fragments of the regulatory, financial and stakeholder challenges.

From a regulatory standpoint, Europe shows heterogeneous progress. Some Member States (e.g. Denmark) have advanced dynamic pricing, aggregator recognition, and broad smart-meter roll-out, enabling participation in multiple flexibility use cases. Others maintain rigid tariff structures, fragmented market rules, or very limited access for aggregators, thereby blocking residential flexibility from entering electricity, balancing or local grid markets. A particularly important blind spot is the absence of TABS recognition in EPC methodologies across all observed countries, which structurally prevents these systems from receiving value for their thermal storage characteristics. This regulatory invisibility is repeatedly identified as a major barrier to scaling TABS-based flexibility.

Stakeholder barriers also show EU-wide patterns. End-users generally lack awareness of flexibility services, distrust remote control mechanisms, and remain skeptical about the ability of TABS and heat pumps to maintain comfort during DR events. These concerns are intensified by inconsistent communication, unclear responsibilities, and insufficient training within the HVAC sector. Manufacturers, installers and consultants often lack incentives to promote flexible-ready solutions, reinforcing conservative design practices. These issues appear in all six countries examined in the report and represent a structural barrier that cannot be addressed by technology alone.

Financial barriers remain one of the most decisive constraints across Europe. Time-of-use and dynamic tariffs are available in some Member States, but the portion of the electricity bill exposed to hourly price signals is typically small, limiting economic motivation for DR. Explicit financial mechanisms that reward flexibility—such as local flexibility markets, capacity payments, or balancing-market access—exist mostly as pilots and remain inaccessible to small residential assets. Subsidies for renewable heating rarely include flexibility requirements, and almost no programme recognises or financially supports TABS as a thermal storage asset. As the report shows, end-users and installers perceive upfront costs as high and the return on investment for flexibility as uncertain, contributing to slow adoption across all markets.

Overall, the European context is characterised by strong policy ambitions for electrification and renewable expansion, yet insufficient alignment across regulatory, financial, and stakeholder frameworks that would allow residential heat pumps and TABS to deliver meaningful flexibility. The evidence suggests that thermal flexibility will not scale through technology readiness alone. Instead, a coherent EU-wide framework—covering dynamic tariffs, aggregator access, TABS recognition in EPBD methodologies, targeted incentives, and capacity-building for installers—is necessary to bridge the persistent gap between technical potential and real deployment.

4.1.8 Other market Regions — China

China is emerging as the world's most ambitious testbed for large-scale thermal flexibility, driven by rapid urbanization, a strong electrification agenda, and the national Dual Carbon commitment to peak emissions by 2030 and achieve neutrality by 2060 (Yan, 2022). As highlighted in recent assessments, China's electricity consumption already exceeds one trillion kWh in a single month, and heating demand remains enormous, with 9.3 billion GJ used annually in buildings alone. This scale establishes both the urgency and feasibility of thermal flexibility as a decarbonization lever.

The country's heating landscape differs sharply from Europe. Northern China has one of the world's most extensive district heating infrastructures, with more than 560,000 km of pipelines, and many cities display heating densities above 300 TJ/km² (Yan, 2022). This existing network provides a ready-made backbone for integrating thermal storage, waste heat recovery, and large-scale heat pumps. Because China's cities are extremely large and dense, they can absorb and redistribute vast quantities of thermal energy, enabling forms of load shifting that would not be technically or economically viable in smaller European cities.

A central insight from the literature is that conventional natural-source heat pumps cannot meet China's high-intensity, high-density heating loads. Air-source heat pumps cause local microclimate disruptions and are only viable in lower-density districts, while ground-source heat pumps face thermal creep, land-use conflicts, and long-term attenuation problems in dense urban areas (IEA, 2021). Consequently, China is turning toward waste heat recovery, long-distance transport, and thermal network integration—all of which create new forms of thermal flexibility at scale.

China possesses an extraordinary endowment of waste heat: approximately 50.5 billion GJ/year, declining to 19 billion GJ/year by 2050 but still exceeding projected heating demand. Waste heat from power stations, steel mills, cement plants, data centers, and wastewater systems can be captured, upgraded using absorption heat pumps, and transported 50–200 km through large-scale transmission networks. These networks, already piloted in Taiyuan, Haiyang, and Tangshan, enable both spatial and temporal decoupling of heat supply and demand—a critical form of flexibility.

Seasonal thermal energy storage (STES) systems further augment flexibility. China is pioneering water-displacement reservoirs with 85–90 percent thermal efficiency and low cost compared to batteries or pumped hydro. Because winter heating demand is highly concentrated, STES allows summer waste heat to be stored and released months later, smoothing seasonal peaks and reducing the need for fossil backup systems.

Real-world implementations demonstrate these concepts at unprecedented scales. In Taiyuan, a thermal-power-waste-heat project serves 76 million m², cutting 7.45 million tons of CO_2 annually. The Haiyang nuclear waste heat system supplies 12.5 million m² and plans to expand to 200 million m², with heat delivered at a competitive cost. The Tangshan steel-to-Beijing pipeline transports industrial waste heat across provinces and integrates seasonal storage to supply 91.5 million GJ/year, with a ten-year payback. These cases illustrate not only technical feasibility but also economic viability, confirming that thermal flexibility is already operational in China (IEA, 2021).

China's approach is therefore distinctive: flexibility is achieved not primarily through individual buildings or residential heat pumps but through territorial-scale thermal systems combining waste heat, electrification, district networks, and integrated storage. This system-level strategy positions China as a global leader in high-density, low-carbon thermal flexibility, offering a model that could be replicated in countries with similar urban forms, such as Japan and South Korea (IEA, 2021).

4.1.9 Other market Regions — Canada

Canada's boundary conditions for energy flexibility are largely defined by its vast geography and cold climate, falling mainly within ASHRAE climate zones 7 and 8, which are among the coldest regions globally. Long heating seasons dominate national energy demand, while the need for cooling is steadily increasing due to climate change and rising summer temperatures. These conditions make technologies such as heat pumps (HPs) and Thermally Active Building Systems (TABS) particularly relevant, as they can deliver both heating and cooling while offering valuable opportunities for thermal load shifting and storage.

The Canadian electricity mix is dominated by hydropower (around 60%), supplemented by nuclear energy and fossil fuels, while variable renewable energy (VRE) sources such as wind and solar represent only about 7% in 2023, with projections of 13% by 2030. This relatively low share of variable generation reduces short-term flexibility needs compared to highly renewable systems like Denmark or Germany, but flexibility still plays a crucial role in managing winter peak loads, which can exceed 40% of household energy use.

Infrastructural readiness is advancing but uneven. Approximately 80% of Canadian households are equipped with smart meters, with nationwide coverage expected to reach 94% by 2029. However, dynamic electricity tariffs—a key tool for activating flexibility—are only available in select provinces such as Ontario, which uses time-of-use pricing. Provinces like Quebec and Alberta continue to apply flat-rate tariffs, limiting consumer engagement. The penetration of heat pumps remains modest at around 6% of residential buildings, although federal and provincial programs are promoting rapid growth to meet national decarbonization goals.

From a regulatory perspective, flexibility integration remains at an early stage. There is no consistent national framework for aggregator participation, and energy performance standards still emphasize efficiency over adaptability. Policies encouraging dynamic operation, thermal storage utilization, or building-side flexibility remain fragmented across provinces.

These regional conditions reveal a country well positioned to expand flexibility but still in the process of creating mechanisms to enable it. Canada's combination of cold climate, growing electrification, and widespread smart metering offers a solid technical foundation. To transform this potential into practice, flexibility must be embedded within regulatory structures, pricing systems, and building standards. This alignment—linking technology, policy, and user engagement—can allow Canada to move from isolated pilot projects toward a mature, scalable model of thermal and electrical flexibility suited to its unique climatic and energy context.

4.1.10 Other market Regions — USA

The United States offers large technical potential for building-based flexibility, but regional boundary conditions vary strongly by climate, grid structure, and market rules. From an electricity-system perspective, the U.S. generation mix is still dominated by fossil fuels, yet variable renewables are now material and growing: in 2023, renewables provided about 21.4% of U.S. utility-scale electricity generation, with wind ~10% and utility-scale solar ~3.9% (plus additional small-scale PV). This increasing contribution of wind and solar raises the value of demand-side flexibility—particularly for electrified heating and cooling—because flexible loads can be shifted to hours with higher renewable output and lower system marginal emissions (U.S. EIA, Electricity generation, capacity, and sales in the United States, 2025). A defining U.S. boundary condition is climate diversity. Heating-dominated regions (upper Midwest, Northeast, Mountain states) have strong winter peak relevance, making flexibility valuable for peak shaving, congestion management, and supporting reliability during cold snaps. Mixed and cooling-dominated regions (South, Southwest, parts of California) face large summer peaks, where flexible cooling and heat-pump operation can align well with daytime solar production. This climate heterogeneity means that "one" U.S. flexibility strategy does not exist; the most relevant services (winter peak reduction vs. summer peak shifting, local feeder congestion relief vs. system balancing) depend on regional load shapes and resource portfolios. A second key boundary condition is metering and digital readiness, which is comparatively strong at national scale but uneven across utilities and states. Nationally, U.S. utilities reported roughly 119 million advanced metering infrastructure (AMI) installations in 2022, corresponding to about 72% of all electric meters, and about 73% of residential meters. This level of AMI penetration provides a robust foundation for time-varying tariffs, automated control, and the measurement/verification needed for aggregated demand response and flexibility programs—although the remaining gap and differences in AMI functionality (e.g., two-way capabilities, data access latency, customer data pathways) still matter for scaling "hands-off" flexibility solutions (U.S. EIA, How many smart meters are installed in the United States, and who has them?, 2025).

Market design and grid governance create the biggest variability in the U.S. opportunity space. Unlike many European countries, U.S. electricity markets are patchwork: some regions are served by organized wholesale markets run by ISOs/RTOs (e.g., PJM, CAISO, ISO-NE, NYISO, MISO, SPP, ERCOT), while others remain vertically integrated or partially restructured. This affects whether flexibility from buildings can earn revenue beyond retail bill savings. A major national-level enabler is FERC Order No. 2222, which requires regional grid operators to open their wholesale markets to aggregations of distributed energy resources (DERs)—explicitly including the types of small assets that can be bundled (e.g., behind-the-meter storage, controllable loads, and demand response). In practice, Order 2222 improves the legal pathway for aggregated residential and small-commercial flexibility, but implementation timing and details differ by ISO/RTO, and distribution-utility coordination requirements can still be a practical barrier for building-scale assets (FERC, 2025). For heat pumps and building thermal mass (including TABS), the U.S. boundary conditions therefore hinge on three regional factors: (1) the local peak driver (winter vs. summer), (2) the availability of AMI and customer-facing rate options that reward flexible operation, and (3) the market access pathway (retail-only savings vs. participation—often via aggregators—in ISO/RTO programs and wholesale markets enabled under Order 2222). Where AMI data access, dynamic pricing, and aggregation frameworks align, flexible operation of heat pumps and thermal storage can deliver both customer value (bill savings) and system value. Where one or more pieces are missing, flexibility may remain limited to pilot programs or manual load shifting with uncertain persistence.

4.2 Best practice examples and incentives

4.2.1 General possible incentives (monetary and other)

Interviews conducted across six countries—Austria, Belgium, Canada, Denmark, Germany, and Spain showed that incentives are the most decisive element for unlocking flexibility in residential buildings. While technologies such as heat pumps (HPs) and Thermally Activated Building Systems (TABS) are technically ready, participation depends on whether households and market actors receive clear, fair, and tangible rewards. Experts agreed that flexibility must make sense not only technologically but also economically and socially for those expected to deliver it.

Monetary incentives emerged as the strongest driver of participation. Over 80% of interviewed experts emphasized that dynamic or variable pricing is necessary to trigger behavioral change. However, fewer than 15% of households across the six countries are currently exposed to real-time or dynamic tariffs. Denmark stands out as the only country where hourly variable tariffs are mandatory for all electricity suppliers, supported by 98% smart-meter coverage. This framework enables households to achieve measurable financial savings, typically between 5% and 12% per year, when they adjust their electricity use to lower-price periods. In comparison, Germany and Austria have introduced time-of-use tariffs but only on a voluntary basis, resulting in low adoption. The German §14a EnWG scheme allows flexible customers to receive reduced grid fees, yet fewer than 2% of residential HP owners have enrolled due to administrative complexity. Spain and Belgium continue to rely largely on static tariffs that do not reflect real-time market conditions, offering limited financial motivation. Canada presents a mixed picture: provinces like Ontario, where 90% of households have smart meters, offer dynamic pricing through the IESO program, whereas others still apply flat rates that discourage flexibility.

Experts also underlined the value of financial support for flexible-ready technologies, such as advanced controllers and small-scale storage systems. Danish pilot projects have shown that modest time-based rebates—typically around 0.15–0.25 DKK per kWh during off-peak hours—can reduce evening peak loads by 20–30%, while maintaining user comfort. Similar results were reported in Germany, where field studies demonstrated up to 48% peak-load reduction using optimized control of HPs and booster systems.

Beyond direct economic benefits, non-monetary incentives play a key role in maintaining long-term engagement. About 70% of experts highlighted that environmental and social motivations—such as contributing to CO_2 reduction or supporting renewable integration—significantly enhance user commitment, especially when the results are made visible. Danish utilities that provide real-time feedback through digital apps showing energy and emission savings report user retention rates above 80% after six months. In Germany, similar dashboards have maintained daily demand shifts even without strong monetary compensation.

Social and community-based incentives were also seen as effective, particularly when users participate in cooperative or neighborhood energy schemes. In Austria and Belgium, local energy-sharing initiatives reached participation rates of 60–70%, compared with below 20% in individual household programs. These results suggest that collective engagement and trust within communities amplify the impact of economic incentives and help normalize flexible behavior.

Experts agreed that regulatory incentives are essential to make flexibility an integral part of the energy system. Current laws mainly reward renewable generation, not flexible demand. Interviewees suggested measures such as simplified aggregator registration, reduced network tariffs for flexible consumers, and tax deductions for verified grid-supportive operation. They estimated that coordinated financial and regulatory incentives could unlock up to 25–30% of the currently unused flexibility potential in residential buildings.

The interviews make clear that flexibility thrives where monetary and non-monetary incentives reinforce one another. Economic benefits attract participants, but sustained engagement depends on fairness, transparency, and shared environmental purpose. Denmark's example demonstrates how these layers interact: legal access to dynamic tariffs ensures opportunity, digital feedback builds trust, and modest but predictable rewards make participation worthwhile. When financial savings, social value, and environmental contribution align, flexibility moves from a policy concept to an everyday reality for households and communities alike.

4.2.2 Rough calculation about potential

Buildings inherently store heat in their walls, floors, ceilings, and furnishings. This thermal mass can act as a distributed energy storage system when combined with intelligent control strategies. By modulating heating setpoints (temporarily raising or lowering indoor temperatures within acceptable comfort limits), thermal energy can be stored or released without additional hardware. This approach enables short-term demand response actions such as peak shaving and load shifting, aligning energy consumption with periods of high renewable generation or low grid stress (Johra H. H., 2019). This approach has multiple benefits:

- Cost-effectiveness: Utilizing existing thermal mass avoids the high capital costs associated with batteries or centralized thermal storage. Implementation primarily requires smart thermostats or building automation systems, which are increasingly common.
- Scalability: Every conditioned building contributes to the aggregate storage potential, creating a vast, decentralized resource that strengthens local grid resilience.
- Environmental Benefits: Demand response through thermal storage reduces reliance on CO_2-intensive peak generation and minimizes the need for network reinforcements.
- Continuous Availability: Unlike electric vehicle batteries, which depend on connection status, thermal storage is always accessible within the building envelope.

A nationwide assessment of the building stock in Denmark demonstrates the magnitude of this untapped potential (Johra H. G., 2024). By applying heating setpoint modulation of ±2 K around the neutral temperature, the following theoretical storage capacities were estimated for Denmark:

- 13 GWh for short-term modulation (1 hour)
- 45 GWh for typical modulation (5 hours)
- 130 GWh for extended modulation (24 hours)
- These figures are striking when compared to other storage sources:
- Equivalent to the combined capacity of all industrial-scale hot water tanks in Danish district heating plants.
- Comparable to the battery capacity of Denmark's entire passenger car fleet if fully electrified (≈2.6 million EVs).

For context, a 1-hour modulation represents roughly half of Denmark's daily residential electricity demand, while a 24-hour modulation matches the daily heat production of all district heating plants or the total residential heating demand on a winter day. This illustrates the potential for thermal mass to play a pivotal role in balancing energy systems.

Energy storage in indoor thermal mass has great potential through dynamic pricing, demand response, and smart control, enabling buildings to shift heating and cooling loads in time without compromising occupant comfort. By exploiting the inherent thermal inertia of buildings, indoor environments can function as decentralized, low-cost energy storage systems that enhance grid flexibility, complement other storage technologies, and support renewable energy integration. Leveraging thermal mass through setpoint modulation is highly scalable and can be rapidly deployed using existing building automation infrastructure, making it a practical pathway toward decarbonization and smart grid stability as dynamic pricing and demand response programs become more prevalent (Johra H. H., 2019). The capacity of buildings to provide flexibility is mainly influenced by the following factors:

- Insulation and envelope performance: Well-insulated buildings have higher thermal time constants, allowing indoor temperatures to remain stable for longer periods. This enables more efficient and longer-duration load shifting with reduced energy losses.
- Thermal mass distribution: The amount and placement of thermal mass, determined by construction materials and building design, directly affect storage capacity. Older buildings often possess higher thermal mass but may underperform due to weaker insulation, while newer buildings typically combine improved insulation with optimized mass utilization.
- Heating system type: Systems that actively engage the building structure, such as underfloor heating and TABS, enable much greater activation of thermal inertia than conventional convective systems, significantly increasing the potential for indoor thermal energy storage.

4.2.3 Austria — Best practices and incentives for leveraging TABS flexibility (monitoring evidence and economic business cases)

The following best-practice cases are derived from Austrian monitoring and practice-oriented documentation on Thermally Activated Building Systems (TABS). Together, they illustrate how TABS flexibility can create value through (1) reduced investment costs (CAPEX) by downsizing generation equipment using the building's inherent thermal inertia, (2) reduced operating costs (OPEX) by shifting loads with predictive control under variable electricity tariffs and PV availability, and (3) improved life-cycle economics when TABS are assessed with a life-cycle cost perspective that captures efficiency gains, free-cooling opportunities, and lower long-term total cost.

Case 1 — Passive flexibility: downsize heating equipment (CAPEX saving)

A particularly strong best practice for TABS flexibility is the passive use of thermal inertia to reduce required installed heating capacity. Instead of sizing heating generation strictly to the peak design load, the building's activated mass is used as a buffer that smooths demand and allows the heating system to run more steadily over long periods. This approach can create a direct investment (CAPEX) incentive, because smaller heat pumps (and potentially smaller auxiliaries) are sufficient to meet comfort requirements when the building mass and TABS system are designed and operated accordingly. A concrete monitoring example is the Steiner Haustechnik building: the documentation reports a total building heating load of 1.1 MW, while the installed heating system consists of three two-stage brine/water heat pumps (45/90 kW each), i.e., 270 kW installed heating capacity, a reduction of 75%. While no direct proportional, cost savings for the energy generation unit in a similar range can be expected for such systems. This illustrates a clear business case: thermal activation can enable significant downsizing of generation technology while maintaining comfort through the inertia of the building structure.

Case 2 — Active flexibility: predictive control + variable tariffs (OPEX saving)

TABS systems also enable active flexibility when paired with predictive control strategies and variable electricity price signals. Because TABS operate with large thermal storage capacity and slow dynamics, they are well suited to shift heating/cooling demand in time—for example, preheating or precooling during low-price hours and reducing operation during expensive hours—while keeping indoor temperatures within comfort limits. This creates a strong operational (OPEX) incentive through electricity bill savings and supports higher self-consumption when PV is available. The potential of using storage in conjunction with even hourly thermal storage capacity in couling with heat pumps is further illustrated in Figure 70, which showcases how fluctuating intraday energy prices can create cost savings and business opportunities through much lower or even negative electricity costs during certain stretches of the day.

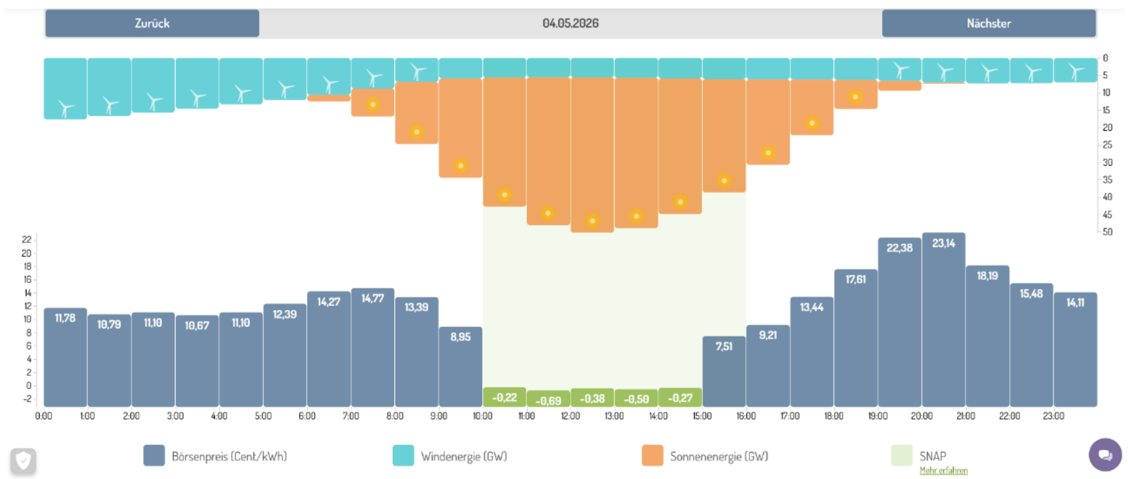

Figure 70: Screenshot for variable electricity prices from the market actor Awattar, illustrating the cost savings potential by being able to shift several hours of energy demand (compare maximum cost of 23,14 c/kWh in the evening peak with negative energy costs during the midday). Source: https://www.awattar.at/

The study explicitly highlights that the large storage mass offers considerable flexibility potential for using variable electricity tariffs and integrating renewable energy sources, and it recommends dynamic tariffs, predictive control, and aggregation models as key enablers for realizing this value in practice. In other words, the best practice is not only technical; it requires aligning control logic (predictive operation) with market conditions (dynamic pricing) so that flexibility becomes financially visible and repeatable.

Case 3 — Life-cycle incentive: LCC framing + free cooling & efficient heat pumps (total-cost advantage)

A third best practice is to frame TABS deployment using life-cycle cost (LCC) rather than only upfront investment, because TABS provide multiple long-term economic benefits. The document explains that thermal activation enables heating and cooling with low supply and return temperatures, which improves heat pump efficiency and makes free cooling feasible via ground sources (e.g., boreholes, ground collectors, or groundwater). With large heat exchange areas, overall energy demand can be reduced, and the system can remain economically attractive over the full use phase even if initial costs are higher. The study reports that LCC analyses in multiple cases show TABS can be cheaper over the operating lifetime than conventional systems, and it cites an empirical comparison where TABS achieved up to 31% lower "global cost" over 15 years than fan-coil systems. In addition, it reports literature-based annual energy savings of about 15–40% versus convective systems when TABS are combined with variable electricity tariffs and free cooling. This best practice therefore supports a strong "total-cost" incentive: reduced energy and maintenance costs compensate for higher CAPEX and deliver lower long-term cost of ownership.

4.2.4 Denmark best-practice case: National-scale flexibility from Denmark's building stock

A strong Danish best-practice case for leveraging TABS flexibility is to treat building thermal mass as a controllable thermal storage resource at national scale. (Johra H. G., 2024) quantify the thermal storage capacity of the entire Danish building stock by combining Danish building archetypes with national building registry data, thereby translating building physics into a system-level flexibility potential (Johra H. H., 2019). The study frames flexibility as controlled setpoint modulation (e.g., ±2°C over 1 h, 5 h, and 24 h) that allows buildings to store or release heat while maintaining comfort, enabling load shifting and peak reduction when energy prices are high or grid conditions are tight. The authors demonstrate that the aggregated storage capacity in Danish buildings is "very appreciable" and comparable to major storage assets (e.g., central storage capacity in district heating plants, or combined energy storage capacity of an entire fleet of electric vehicles) and energy benchmarks. These results support the argument that Denmark already possesses a large, low-cost flexibility resource embedded in its building stock. This also creates a clear incentive for further implementation of dynamic energy prices and smart controls leveraging building energy storage assets (e.g., predictive control for TABS and heat pumps) to unlock measurable economic value for end users while providing grid services that support integration of renewables.

4.2.5 Germany best-practice case: "Wind Heating 2.0" — using TABS as long-term thermal storage to absorb surplus wind electricity (Fraunhofer IBP)

In Germany, a strong best-practice example for leveraging TABS flexibility is the Fraunhofer IBP "Wind Heating 2.0: long-term storage" (Kersken, 2026), which couples the electricity and heating sectors by converting surplus renewable electricity (especially winter wind oversupply) into heat and storing it in long-term thermal storage systems (1-2 weeks), including thermo-active building systems (TABS) with room-side insulation. The project explicitly targets situations where Germany experiences very low or even negative electricity prices during high-wind events and where wind generation may otherwise be curtailed for grid stability. Buildings with "Wind Heating 2.0" are operated to charge the thermal storage when surplus electricity and grid capacity is available and then reduce or avoid heating electricity consumption during periods of high grid utilization, stated as one to two weeks in the project description. A key enabling measure is the project's predictive control system, which learns the building's behaviour from temperature and consumption data and uses a weather forecast to predict heating demand for up to 7.5 days, automatically adjusting the storage charging level to cover the coming week's needs. This demonstrates a clear incentive structure for Germany: turn price and grid signals into measurable cost savings and grid services, while maintaining thermal comfort through the buffering effect of building mass and dedicated thermal stores. Excess electricity demand coverages of 85% and above are possible.

4.2.6 Practical Recommendations for Scaling Thermal Flexibility and TABS in Buildings

Flexibility from buildings (including the use of thermal mass and TABS) is technically feasible, but it remains underused because it is not yet treated as a routinely measurable, contractable, and verifiable service across building regulation, market participation rules, data ecosystems, and workforce practice. The recommendations below translate the report's findings into implementable actions by explaining the underlying mechanism behind each gap and then specifying a concrete remedy.

Make flexibility measurable in building performance frameworks: Flexibility often fails to scale because it is not represented in the formal assessment and disclosure systems that drive decisions (e.g., building performance regulation, renovation planning, public procurement, and financing requirements). When an attribute is not measured and reported, it is rarely specified by clients and rarely optimized by designers. A practical remedy is to define a small, standardized flexibility indicator set that can be reported alongside energy performance and indoor-environment requirements. A workable package includes: (1) thermal storage capability (effective storage over a defined comfort band), (2) controllability/readiness (automated scheduling and actuation capability), (3) response characteristics (response time and sustainable duration), (4) comfort safeguard envelope (maximum allowable drift/ramp and limits by zone), and (5) verification readiness (metering resolution and data retention). These indicators should be paired with short guidance for calculation and checking at commissioning and periodic review, so flexibility becomes auditable rather than aspirational (see also (Commission, Energy Performance of Buildings Directive (policy overview), 2025), (EUR-Lex, Directive (EU) 2024/1275 on the energy performance of buildings (recast), 2025) and (Commission, Smart Readiness Indicator (SRI) overview, 2025)).

Reduce transaction costs for small building assets to participate in flexibility schemes: Building-scale flexibility is frequently excluded not because actors are unwilling, but because participation rules and compliance burdens (qualification, baselining, verification, settlement) were designed around large assets. This creates transaction costs that exceed the value a single building can capture. The practical remedy is to implement simplified participation pathways for small portfolios: (1) standardized contracts clarifying roles and customer protections, (2) streamlined prequalification based on metering capability and commissioning evidence, (3) standardized baselines suitable for thermal loads (weather-aware but not overly complex), (4) settlement rules compatible with short time intervals and aggregation, and (5) explicit consumer risk limits (comfort constraints and event frequency caps). This approach targets the structural cause—procedural and economic friction—rather than treating participation gaps as a "missing actor" problem, see (EUR-Lex, Regulation (EU) 2019/943 on the internal market for electricity, 2024) and (EUR-Lex, Summary: Internal market for electricity (Regulation (EU) 2019/943 as amended), 2019).

Treat interoperability and data access as enabling infrastructure: Flexibility often does not scale because each building requires bespoke integration (vendor-specific interfaces, inconsistent metadata) and because data governance is handled case-by-case, which increases cost, delay, and perceived risk. A practical remedy is to define a minimum, permissioned dataset required for flexibility dispatch and verification and to require interoperable interfaces in building system procurement. The minimum dataset should specify, at an appropriate time resolution, (1) electricity power/energy (whole building and key sub-metered loads if available), (2) dispatch signals and/or applied setpoints, (3) availability status (what capacity is available and when), (4) essential comfort proxy variables (e.g., zone temperatures needed to enforce comfort constraints), and (5) limited contextual variables needed for verification (e.g., outdoor temperature; equipment status/fault flags where feasible). This aligns data exchange with data-minimization and purpose-limitation principles, while enabling repeatable verification and settlement. Interoperability requirements should be written into procurement (documented API, standardized naming/metadata, export capability), so integration becomes routine rather than bespoke (EUR-Lex, General Data Protection Regulation (GDPR), Regulation (EU) 2016/679, official text., 2016).

Provide a concrete operational blueprint for delivering thermal flexibility reliably: Flexibility adoption stalls when stakeholders lack a repeatable operational method that connects tariffs or flexibility requests to building operation while protecting comfort. A practical blueprint is to use day-ahead scheduling with short time-step updates (e.g., 15-minute), with explicit objectives and constraints: objectives such as minimizing energy cost, reducing peak demand charges, and meeting contracted flexibility events; constraints including zone comfort bands, maximum ramp rates, and equipment operating limits. The blueprint should be paired with a commissioning and verification checklist: sensor validation, actuator testing, simplified model calibration (where needed), comfort safeguard testing during trial events, agreement on baselines, and periodic recommissioning (e.g., seasonally) to address drift and changing building use. This turns flexibility from “potential” into a repeatable practice that can be specified, commissioned, monitored, and audited (IEA EBC Annex 67, 2025).

Shift incentives toward verified performance and enable value stacking: Flexibility is often not sustained because incentives and procurement mechanisms reward installation rather than delivered performance, which weakens attention to commissioning quality, control tuning, and long-term operation. A practical remedy is to recommend performance-linked mechanisms that reward verified outcomes such as peak reduction, event compliance rate, or kW shifted (with comfort compliance as a non-negotiable condition). Where direct flexibility payments are not feasible, an intermediate step is to attach support to verifiable “readiness” conditions (metering granularity, interoperability, commissioning evidence, and time-bound operational reporting). In parallel, the report should explicitly support value stacking—combining bill savings (e.g., peak-charge avoidance) with market-based or local network services where allowed—because single-revenue models are often too fragile to justify investments in controls and commissioning. The EU-wide move toward 15-minute day-ahead market time units increases the value of time-resolved flexibility and makes these operational approaches more economically meaningful, see (Commission, Day-ahead markets move to 15-minute trading intervals, 2025), (ENTSO-E, 2025) and (SPOT, 2025).

Close the skills and accountability gap with clear responsibility and targeted training: Flexibility performance often degrades after installation because accountability is fragmented: design teams focus on compliance, contractors on delivery cost, and operators on stability and comfort—leaving flexibility without a clear owner. A practical remedy is twofold. First, implement targeted training for designers, commissioning engineers, and facility managers on thermal mass/TABS operation, scheduling logic, and verification. Second, embed accountability in procurement and O&M by requiring "flexibility commissioning," monitoring/reporting KPIs (event success rate, comfort excursions, peak metrics), and scheduled recommissioning. This ensures flexibility is delivered as an operational service over time, not merely as an initial pilot effect, see (Skills, 2025) and (EMPL), 2022).

Strengthen national sections with "mechanism, reason, action" closures: To make national findings more actionable without adding excessive length, each country subsection can end with one concise "mechanism → reason → action" statement tailored to that context. For example, where static time-of-use pricing dominates, the action can be to strengthen peak-based components or allow more time-resolved signals so flexibility has monetary value; where enrollment or verification is complex, the action can be standardized baselines and simplified prequalification for small portfolios; where data exchange is fragmented, the action can be a minimum dataset and interoperability procurement requirements; where awareness is limited, the action can be a pipeline of pilots with standardized measurement and public reporting. This preserves the mapping value while making each country section immediately usable for implementation planning (Commission, Energy performance of buildings, 2025).

4.3 Guidelines for indoor comfort

4.3.1 Norms and standards for indoor comfort

Ensuring indoor comfort is a fundamental requirement for the successful implementation of flexibility and demand response (DR) measures in buildings. Across Europe and North America, energy strategies consistently emphasize that flexibility measures must not compromise thermal comfort or indoor air quality, see (ISO, 2005), (CEN, 2019) and (American Society of Heating, 2021). International standards such as ISO 7730:2005, EN 16798-1:2019, and ASHRAE Standard 55-2021 define the environmental parameters that must be respected when buildings modulate heating, cooling, or ventilation to support energy flexibility.

These standards classify indoor environments into categories A, B, and C, representing progressively lower levels of occupant satisfaction. For example, ISO 7730:2005 defines acceptable operative temperature ranges for Category B as 20–24 °C in winter and 23–26 °C in summer, allowing short-term deviations up to ±2 K during load-shifting events if occupants' overall thermal comfort is maintained (ISO, 2005). Such tolerances are particularly relevant for DR operation, where short-duration setpoint shifts may be applied to reduce peak loads or align operation with renewable energy availability.

Both EN 16798-1:2019 and ASHRAE 55-2021 recommend a relative humidity range of 30–60 % to minimize discomfort, microbial growth, and static electricity. EN 16798-1:2019 also stipulates that indoor CO_2 concentrations remain below 1000 ppm for Category I spaces, providing a benchmark for maintaining indoor air quality during ventilation modulation. These requirements ensure that temporary DR actions, such as reduced ventilation or small setpoint changes, remain within safe physiological thresholds.

Although these standards describe acceptable steady-state conditions, they do not explicitly define operational limits for DR events. As a result, national interpretations differ regarding the allowable duration and frequency of comfort deviations. Clear specification of these aspects is necessary for consistent and compliant DR implementation, especially in automated systems.

Empirical evidence supports the potential for DR without compromising comfort. Field studies from Denmark and Germany, reported in IEA EBC Annex 84 (Marsza-Pomianowska, 2025), show that most users tolerate temperature reductions of 1–2 °C during nighttime or short DR events when thermal recovery occurs within a predictable timeframe. Comfort remains perceptibly stable as long as deviation periods are short and communicated in advance. Task 43 interviews confirm these findings, identifying comfort concerns as the most common barrier to participation but also showing that acceptance increases markedly when DR events are predictable, reversible, and accompanied by clear information. Up to 80 % of users accept DR events when they retain manual override options.

Maintaining user autonomy is therefore an essential dimension of comfort compliance. Standards provide technical thresholds, but perceived comfort depends heavily on users' sense of control. DR strategies benefit from integrating override functions, transparent communication, and real-time feedback, which sustain trust and long-term engagement. To ensure that indoor conditions remain within standardized comfort boundaries during DR, reliable monitoring of operative temperature, humidity, air quality, and local effects is required. This creates a direct connection between the comfort requirements described in this section and the sensory equipment detailed in the subsequent sections. By linking standardized comfort criteria with automated control, measurement technologies, and user-centred communication, buildings can provide meaningful flexibility while fully safeguarding occupant comfort and well-being.

4.3.2 Necessary sensory equipment to measure thermal comfort

Reliable measurement of thermal comfort is essential for verifying that demand response actions remain within the limits defined by EN 16798 or ISO 17772-1 (ISO I. , ISO 17772-1: Energy performance of buildings: Indoor environmental quality: Part 1: Indoor environmental input parameters for the design and assessment of energy performance of buildings, 2017). Comfort in dynamic conditions requires accurate sensing of the physical variables influencing perceived temperature. The following equipment represents the minimum set required for assessing thermal comfort in residential and non-residential buildings participating in flexibility programs.

1. Core measurement: operative temperature through a black globe thermometer

Operative temperature reflects the combined influence of air temperature and radiant temperature. The preferred method for estimating this variable in practical settings is the black globe thermometer, which provides a response close to the mean radiant temperature perceived by occupants. The correct globe size and physical characteristics are defined in ISO 7726 (ISO I. , 1998) and ISO 19567-1 (ISO I. , 2021), which specify a standard blackened copper sphere with a diameter of 150 mm. This ensures adequate thermal response time and limits error from convective influences. Using smaller globes is permitted, but only when faster response is required, and the manufacturer provides validated correction formulas for low thermal mass devices.

2. Alternative instruments for radiant and operative temperature

If a standard black globe cannot be used, ISO 17772-1 (ISO I. , 2017)allows alternative sensing solutions provided that accuracy is maintained. Three instruments are suitable:

1. Shielded air temperature sensor combined with a six-directional radiant temperature sensor array. Directional sensors capture radiant asymmetry and allow calculation of mean radiant temperature when complex radiation fields exist.
2. High-accuracy surface temperature sensors used with view factor calculations. This approach is useful in buildings with large radiant surfaces such as TABS.
3. Sensitive thermistors or thermocouples installed inside a low-mass globe. These provide faster dynamic responses for DR events but require calibration to match the reference performance defined in ISO 7726.

3. Thermocouples for radiant temperature assessment

Thermocouples can be used to approximate radiant temperature when mounted in a small sphere or in a thin blackened shell. Their advantage lies in high sensitivity and low masses. For dynamic DR applications, thermocouple-based globes offer rapid response, but they are more sensitive to air movement and require careful shielding. Calibration against a standard 150 mm globe is essential to ensure compliance with EN 16798 comfort categories.

4. Sensor placement and distance from openings

Accurate measurement requires placing sensors in representative occupied zones. ISO 17772-1 and EN 16798 recommend a height of 0.6 to 1.1 m for seated activities and 1.1 to 1.7 m for standing activities. Sensors must avoid direct influence from external openings, solar radiation, and local drafts. Guidelines for placement include:

- Maintain a distance of at least 1 m from windows, exterior doors, and ventilation terminals.
- Avoid locations with direct sunlight, reflections from glazed surfaces, or shading from furniture.
- In large rooms, position multiple sensors to capture local variations, particularly when DR actions cause temporal temperature gradients.

5. Influence of heat sources: floor heating versus ceiling heating

Thermal measurement must reflect the actual distribution of radiant fields. When heat is emitted from the floor, sensors positioned too close to the ground may overestimate operative temperature due to strong upward radiation. Conversely, in buildings heated from the ceiling or with radiant panels, sensors placed too high may capture excessive radiant load compared to what occupants experience. To ensure representativeness:

- Place sensors at mid-height when radiant sources are dominant.
- Avoid placement directly under radiant panels or above floor heating hotspots.
- For TABS systems, combine globe temperature with slab temperature sensors to understand the dynamic radiant contribution.

6. Summary of minimum required equipment

A minimal sensing package appropriate for EN 16798 comfort verification in flexible buildings includes:

- One standard black globe thermometer compliant with ISO 7726

- A calibrated air temperature and relative humidity sensor
- Optional thermocouple-based globe or radiant array when faster dynamic response is required
- Correct placement strategy avoiding local influences and radiant bias

This equipment ensures that thermal comfort remains within the acceptable ranges defined by EN 16798 during flexibility events while providing robust data for control systems and post-event verification.

4.4 Additional non-technical effects on TABS deployment

4.4.1 Adaptability of TABS

Adaptability is one of the most important qualities of Thermo-Active Building Systems (TABS), as these systems offer a flexible means of responding to changing thermal demands, climatic fluctuations, and future energy-system constraints. As (Olesen B. W., 2012) explain in their foundational ASHRAE overview of radiant systems, the large thermal mass used in TABS allows buildings to buffer temperature swings over extended periods, making them particularly effective for shifting heating or cooling loads to times when energy is cleaner or less expensive. This capacity to preheat or precool during off-peak hours significantly reduces dependence on fossil-intensive peak electricity and contributes to grid stability.

The adaptability of TABS is further strengthened when combined with intelligent control approaches. (Lehmann, 2007) demonstrate that TABS can operate effectively across diverse climates and occupancy patterns when paired with predictive control, weather-based optimization, and demand-response strategies. These controls anticipate future conditions rather than simply reacting to them, ensuring that indoor comfort and energy efficiency are maintained even under dynamic and uncertain circumstances. Moreover, because the thermal inertia of TABS aligns well with renewable energy integration—absorbing excess solar or wind energy and smoothing fluctuations, TABS offers a future-ready adaptability at both the building and grid scale. These characteristics position TABS as a long-term, resilient solution capable of maintaining high performance throughout the building lifecycle

4.4.2 Circularity of TABS

Circularity is an inherent strength of TABS because the hydronic pipes are embedded directly within the concrete structural slabs, allowing a single building component to fulfil both load-bearing and thermal-conditioning roles. This dual functionality reduces the need for additional materials, avoids frequent replacement of mechanical units, and lowers long-term embodied carbon. The European Commission’s Circular Economy Action Plan (Commission, 2020), which defines the EU’s most widely adopted circular construction strategy, highlights the importance of long-lived components that maximize material utility throughout their lifecycle—an approach to which TABS naturally adhere due to their durability and minimal replacement requirements.

Research on hydronic concrete slabs further reinforces this circularity perspective. (Pomianowski, 2011) demonstrate that TABS-integrated slabs can store and release heat efficiently over decades, confirming that the embedded systems retain performance without major interventions. Only peripheral equipment—such as pumps, manifolds, and control units—requires periodic updating, meaning that renovation cycles generate minimal waste compared to traditional HVAC systems. When paired with low-clinker cement, recycled aggregates, or modular distribution components, TABS support even higher circularity by reducing embodied emissions at construction and limiting end-of-life material loss. Thus, TABS illustrates how structural thermal mass can directly contribute to circular-building strategies that prioritize longevity, reduced waste, and efficient resource use.

4.4.3 Acceptability of TABS

Acceptability of TABS depends on how occupants, building owners, and professionals perceive the system's comfort performance, controllability, and long-term value. Because TABS rely on large radiant surfaces and slow, steady temperature variations, they create highly uniform and low-noise indoor environments, an important factor for occupant satisfaction. International comfort standards such as ISO 7730 (2005/2021), which govern the application of the PMV–PPD indices, demonstrate that radiant systems like TABS can maintain thermal comfort very effectively when room temperatures remain stable. This is especially beneficial in offices, universities, and residential settings where consistent comfort is valued.

However, TABS' slow response time may initially challenge user expectations for rapid temperature adjustments. (Olesen B. W., 2012), in an influential ASHRAE analysis on radiant floors and ceilings, notes that embedded water-based systems require users to understand the temporal behavior of radiant thermal mass. This means clear communication and user-friendly interfaces are essential to ensure users perceive the system as controllable and predictable. From the building owner's perspective, TABS offer strong acceptability due to their long lifespan, minimal maintenance, and compatibility with low-temperature heating and high-temperature cooling—key requirements for integrating renewables and reducing operational carbon. Their ability to participate in load shifting and interact with smart-grid strategies further enhances policy and market acceptability. When these user, owner, and policy dimensions are addressed holistically, TABS present a highly acceptable, future-proof solution.

5 Subtask D – Standardisation and KPIs

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Thermally Activated Building Systems (TABS) are characterized by a wide variety of parameters that describe their performance, material characteristics, and interaction with the built environment. These indicators serve different purposes and are typically divided into two main groups: Key Design Indicators (KDI) and Key Performance Indicators (KPI).

KDIs are primarily associated with the physical and geometric characteristics of the construction elements that function as thermal storage. These include fundamental material properties such as specific heat capacity, density, and thermal conductivity as well as macro-scale design factors such as cross-sectional dimensions, construction type (e.g. solid concrete slabs vs. sandwich panels), and total volumetric capacity of the thermal mass. Aggregated values such as the mean building mass per unit area or the effective thermal mass index are often used in building-scale simulations and assessments to generalize TABS design across different buildings and climates, see (Zhou, 2008), (Dorer, 2009) and (Arteconi A. H., 2013).

In contrast, operational KPIs focus on the dynamic behavior of TABS in real or simulated environments. The central aspect of this class of indicators is the energy flexibility potential of the system, i.e. its capacity to shift, modulate or delay heating and cooling loads in response to external signals such as energy prices, demand-side management incentives, or fluctuating renewable energy availability. Numerous indicators have been proposed in the literature to quantify this flexibility, ranging from load shifting indices and power modulation depths to time-delay margins and thermal resilience factors, see (Reynders G. D., 2017), (Kavgic, 2010), (Bacher, 2011) and (Salom, Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data, 2014). The variety of proposed KPIs reflects both the complex nature of building-thermal interaction and the diversity of use cases and boundary conditions, which complicate standardization efforts.

Nevertheless, practical applicability is a critical requirement for any KPI used in planning, operation, or policy frameworks. Highly complex or overly abstract indicators may offer precision but risk being unusable in practice. Instead of listing

Rather than providing an exhaustive list of all proposed indicators, this report takes a reductionist approach. It seeks to distill the existing complexity into a robust and application-oriented subset of KPIs. To establish a common ground, the next chapter first provides a concise overview of the broader landscape of KDIs and KPIs. Following this summary. These indicators are selected to be sufficiently simple and transparent to support practical comparison and evaluation of TABS performance across diverse building contexts. Given the fundamental importance of thermal storage capacity and energy flexibility, the following two sections provide in-depth methodological and conceptual analyses of these two key topics. These “deep dive” chapters also illustrate how basic KDIs and operational KPIs can be aggregated into higher-level metrics that offer meaningful insights into the performance of TABS as complex, integrated components of modern energy-flexible buildings.

5.1 Overview of most relevant KDIs/KPIs for TABS

This chapter provides a structured overview of the indicators used to characterize TABS, categorizing them into physical design parameters, operational performance metrics, and the boundary conditions of indoor environmental quality.

5.1.1 Material/Design (KDIs)

Key Design Indicators (KDIs) define the static thermal potential of a building based on its physical and geometric configuration. While the introduction provided a general classification, we categorize these indicators more specifically into three levels: the material level, the cross-sectional level, and the system integration level.

Material-level indicators constitute the physical basis of TABS performance. The storage medium, typically reinforced concrete, is characterized by its thermal diffusivity, which describes the rate at which temperature changes propagate through the component. In technical applications, the thermal coupling between the fluid-carrying pipes and the building mass is influenced by the thermal conductivity of the concrete and the specific aggregates used (Olesen B. W., 2012).

Cross-sectional and geometric indicators describe the internal arrangement of the activated elements. Primary parameters include the pipe spacing and the concrete covering. These factors determine the internal thermal resistance of the slab and influence the uniformity of the surface temperature distribution (M. Gwerder, 2008). Additionally, the construction type, such as solid slabs, hollow-core slabs, or sandwich panels, defines the volumetric heat capacity. This KDI is a required input for calculating the maximum energy quantities that can be stored during a charging cycle (Olesen B. W., 2012).

System-level indicators aggregate these properties for assessments at the building scale. This includes the design supply temperature and mass flow, which are determined during the sizing of the hydraulic system to ensure that the required heating or cooling loads can be met under peak conditions while remaining within the material's thermal limits (Kyu-Nam Rhee, 2017).

Establishing these KDIs during the planning phase defines the thermal constraints of the system. Furthermore, they serve as the baseline for the operational KPIs, as the dynamic flexibility of TABS is fundamentally limited by its physical design (Kyu-Nam Rhee, 2017).

5.1.2 Energy/Operation (KPIs)

In addition to the various definitions of energy flexibility (Li, Wang, Hong, & Piette, 2021), a number of KPIs have been proposed in recent years to quantify the energy flexibility potential of TABS (Airò Farulla, et al., 2021). Three overarching categories can be identified to which the respective KPIs can be assigned: energy, time and costs (Reynders G. D., Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings, 2017). In particular, for the use of building thermal mass (BTM) through thermally activated building systems (TABS), a distinction can be made between KPIs for the planning phase, the design phase or the operational phase, where the operational phase is highly dependent on the availability of real measured or simulated data. Since the design phase allows predictions to be made about how the system will operate, the operational KPIs can be largely introduced in advance (Li, et al., 2023). Within operation, further categories can be found, such as grid interaction, load shifting or thermal storage (Marotta, Guarino, Cellura, & Longo, 2021).

A KPI often used in the literature is the Flexibility Factor (FF), which assesses the shift of quantities (energy, emissions etc.) from times with penalties to times without penalties (Li, et al., 2023). The range of values here typically goes from -1 to 1, with a value of 1 indicating that none of the quantities fall within the time with penalties. For example, Le Dreau et al. (Le Dréau & Heiselberg, 2016) use the Flexibility Factor for heat supply that should be provided by demand response, especially in times of low energy prices. It should be emphasised that the flexibility factor does not require the calculation of a reference control without demand response (DR) events.

Equally popular is the Flexibility Index (FI), which assesses the savings in a DR event compared to a reference control without demand response. In terms of monetary savings, Junker et al. (Junker, et al., 2018) also refer to this as the Expected Flexibility Savings Index (EFSI).

Reynders et al. (Reynders, Saelens, & Diriken, 2015) took a closer look at the storage capacity of BTMs and proposed the additional energy demand when increasing the room temperature setpoint (upward event), compared to the reference control, as the available capacity of active demand response (ADR). The derived ADR efficiency is also presented, which compares the energy saved in the period following an ADR event. Foteinaki et al. (Foteinaki, Li, Heller, & Rode, 2018) have extended the concept by adding the reduction of the room setpoint temperature and the resulting phases in the downward event. Kathirgamanathan et al. (Kathirgamanathan, Murphy, Rosa, Mangina, & Finn, 2018) have further extended the variation of energy demand compared to a reference control to the general electricity demand, calling it Available Electrical Energy Flexibility (AEEF). Similarly, the calculation of the efficiency for downward events was added.

Motivated by energy performance certificates for buildings, Arteconi et al. (Arteconi, Mugnini, & Polonara, 2019) proposed the Flexibility Performance Indicator (FPI), which aims to assess the flexibility of buildings with electric heating and cooling based on the calculation of four flexibility parameters. These include the response time to reach the setpoint temperature after the start of a demand response event, and the variation in energy consumption between the DR event and the reference control.

Since TABS fundamentally utilize the building's thermal mass as a form of thermal energy storage (TES), it is also relevant to consider metrics developed specifically for characterizing storage technologies. Ibrahim et al. (Ibrahim, Ilinca, & Perron, 2008) emphasized the growing importance of energy storage for stabilizing power grids and compared various technologies based on metrics including Storage Capacity, Available Power, Efficiency, Durability, and energy densities per mass and volume. To support the assessment of storage in near-zero energy buildings, Del Pero et al. (Del Pero, et al., 2018) proposed simplified metrics such as Recharging Energy, Depth of Discharge, and the Specific Cost of the Storage. Focusing specifically on TES in renewable energy systems, Palomba et al. (Palomba & Frazzica, 2029) proposed a set of metrics categorized into technical, socio-economic, and environmental types. The technical metrics include parameters such as Charge and Discharge Temperature, Volumetric Energy Storage Capacity, and the Expected Lifetime.

However, the large number of proposed KPIs also illustrates that no single indicator is sufficient to comprehensively assess the energy flexibility potential of TABS or building thermal mass. The suitability of a KPI strongly depends on the intended application, the considered system boundary, and the phase of assessment. Indicators such as the Flexibility Factor (FF) are particularly useful for evaluating the temporal shift of energy demand in relation to dynamic electricity prices or carbon intensity signals, since they quantify how effectively consumption is moved away from unfavorable periods without requiring a separate reference case. In contrast, indices based on comparison with a reference control, such as the Flexibility Index (FI), ADR efficiency or AEEF, are more suitable for quantifying the actual impact of demand response strategies on energy consumption and operational savings. These KPIs therefore provide valuable insight into the effectiveness of specific control strategies, but their results are highly dependent on the definition of the reference operation and the selected boundary conditions. The evaluation of upward and downward flexibility events must additionally consider thermal comfort constraints and the duration of the recovery phase, since high flexibility potentials may otherwise be achieved at the expense of occupant comfort or increased rebound effects.

Furthermore, the literature increasingly emphasizes that flexibility assessment should not be limited to short-term load shifting alone but should also account for the storage characteristics and long-term system benefits of TABS. Metrics originating from the field of thermal energy storage therefore complement conventional flexibility indicators by enabling the evaluation of storage capacity, charging and discharging behavior, efficiency, and lifetime performance. Technical storage indicators such as usable storage capacity or storage efficiency become relevant when TABS are integrated with renewable energy systems, heat pumps, or district heating networks. At the same time, socio-economic indicators such as operational cost savings, peak load reduction, or avoided renewable curtailment are required to evaluate the broader energy system benefits. The reviewed literature therefore suggests that the assessment of TABS flexibility should be multi-dimensional and application-oriented. Grid-oriented applications may prioritize indicators related to peak shaving and load shifting, while building-oriented analyses may focus more strongly on comfort preservation and operational efficiency. Consequently, a combination of complementary KPIs rather than a single universal metric appears to be the most appropriate approach for evaluating the flexibility potential of TABS across different operational contexts.

5.1.3 Thermal comfort

Thermal comfort serves as a mandatory boundary condition for TABS operation. In this context, comfort is treated as a constraint rather than an optimization variable; energy flexibility can only be utilized if the indoor environmental quality remains within the limits defined by standards such as EN ISO 7730 or ASHRAE 55.

Due to the high proportion of radiant heat exchange and the self-regulating effect of the activated surfaces, TABS influence the thermal environment differently than convective systems (Kyu-Nam Rhee, 2017). However, their high thermal inertia requires precise planning of the supply temperature levels and charging times to maintain temperatures within the required comfort bands. Therefore, comfort metrics, primarily the operative temperature and the Predicted Mean Vote (PMV), must be evaluated alongside operational KPIs. In flexibility assessments, this is typically represented by "comfort violation" indices, which quantify the duration and magnitude of temperature deviations (Le Dréau & Heiselberg, 2016). This ensures that load-shifting measures remain compatible with the primary requirement of maintaining a suitable indoor climate.

5.2 Deep dive thermal storage capacity

Storage capacity is one of the key aspects and KPIs of any energy storage system. TABS systems are no exception, with the design of active layers, the choice of materials and the allowed temperature boundaries affecting the average storage density of building integrated slabs. The intention of this chapter is to assess how the thermal storage capacity can be determined for different materials and designs. Subsequently, simplifications are explored to reduce the complexity of detailed calculations to a degree that is usable by the wider industry that has no access to scientific methods at a large scale. This will make this important parameter more accessible for planers, implementers and operators of TABS energy storage.

Most of the TABS systems encountered in Task 43 are based on sensible heat storage without phase change[1], which is why the following sections focus solely on sensible heat storage.If reference to a base of per Kelvin and m³ volume (more important than mass as a reference base in buildings), the specific energy storage density of any material is solely defined by its physical properties, namely density ρ_{TAB} and specific volumetric heat capacity $c_{pV,TAB}$.

Equation 5:

$$specific\ energy\ storage\ density\ \ q_{TAB} = \rho_{TAB} * c_{pV,TAB} \qquad \left[\frac{kJ}{m^3K}\right]$$

Different materials can offer different levels of specific energy storage density via their physical properties. This is illustrated in Figure 71 which highlights the volumetric energy storage density of construction and energy storage materials commonly used in buildings.

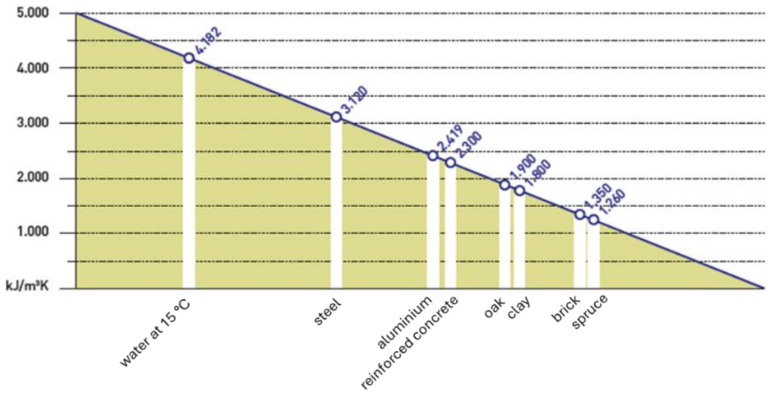


Figure 71: Comparison of the volumetric energy storage density of construction and energy storage materials commonly used in buildings. Source: (Klima- und Energiefonds, 2020)

Choosing the fitting storage material is, however, not only driven by picking the one with the highest specific storage density per kelvin but is influenced by a variety of additional factors, including:

- Embedded carbon
- Material cost
- Material availability
- Heat conductivity
- Possibility to integrate storage materials within existing structures (dual purpose)

---

[1] Specialized systems like PCM encapsulated in concrete are presented in Subtask A. Their storage density not only consist of the sensible part but also includes the latent heat stored via the phase change of the PCMs. Due to their, so far, niche applications, this section focuses on sensible heat storage only.

As highlighted in the figure above, water as a material offers excellent performance in the first 4 categories but requires dedicated additional space within a building. Even though it sports the highest specific storage density per m³, it incurs indirect costs by taking up additional volume that could be used otherwise in a building unit. This is one of the key strengths of TABS as energy storage – by using elements that already serve a primary, structural purpose for a second service within the building, cost savings can be achieved which in turn allow for the integration of a higher total storage volume and storage capacity compared to classic hot water buffer storages.

One of the key challenges of this dual-purpose usage is that building slabs have for the most part direct contact to the indoor environment and interact with it[2]. This results in additional boundaries for the usable temperature gradient besides the physical stability of the material. Surface temperature and room temperature must not exceed boundaries defined by thermal comfort maps as highlighted in Figure 72.

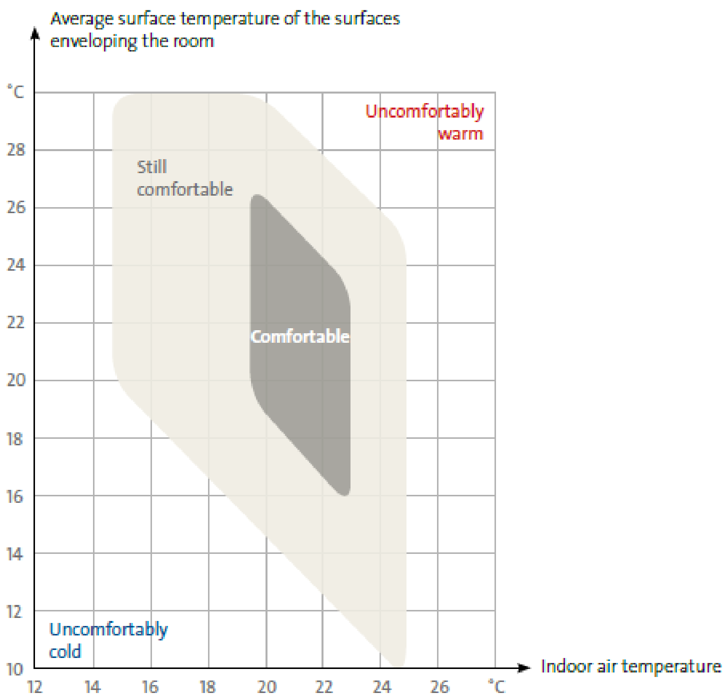


Figure 72: Comfort range as a function of surface temperature and indoor air temperature. Source: (Felix Friembichler, 2016)

This means that the specific energy storage density needs to be multiplied by the allowed temperature gradient of the material with respect to thermal comfort to compute a maximum energy storage density.

Equation 6:

$$energy\ storage\ capacity\ Q_{TAB,K} = q_{TAB} * V_{TAB}\ \left[\frac{J}{K}\right]$$

Equation 7:

$$max\ energy\ storage\ capacity\ Q_{TAB,max} = q_{TAB} * V_{TAB} * \Delta T_{max}\ [J]$$

[2] During the task, system concepts from Austria, Switzerland, Germany and Norway could be identified that use insulated foundation slabs as energy storage. These systems are not affected by the interaction with the indoor environment; however, they face other challenges affecting their performance.

Throughout the year the allowed temperature boundaries will change as different minimum and maximum temperatures are tolerable for winter and summer respectively. It might also change by taking other parameters into account like occupation, e.g. in office buildings or event locations. No occupation allows for time intervals with extended temperature bands for energy storage. The maximum storage capacity and the temperature band in which energy storage is allowed to occur, is therefore a changing parameter. Still, at every point during operation, the fraction between current maximum storage capacity and already used capacity defines the state of charge of such a system.

Equation 8:

$$current\ state\ of\ charge \qquad SOC_{TAB} = \frac{Q_{TAB}(t)}{Q_{TAB,max}(t)} \quad [-]$$

5.2.1 Challenges in computing a state of charge during operation

Knowing and communicating the state of charge of building integrated TABS energy storage is crucial for aggregation and operation of individual, distributed storages to achieve meaningful loads for overarching energy grids. Even though the operating criteria are very sensitive due to high time constants, immediate connection to end users and a very narrow temperature band, usually the available instrumentation and senor equipment in buildings does not allow for a perfect determination of the actual state of charge. Implementing a slew of additional sensors on the other hand would increase cost and complexity of the system, hampering its market uptake and end user acceptance. Therefore, simplifications and extrapolation of available sensor data are necessary to compute a state of charge with sufficient accuracy to not compromise indoor climate comfort. This affects the following parameters from the previously mentioned calculations:

Usable storage volume/mass

TABS components are completely integrated in the overall building. They have, for the most part very good contact with the indoor environment but also other parts of the structural building elements. To compute a representative state of charge, it is crucial to know what parts of a TABS system are undergoing temperature change during operation and which parts don't. This is highlighted in Figure 73 which showcases the heat flux in an activated ceiling, highlighting that the insulation layer inhibits heat transfer and therefore closes off the storage slab from the floor of the top room and is a specific characteristic that is determined by the chosen building and slab design during the planning phase.

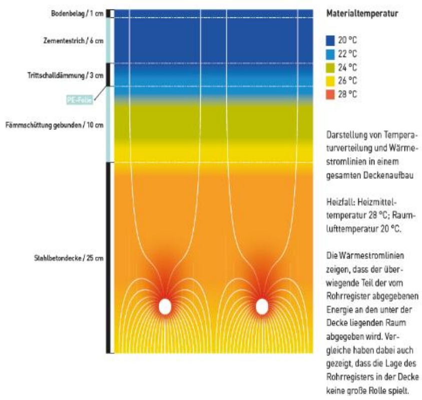
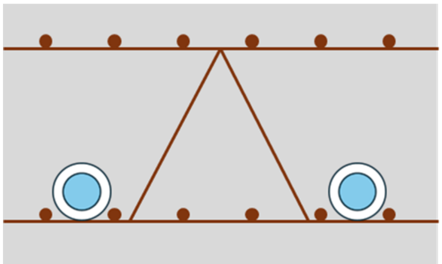


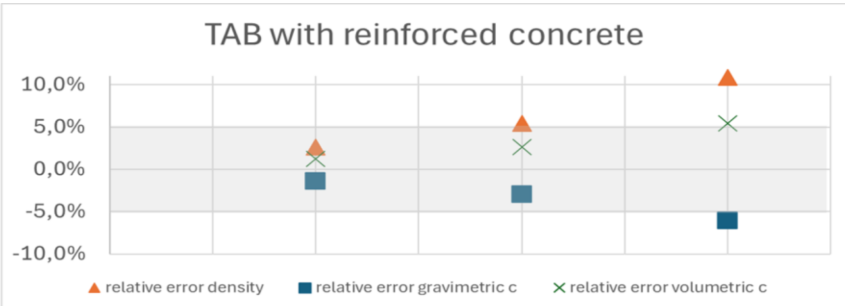
Figure 73: Heat flux in an TABS activated ceiling (cross section), indicating lower heat flux to the upper part that is equipped with an insulation layer. Source: (Felix Friembichler, 2016)

Physical properties: Density, gravimetric and volumetric heat capacity

TABS systems consist of different materials that are combined into one element. The main parts are the bulk structural component (concrete + steel railings, wood, clay), the piping (plastic, copper) and the heat transfer medium (water or other)[3]. The average cp and density of the entire TABS component can be calculated from the sum of the individual values. However, since the exact knowledge of the dimensions of all subcomponents and their individual cp is often not available or impractical to compute for real scale implementations, approximations can help to give a satisfactory estimate of the average density and specific heat capacity. To verify this approach and quantify the resulting error margins, two prototypical TABS slabs and their physical properties have been evaluated in this report, one with steel reinforced concrete and one with spruce wood as bulk structural component (assumptions for mass and volume fractions can be found in footnote[4]). Figure 74 presents the physical properties chosen as the base for calculation and the resulting error margins[5] for 3 slab designs for the reinforced concrete TABS (standard, non-bulk mass fraction x 2, non-bulk mass fraction x 4).



material [-]	density ρ [kg/m³]	gravimetric c [kJ/kgK]	volumetric c [kJ/m³K]
concrete	2.000	1	2.000
steel	7.850	0,5	3.925
PE piping	950	1,9	1.805
water	1.000	4,19	4.190



TAB concrete [-]	error density ρ [%]	error gravimetric c [%]	error volumetric c [%]
standard	2,6	-1,4	1,3
2 x non-bulk mass	5,4	-3,0	2,7
4 x non-bulk mass	10,9	-6,1	5,5

Figure 74: Overview of the physical properties chosen as the base for calculation and the resulting error margins for 3 slab designs for the reinforced concrete TABS. Source: AEE INTEC

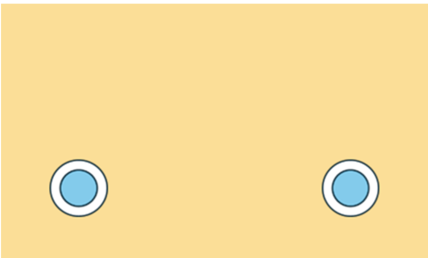
[3] By using PCM within TABS systems, the sensible heat storage as complemented by latent heat storage. This means that the latent heat of the PCM has to be taken into account in addition to the sensible heat storage capacities within the entire TABS component.

[4] Assumptions for calculation: The fraction of steel within the reinforced concrete is assumed with 80 kg/m³. The piping is assumed to consist of 4,6m PE pipe/m² (VA 20 cm) with an outer diameter of 0,017 m and an inner diameter of 0,013 m. The heat transfer medium is assumed to be water.

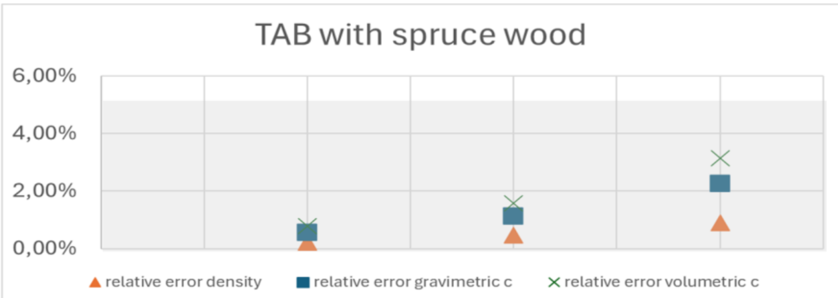
[5] The relative errors are calculated with the physically correct value as a base (the aggregate of individual material properties).

The calculated results show an acceptable error margin of only 1,3% for the volumetric specific heat capacity by using only the physical properties of the bulk mass (concrete) for computation. The volumetric specific heat capacity is underestimated if only the bulk mass is used, which even works as an additional safety margin for assuming state of charge. The density is underestimated by using only the bulk mass, which is mainly caused by the high density of steel, which accounts for 4% mass fraction of the entire structure. The gravimetric specific heat capacity is overestimated, due to the steel parts in the real structure which exhibit a lower gravimetric heat capacity than concrete. The calculations presented in this section have been performed under assumptions of typical mass fractions and pipe diameters widely used in industry. Still, it represents a specific result for exactly the chosen slab composition. To further generalize the findings for reinforced concrete, 2 additional systems have been evaluated, one with two-times non-bulk mass fraction (steel, pipe material, heat transfer medium) and one with four times non-bulk mass fraction. All three systems stay below an error margin of 6% in estimating the volumetric specific heat capacity, with the four times non-bulk scenario already being very unrealistic in real implementation. Therefore, the conclusion can be drawn, that using the density and specific heat capacity (especially the volumetric) of the bulk structural component, pure concrete, is sufficiently accurate for real scale implementations to estimate the state of charge of reinforced concrete TAB slabs.

Figure 75 presents the physical properties chosen as the base for calculation and the resulting error margins[6] for 3 slab designs for the spruce wood TAB (standard, non-bulk mass fraction x 2, non-bulk mass fraction x 4).



material [-]	density ρ [kg/m³]	gravimetric c [kJ/kgK]	volumetric c [kJ/m³K]
spruce wood	470	2,7	1.269
PE piping	950	1,9	1.805
water	1.000	4,19	4.190



TAB concrete [-]	error density ρ [%]	error gravimetric c [%]	error volumetric c [%]
standard	0,23	0,45	0,91
2 x non-bulk mass	0,26	1,13	2,27
4 x non-bulk mass	0,79	1,58	3,15

Figure 75: Overview of the physical properties chosen as the base for calculation and the resulting error margins for 3 slab designs for the spruce wood TAB. Source: AEE INTEC

[6] The relative errors are calculated with the physically correct value as a base (the aggregate of individual material properties).

The calculated results show an acceptable error margin of only 0,91% for the volumetric specific heat capacity by using only the physical properties of the bulk mass (spruce wood) for computation. The volumetric specific heat capacity is underestimated if only the bulk mass is used, which even works as an additional safety margin for assuming state of charge. The density is underestimated by using only the bulk mass, but significantly less than in the reinforced concrete due to the absence of steel with its very high density. The gravimetric specific heat capacity is underestimated due to the same reasons. The calculations presented in this section have been performed under assumptions of typical mass fractions and pipe diameters widely used in industry. Still, it represents a specific result for exactly the chosen slab composition. To further generalize the findings for spruce wood, 2 additional systems have been evaluated, one with two times non-bulk mass fraction (pipe material, heat transfer medium) and one with four times non-bulk mass fraction. All three systems stay below an error margin of 4% in estimating the volumetric specific heat capacity, with the four times non-bulk scenario already being very unrealistic in real implementation. Therefore, the conclusion can be drawn, that using the density and specific heat capacity (especially the volumetric) of the bulk structural component, spruce wood, is sufficiently accurate for real scale implementations to estimate the state of charge of reinforced concrete TAB slabs.

Accurate temperature estimates for TAB slab temperature

For state of charge assessment, it is crucial to determine which sensor to use for approximating the entire building slab temperature or what weights to allocated to multiple sensors should they be available. General sensor equipment usually provides values for heat transfer media return flow and partially sensors within the slab. Sensors on the surface of the slab are very rare and should not be considered standard equipment. The Austrian research project BTTAB uses the return flow sensor for approximating the state of charge of the slab. However, this suffers from the challenge that the value is only a good approximation at times when the circuit is in operation.

Building on this, ST-D Leader TU Darmstadt and AEE INTEC used thermal simulations to investigate which of three potential sensors (surface, return water or core) most closely corresponds to the dynamics and value of the average slab temperature in TABS, see Figure 76. If this applies to one of the sensors, it could therefore be used to estimate the SOC during operation. In the first step, the temperature behavior of TABS was simulated for standardized boundary conditions, with a focus on one charge and corresponding discharge phase (48h for each phase). In the simplified simulation, a room with a floor area of 20 m² and a constant air temperature of 22 °C was adopted. The single TABS slab has a total pipe length of 100 m, with a spacing of 20 cm between adjacent parallel pipes, and a concrete thickness of 20 cm. Regarding operation, a feed water temperature of 30 °C was selected. In the parametric study, key TABS parameters were varied to evaluate their influence on the temperature profiles of the individual sensors (Table 12, next page). Here, T_{fw} and m_{fw} denote the feed water temperature and mass flow rate, respectively, while T_{air} represents the constant boundary room air temperature.

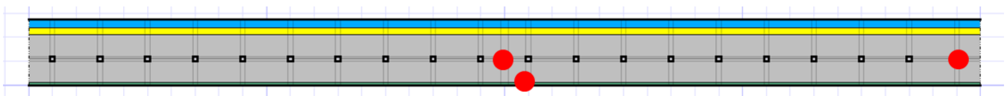


Figure 76: 1 Cross-sectional view of the simulated TABS and investigated virtual sensor positions (surface, return water and core). Source: Yang Xue, TU Darmstadt

Table 12: Summary of the parametric simulation for a single TABS. Source: Yang Xue, TU Darmstadt

Scenario	T_fw (°C)	T_air (°C)	m_fw (kg/s)	Pipe length (m)	Pipe diameter (cm)	Thickness (cm)
1	30	22	0.1	100	2	20
2	30	22	0.1	135	2	20
3	30	22	0.1	100	2	30
4	30	22	0.1	100	4	20
5	40	22	0.1	100	2	20
6	30	22	0.05	100	2	20
7	Identical to Scenario 1, with the material changed from concrete to wood.					

The temperature evolution curves of each sensor position under the seven distinct scenarios and its deviation from the average TABS temperature was calculated and is illustrated in Figure 77. For better evaluation, the temperature curves were divided into three phases, namely charging, steady-state, and discharging, corresponding respectively to the temperature increase, thermal equilibrium, and passive discharge process. In the steady-state phase, the temperatures at all positions within the slab show a constant difference from the average TABS temperature. During this phase, the temperature difference only depends on the thermal conductivity of the slab material and since it is constant, the temperature at any position can be used to estimate the average temperature of the TABS.

In contrast, the results in the charge phase show different patterns as in the steady-state phase: The deviation between the return water temperature and the average TABS temperature is strongly influenced by the scenarios, when the feed water temperature or the TABS material is changed (scenario 5 and 7), the absolute deviation consistently exceeds 5 K. In addition, within approximately the first two hours after starting the heating, the return water temperature rises very rapidly and then gradually levels off, causing the temperature deviation curve to first increase and then decrease. Hence, using return water temperature to estimate the TABS average requires caution regarding the TABS configuration and the charge phase timing, avoiding data direct from the heating start.

Regarding the absolute error of the surface and core temperatures relative to the TABS average temperature, it remains within 2 K and is only slightly affected by changes in TABS configuration, operational conditions, or material in the charging phase. When comparing these two, the core temperature is less sensitive to variations in TABS parameters but exhibits a higher absolute deviation than the surface temperature. For the core temperature, changing the feed water temperature (scenario 5) affects only the deviation magnitude, while changing the material (scenario 7) alters the deviation pattern, which first decreases and then increases. This is caused by low thermal conductivity of wood, whereby the middle point warms slowly at the onset of heating, resulting in a temperature lower than the TABS average at the beginning. Regarding the surface temperature, increasing feed water temperature only increases the absolute deviation (scenario 5). However, increasing the slab thickness (scenario 3) and using other material vary the deviation curve due to the change in the time constant of the TABS.

In the discharge phase, the temperature differences at all positions relative to the TABS average temperature are below 3 K. Importantly, the deviation between the return water temperature and the TABS average remains nearly constant, except for the initial steps after heating starts, which differs from the observations reported in Project BTTAB. This may be due to return water sensors typically being installed at the end of the overall hot water circuit rather than at the slab piping end as in the simplified simulation. The middle and surface temperatures follow the same patterns as in the charging phase, but with smaller absolute deviations from the TABS average.

In summary, temperatures at all three sensor locations have the potential to estimate the TABS average temperature and the SOC according to the simplified simulation. Nevertheless, their thermal behavior across different phases requires careful selection for varying TABS operating conditions, and it must be investigated whether this behavior persists under varying air temperatures.

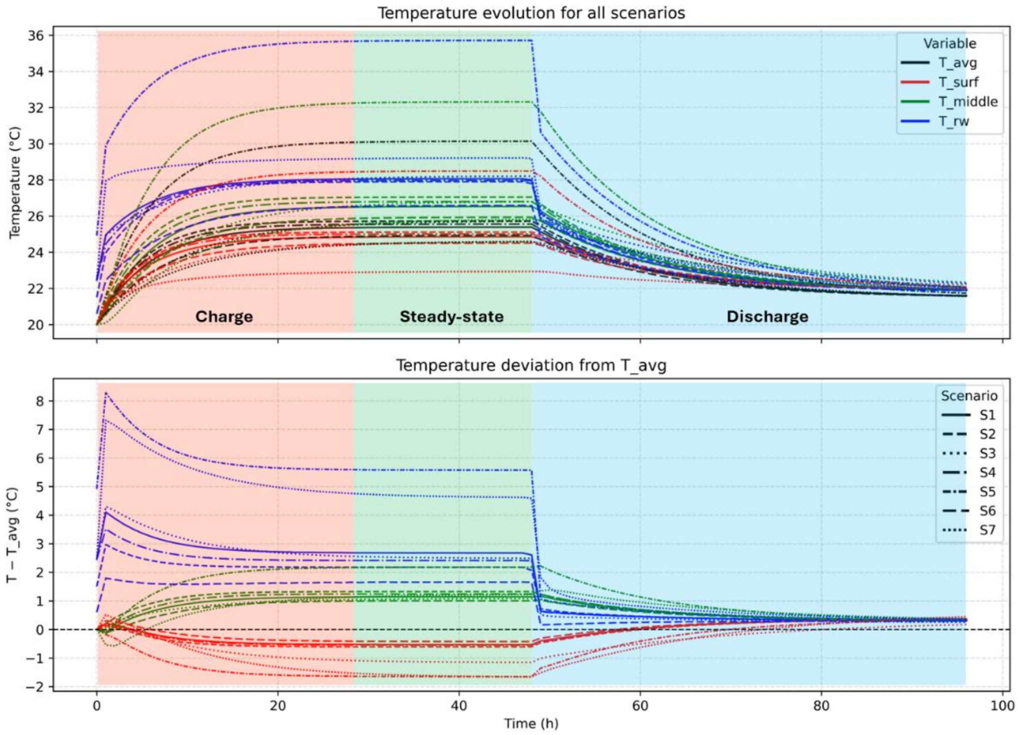


Figure 77: Temperature evolution for various positions in single slab during operation (top) and temperature deviation from TABS average temperature (bottom). Source: Yang Xue, TU Darmstadt

To further identify additional patterns and trends beyond a single charge–discharge cycle and to validate the findings from the previous analysis, an annual simulation with an adjacent room was conducted. Based on the DELPHIN room model described in Subtask B, feed water temperatures of 30 °C and 40 °C were applied to the TABS. The system was controlled using a two-point control strategy to maintain the room air temperature within the range of 20 °C to 22 °C while undergoing repeated charge and discharge cycles. In the previous simulations, the pipe was at the slab center. In the annual simulation, the pipe is located lower in the ceiling slab. To maintain consistency, the region above the pipes of the same height to the bottom surface was used to calculate the TABS average, keeping the pipe further at the region's center.

Several charge and discharge events during TABS operation were extracted and analyzed (Figure 78 and Figure 79). The temperature differences at all three positions to TABS average show periodic variations over the charge–discharge cycles. The return water temperature difference presents a distinctly different waveform with different feed water temperatures, while the core temperature difference shows a significant higher amplitude for higher feed water temperatures. Notably, the difference between the surface temperature and the TABS average temperature follows a consistent trend under both feed water temperature conditions, with an extremely small absolute deviation below 0.25 K. Furthermore, the air temperature in the 40 °C feed water scenario is slightly higher than in the 30 °C feed water scenario. Nevertheless, the patterns and absolute magnitudes of the deviations for surface temperatures remain unchanged.

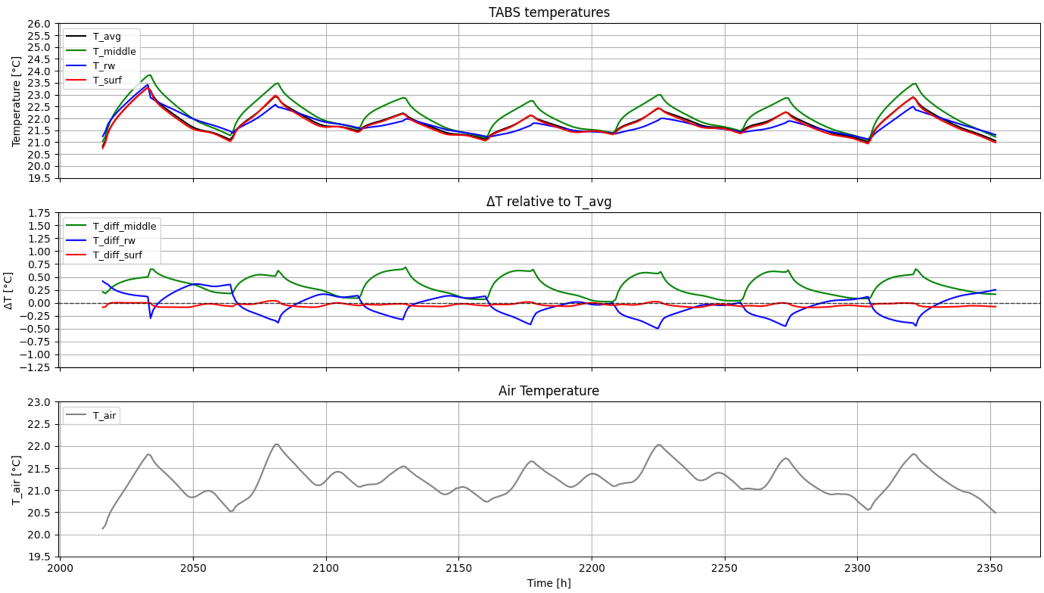


Figure 78: Temperature evolution over one week in January under a 30 °C feed water scenario: at different sensor positions in slab (top), deviation from slab average temperature (middle), and room air temperature (bottom). Source: Yang Xue, TU Darmstadt

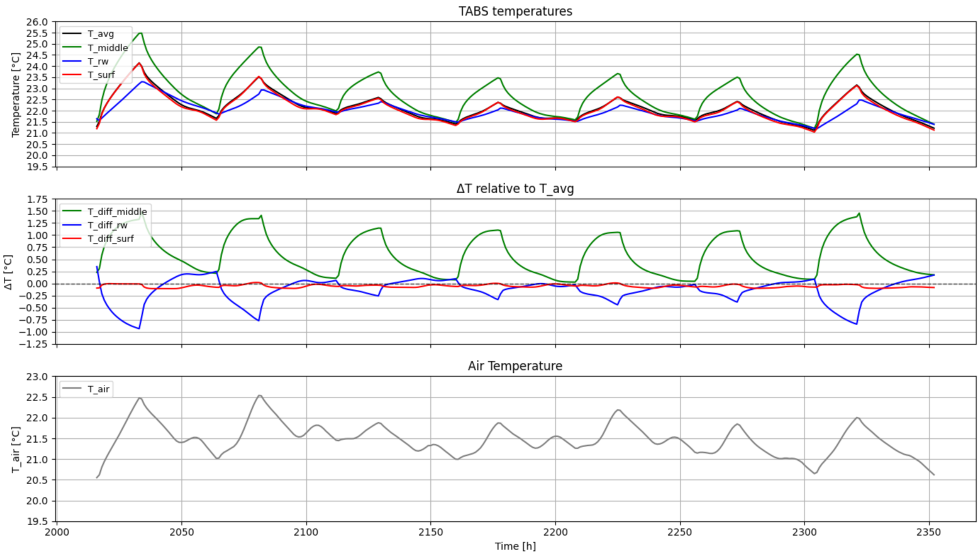


Figure 79: Temperature evolution over one week in January under a 40 °C feed water scenario: at different sensor positions in slab (top), deviation from slab average temperature (middle), and room air temperature (bottom). Source: Yang Xue, TU Darmstadt

The correlations between the temperature differences at different virtual sensor positions and the average TABS temperature, as well as the room air temperature, are presented in Figure 80 and Figure 81. The mass flow rate during operation is illustrated using different colors in the figures. The blue points represent zero mass flow, representing a discharge phase, while all other points correspond to charging events with various mass flow rates. Among them, the difference between the surface temperature and the average TABS temperature presents a zero linear correlation with the room air temperature in both cases. This indicates that during operation, the difference between the surface temperature and the TABS average temperature is not affected by changes in the air temperature. Regarding the other two positions, during both charging and discharging, the deviation curves of the middle temperature and return water temperature relative to the air temperature exhibit a weak positive and negative correlation, respectively. Additionally, the data points cluster together in groups according to the mass flow rate. The absolute differences are much higher, remaining below 1 K.

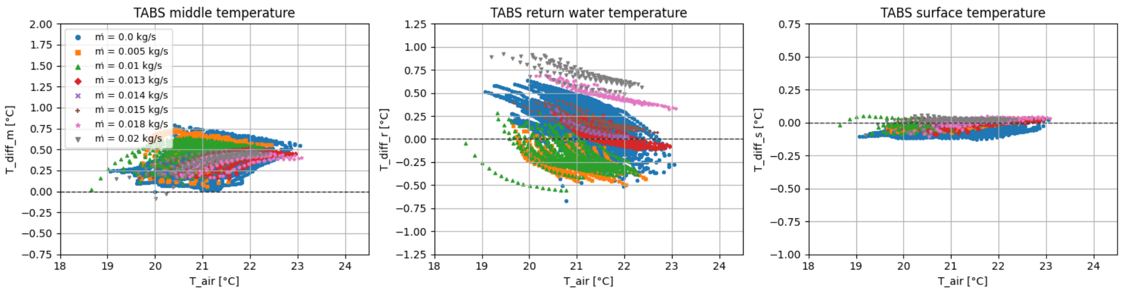


Figure 80: Correlation between temperature deviations from slab average at different positions and room air temperature under a 30°C feed water scenario: middle temperature (left), return water temperature (center), and surface temperature (right). Source: TU Darmstadt

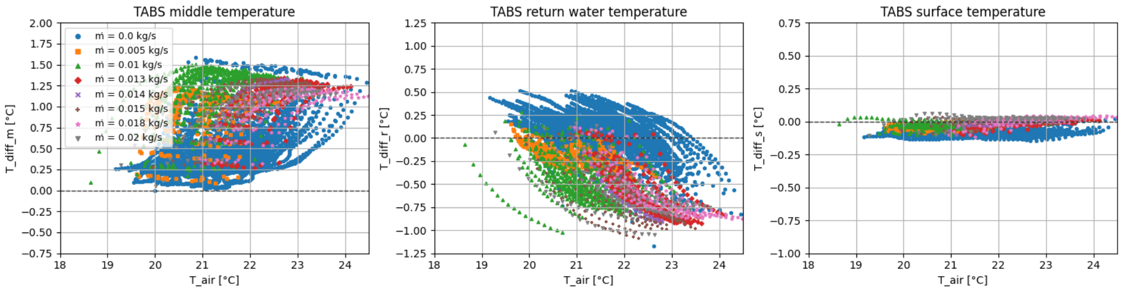


Figure 81: Correlation between temperature deviations from slab average at different positions and room air temperature under a 40°C feed water scenario: middle temperature (left), return water temperature (center), and surface temperature (right). Source: Yang Xue, TU Darmstadt

Based on the more detailed analysis with annual simulation results, the surface temperature has potential for estimating the SOC of TABS, as its difference from the TABS average has general consistency across different air temperatures and mass flow rates. This relationship remains unchanged as long as the TABS configuration is not altered. However, it should be noted that the surface sensor in the simulation is not exposed to solar radiation and corresponding temperature changes, which can distort the difference from the average slab temperature during operation.

The combination of the findings from this section form the basis for a suggested simplified thermal storage capacity calculation which is presented in section 5.4.

5.3 Deep dive flexibility potential

TAB systems are currently mainly used as a regular heating and cooling system, being operated in a constant manner without reacting to outside price signals and without leveraging the full temperature band that would be available for their operation. However, by overheating or subcooling the TABS elements based on e.g. available renewable energy, a building and its integrated TAB systems can act as flexible energy storage with charging and discharging phases as depicted in Figure 82. The figure illustrates which modes of operation can occur in a flexible TAB energy storage over time and how they affect the temperature within the slab.

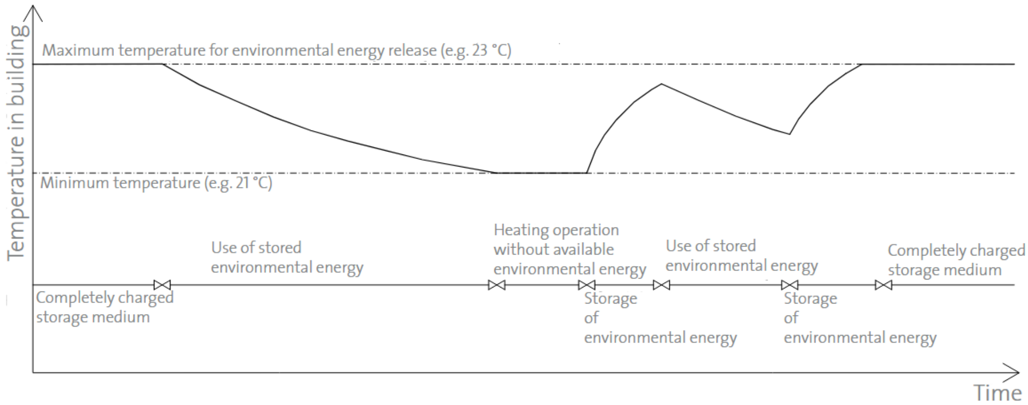


Figure 82: Base principle of a flexible TABS operation. The element is actively overheated until the maximum comfort temperature is reached and then cools down passively until either A) the minimum comfort temperature is reached or B) the next charging event takes place. Source: (Friembichler, Handler, Krec, & Kuster, 2017)

Thermally activated building mass systems (TABS) therefore offer a unique opportunity to contribute to the decarbonization and modernization of the energy system by providing not only thermal comfort but also grid-supportive services, see also (Arteconi A. H., 2013), (Reynders G. D., 2017) and (Foteinaki, Li, Heller, & Rode, 2018). One of the most relevant emerging functionalities of energy-flexible TABS is their capacity to relieve stress on the power grid, especially in the context of increasing shares of fluctuating renewable energy sources such as solar and wind. In this regard, the latent storage and demand shifting capabilities of TABS are becoming a critical asset in integrated energy system strategies. To meaningfully discuss the energy flexibility potential of TABS, a clear definition of energy flexibility is needed. Various international programs have offered conceptualizations. The IEA Energy Storage TCP defines energy system flexibility as:

"The ability of the integrated energy system to adjust supply and demand to achieve energy balance across all timescales in order to integrate higher shares of renewables" (Hauer, 2025).

EBC Annex 67 further specifies flexibility in the building context as:

"The ability to adapt/manage its short-term (a few hours or a couple of days) energy demand and generation according to local climate conditions, user needs, and energy network requirements without jeopardizing the technical capabilities of the operating systems in the building and the comfort of its occupants" (EBC Annex 67, 2021).

Task 43 builds on this and introduces a combined functional definition:

"Energy flexible operation occurs when a technical system reacts to superficial signals and adapts its operation without compromising its primary function in order to produce additional technical and/or non-technical benefits".

Within this framework, TABS can be conceptualized as thermal batteries. Their storage potential emerges from three core components: the state of charge, the charging strategy, and the discharging behavior. While the charging process is typically an active operation (e.g., controlled pre-heating or cooling using surplus energy), discharging occurs passively via thermal radiation or convection to the indoor environment. Due to the large activated thermal mass and its strong thermal inertia, the discharge duration of TABS is significantly longer than that of conventional HVAC systems. This prolonged and stable energy release, facilitated by well-insulated building envelopes, distinguishes TABS as a unique class of building-integrated storage systems.

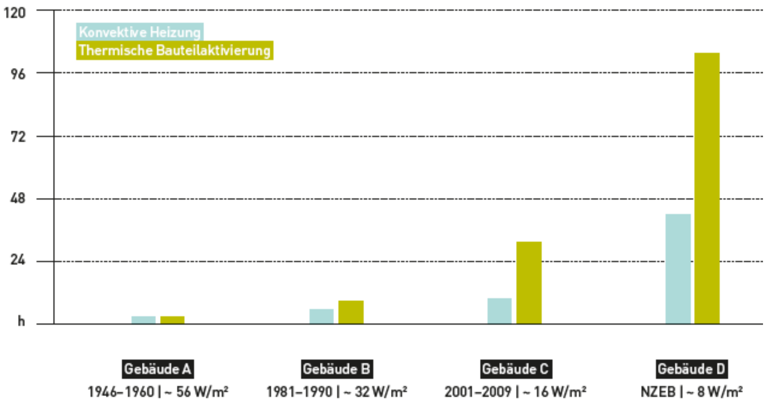


Figure 83: Comparison of different building types and their typical energy storage capabilities within their respective thermal masses for convective heating (blue, left column) and TABS (gree, right column). Source: (Klima- und Energiefonds, 2020)

Numerous methods and indicators have been proposed in recent years to quantify energy flexibility in buildings. The intention of this chapter is to assess what KPIs exist and how they assess "flexibility". These existing KPIs vary significantly in scope, units, time scales, and application contexts, see also (Salom, Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data, 2014), (Saldarriaga, 2022), (Korkas, 2016) and (Stinner, 2016). Figure XX presents an exemplary overview of selected flexibility-related indicators.

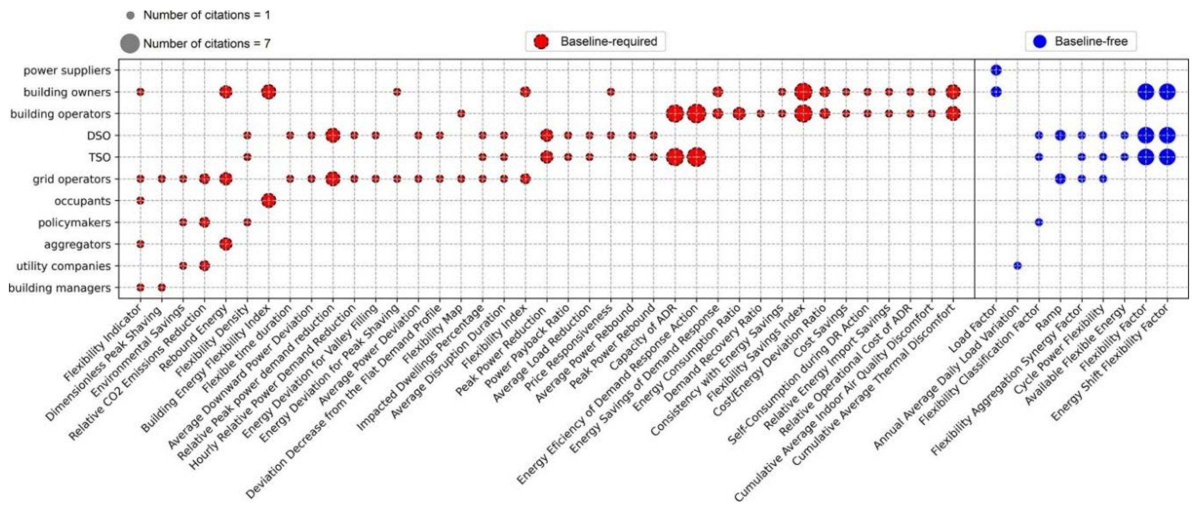


Figure 84: Overview of known KPIs for energy flexibility. Unlike baseline-required KPIs, baseline-free KPIs can be calculated with building data measured in a single scenario. The baseline is an estimation of the consumers' "normal" energy usage, i.e., the energy demand profile without any DR event. Source: (Li H. e., 2023)

For planners, investors, and operators, the key challenge is not the lack of KPIs, but rather their abundance. Choosing suitable indicators requires a clear understanding of the business case and operational targets. For instance, if the goal is short-term load shifting (e.g., photovoltaic surplus absorption), the storage design and control strategy must be tailored to achieve hourly or intraday balancing. Conversely, if the storage is to buffer weekend or seasonal effects, the thermal mass and insulation strategies must be scaled for weekly or annual cycles. Accordingly, the desired storage duration (and its typical recurrence) is a critical design parameter that should guide KPI selection and system optimization. Without this contextual knowledge, KPI comparisons can be misleading or irrelevant.

To identify the optimal TABS construction for an energy flexible use during the design phase, the ability of a KPI to distinguish between different designs plays a crucial role in its selection. While the general assessment of the energy flexibility potential can be informative, it is of limited use if the measured differences between design variations are too small. In such cases, additional or more sensitive KPIs should be consulted. To evaluate this discriminative capability of individual KPIs with respect to TABS design, the author used a validated building model of a single-family house. They investigated the energy-flexible operation of various TABS designs over a one-year period using dynamic simulations. The investigated design parameters included the pipe spacing, the number of parallel loops, and the installation depth within the building component. The annual simulations were then evaluated using 21 different KPIs, with a particular focus on the resulting differences between the designs for each respective KPI, for results see Figure 85.

One of the key findings is the significant impact of the KPI's calculation method. A distinction can be made between KPIs designed to evaluate a single energy flexibility event (lasting minutes to hours) and those that are based on aggregated sums over a multitude of events. For example, the Storage Capacity metric proposed by Reynders et al. (Reynders G. D., Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings, 2017) is calculated for a single event. However, a year-long simulation comprises a multitude of such events, each occurring under varying boundary conditions. The comparison of the different TABS designs reveals that, due to the high variability of events throughout the year, no statistically significant difference in Storage Capacity can be identified. This finding applies to all KPIs that are primarily designed for the assessment of single, isolated events and thus exhibit a statistical distribution when applied over a full year of simulation. It is important to note, however, that while these KPIs can provide a sound assessment of the overall energy flexibility potential, they exhibit limited sensitivity to specific design changes.

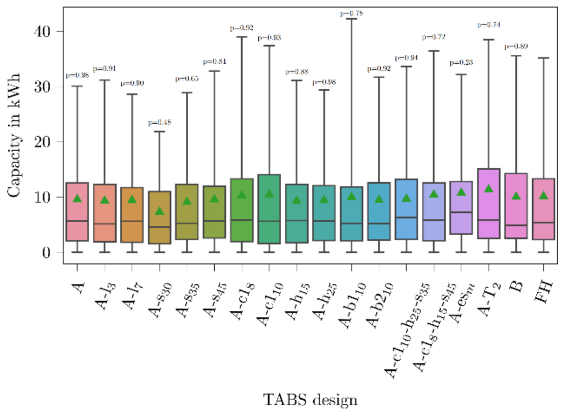


Figure 85: Boxplot of all TABS designs investigated for the event-wise calculated Storage Capacity including a Brunner-Munzel test ($p \leq 0.05$ indicates significance). The box corresponds to 50% of all values, the whiskers include 90% of all values. The green triangle shows the mean value and the black horizontal line inside the boxes shows the median of all values obtained from a one-year simulation (Joscha Reber, 2026).

In contrast, all non-statistical KPIs, which are based on aggregated sums over the year, consistently allow for a clear distinction between different TABS designs and thus form a solid basis for their comparative evaluation. A further insight from the investigation is that some KPIs exhibit very similar sensitivity to variations in TABS designs. Although the conceptual basis of these KPIs may differ, they offer no additional information for distinguishing between TABS designs, making them redundant for this specific purpose. This applies, for example, to the Outlay Shifting Ability (a_{OS}) (Marotta, Guarino, Cellura, & Longo, 2021), which shows a very similar behavior to the Flexibility Factor (FF) (Le Dréau & Heiselberg, 2016) when comparing different designs, see Figure 86.

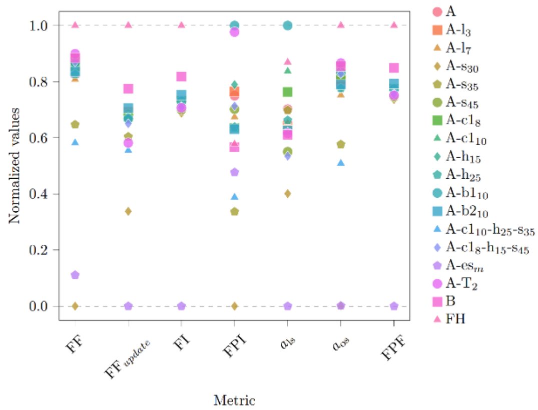


Figure 86: Min/Max-normalized miscellaneous metrics on TABS designs for a one-year simulation. A detailed presentation of the results can be found in Reber et al. 2026 (Joscha Reber, 2026)

The combination of the findings from this section form the basis for a selection process of KPIs which is presented in section 5.4.

5.4 Suggested procedure and simplification for planning and operation of energy flexible TABS

The overall Task 43 report has maintained a predominantly scientific character. Its chapters focus on analytical depth and quantitative evaluation of thermally activated building systems (TABS) and their flexibility potential. However, the explicit mandate of Subtask D was to translate these scientific findings into simplified, accessible, and practically applicable guidance for industry stakeholders. The objective was not to dilute scientific accuracy, but to make the results operational for planners, engineers, contractors, and decision-makers working in real-world market environments. This need for simplification and applicability became particularly evident during workshops, Task 43 meetings, and various exchange formats involving industry representatives. Many practitioners expressed that the analytical tools, modelling approaches, and evaluation methods developed by scientific partners, while valuable, were often perceived as too complex for routine application. Especially in fast-paced planning environments, tools must be intuitive, scalable, and compatible with existing workflows. Consequently, this penultimate chapter aims to translate the key findings of the Task into concrete, actionable guidance for the free market. At the core of successful TABS implementation lies an essential interdisciplinary challenge. Properly functioning TABS systems require the coordinated interaction of building design, user requirements, hydraulic systems, control strategies, HVAC equipment, and increasingly also grid interaction. Traditionally, these domains have operated in relative separation: architects design the envelope, HVAC planners dimension systems, control engineers optimize regulation, and grid operators remain external to building planning processes.

For TABS to unfold their full storage and flexibility potential, these disciplines must converge early in the planning phase. Importantly, this convergence is rarely linear but rather iterative and simultaneous. Assessments in one domain influence possibilities in another. For example, if a building's thermal mass or geometry does not allow for substantial storage capacity, certain use cases—such as seasonal storage or extended demand shifting—are simply unrealistic. Similarly, if charging equipment is undersized, flexibility operation may not be feasible regardless of control sophistication. Additionally, the ROI for flexibility options prohibits excessive investments for perfect operation and dictates that investments reflect the possible revenue streams that can be accessed via energy flexibility operation now and in the future. The following simplified assessments are considered crucial for successful TABS-based flexibility implementation and are presented in their most condensed and industry-oriented form. Most of the TABS systems encountered in Task 43, as well as the widespread and market ready TABS based on steel reenforced concrete, are based on sensible heat storage without phase change, which is why the presented simplified approach is based solely on sensible heat storage in the TABS.

5.4.1 Simplified state-of-charge estimation during design and operation

Chapter 5.2 demonstrated that the thermal storage capacity of TABS can be estimated using relatively simple base values and sensor data that can be implemented in buildings with acceptable effort. Rather than requiring complex building simulation environments during operation, simplified state-of-charge (SoC) estimations can be derived from temperature measurements, known material properties, and hydraulic parameters. This approach lowers the barrier for practitioners to evaluate available flexibility in both the design phase and operational phase. During design, simplified SoC estimation supports dimensioning decisions and helps to assess whether the intended use case is physically feasible. During operation, it allows operators to understand how much usable storage capacity is currently available without implementing highly advanced modeling frameworks. The simplified approach for estimating the SOC of TABS energy storage that was developed in Task 43 is shown in Figure 87.

$$Q_{TAB}(t) = \rho_{TAB} * c_{pV,TAB} * V_{TAB} * (T_t - T_{min})$$

Average physical properties of TAB element:
For standard construction, using the physical properties of the bulk mass (concrete, timber) is sufficiently accurate and results in errors <5%.

Usable volume for activation:
All bulk mass in proximity to piping can be considered active mass. Set boundaries at layers of different material, especially those with much higher heat flux resistance like insulation material.

Temperature boundaries and average slab temperature:
For temperature boundaries, consult standard indoor comfort diagrams for max and minimum temperature of the surface of the TAB slab. Based on the Task 43 findings, the surface temperature of concrete elements is also the best approximation of the average temperature of the TAB slab for state of charge estimation. Task 43 therefore recommends monitoring of the slab surface temperature.

Figure 87: Simplified approach for estimating the SOC of TABS energy storage, based on the Task 43 findings. Source: AEE INTEC

5.4.2 Clear intention of the use case as basis for system design

Thermal storage in TABS-based systems does not consist solely of the activated concrete slab itself. It must be understood as a system comprising three interacting components A) heat or cold generation technology feeding into the TABS (charging), the B) TABS (storage) and the B) means of discharging the TABS, either actively or passively, which is far more common (discharging), compare also

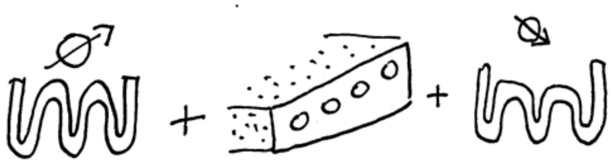


Figure 88: Schematic of the 3 key elements of a TABS flexible energy storage system. A) Charging technology (left), B) TABS storage (middle) and C) discharge of heat or cold (right). Source: AEE INTEC

The interaction of and sizing these three components defines the operational baseline of the storage system and most importantly the time constants (maximum achievable powers) of charging and discharging events as well as the maximum storage capacity (see Figure 89).

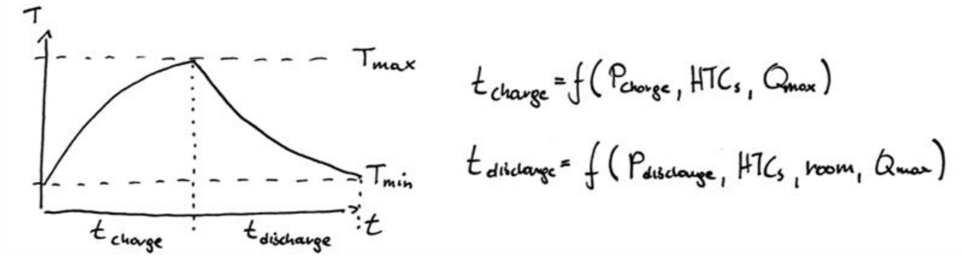


Figure 89: Simplified operation curve of a TABS energy storage system, including the main influences on charging and discharging durations. Source: AEE INTEC

This baseline cannot later be fundamentally altered by control strategies alone. It is therefore a key design indicator (KDI) of the system and must be considered early in the process. The following examples are meant illustrate the importance of this assessment:

- If charging equipment is sized small, grid flexible operation is inherently limited, regardless of control strategy. However, by comparing with section 4.2.3, case 1, this configuration allows the “passive” flexibility in the TABs to enable much reduced HVAC designs and costs, offering incentives for investors. In the Austrian example, TABS allowed the downsizing of the installed heat pump capacity by 75% without compromising comfort.
- If the activated slab volume is small, the storage fills quickly—but also empties quickly. The research and demonstration project AktivDHKS (see section 2.4.4) has set out to design their TABS to be able to bridge the night hours where no PV is available for heat generation via heat pumps. The TABS does not need to be bigger than that, which is a cost savings factor. Any additional TABS capacity would rarely be used in the intended operation regime.
- If discharge occurs very slowly, storage may not be available frequently enough for short-term flexibility markets. However, long discharge durations are a necessary for intra day storages that need to be able to bridge several days of energy shortage and in the extreme for seasonal storages.

Each objective implies different design and control implications. Without clarity regarding storage purpose, KPI selection and control strategy development remain unfocused.

5.4.3 Selecting Appropriate KPIs to Evaluate Performance

As outlined in chapter 5.3, an abundance of KPIs exists to evaluate flexibility performance. However, selecting the appropriate KPI is arguably the most critical step. The "right" KPI depends entirely on the intended use case and the stakeholder perspective. Some KPIs are suitable for evaluating grid services such as frequency response, while others better reflect building-level objectives such as comfort maintenance or cost reduction. Furthermore, different stakeholders prioritize different aspects:

- Grid operators focus on response time, modulation depth, and availability windows.
- Energy suppliers evaluate portfolio-level impacts.
- Building owners prioritize cost savings, self-consumption, or comfort stability.

KPI selection also influences the design of the TABS and especially the installed sensory equipment as this will be necessary to gather the required input data for KPI determination. KPI selection must therefore be performed individually and use-case specific. Figure 90 illustrates this principle conceptually.

Figure 90: Illustration of KPI selection steps from the viewpoints of the main two stakeholder groups, energy suppliers/aggregators (left) and end users/building owners (right). Source: OpenAI prompt by AEE INTEC

5.4.4 Control strategy design

Control is the decisive lever that determines whether TABS function merely as slow-reacting heating and cooling systems or as actively managed thermal storage assets capable of contributing to energy flexibility. While system design defines the physical limits of storage capacity and charging/discharging dynamics, control determines how effectively this potential can be utilized in practice. TABS are controlled by adjusting the temperature and mass flow rate of the fluid circulating through embedded pipes or capillaries.

Because TABS applications range from basic comfort provision to active demand shifting and grid interaction, control approaches must be selected according to system properties and intended use case. Within Task 43, three degrees of control complexity are distinguished. Each level introduces increasing sophistication and computational effort, but also increasing flexibility potential:

- Ad-hoc (measurement-based) strategies
- Predictive (forecast-based) strategies
- Active storage management strategies

Ad-Hoc Strategies Based on Current Measurements

For standard heating and cooling applications, relatively simple control approaches are often sufficient. In systems with shallow pipe installation and lower thermal inertia—comparable in behavior to floor heating systems—direct control of mass flow based on room air temperature measurements may already provide adequate performance. The most common approach is the use of a heating curve that determines the feed temperature as a function of outdoor temperature, indoor setpoint, and estimated building thermal capacity. In many installations, the feed temperature is identical across all zones, while zone-level mass flow rates are modulated via valves to account for solar gains, occupancy patterns, or varying temperature requirements.

However, due to the inherently high thermal inertia of TABS, conventional indoor air temperature control can be problematic. Aggressive controller parametrization may lead to overshooting because temperature feedback reflects past thermal states rather than immediate system response. To mitigate this, slab-embedded temperature sensors close to the surface can provide earlier detection of overheating or overcooling. These sensors also allow simultaneous control of air temperature and radiant surface temperature—the latter being particularly relevant for perceived occupant comfort.

Hybrid systems provide an additional layer of flexibility. Slow-acting TABS can be combined with faster-reacting ventilation or HVAC systems. In such configurations, TABS provide base load coverage and thermal stability, while ventilation systems compensate for short-term fluctuations in internal loads or occupancy. Irrespective of the specific control method, active shading control is essential in modern, well-insulated buildings with significant glazing areas. Without effective solar control, cooling demands may exceed the capacity of TABS systems, limiting flexibility potential and reducing overall efficiency.

Ad-hoc strategies are robust, simple, and cost-effective. However, their capacity to exploit flexibility potential remains limited, particularly in dynamic market environments.

Predictive Strategies Based on Forecasts

As thermal inertia increases and flexibility objectives expand beyond simple temperature control, predictive strategies become advantageous. These approaches utilize weather forecasts, occupancy schedules, and building models to anticipate disturbances and proactively adjust system operation. Building models used in predictive control can be categorized as:

- White-box models, which are highly detailed but require extensive modeling effort and expert knowledge.
- Grey-box models, which simplify physical processes and estimate parameters from data.
- Black-box models, which rely purely on data-driven statistical relationships.

In practice, RC-based grey-box models are most commonly applied for TABS. These resistor-capacitor models capture dominant time constants and thermal interactions between major building components, including walls, slabs, and active elements. They balance physical interpretability with manageable modeling effort.

Model Predictive Control (MPC) is the most prominent implementation of predictive control. MPC solves an optimization problem at each control interval, minimizing a defined objective function subject to system constraints. The objective typically includes targets like energy cost minimization, CO_2 reduction, comfort constraints or equipment limitations. These objectives are inherently conflicting. Minimizing energy cost may compromise comfort; maximizing comfort may increase energy consumption. Therefore, careful tuning of weighting coefficients in the objective function is required to align system behavior with stakeholder priorities. MPC offers significant advantages over simpler control strategies, e.g. explicit handling of constraints, incorporation of forecasts and the ability to manage long time constants and dead times as well as multi-objective optimization. However, MPC requires accurate state and parameter estimation. The controller must reliably know the current temperatures of zones, walls, and active elements. State estimation methods such as Kalman filtering combine measurement data with model predictions to improve reliability. Parameter estimation techniques ensure long-term model accuracy. Without sufficient measurement quality and data availability, predictive control performance deteriorates. Robust sensing infrastructure is therefore a prerequisite.

Predictive strategies significantly enhance flexibility potential, particularly for integrating renewable generation and responding to variable electricity prices.

Active Management of Building Mass as Storage

The highest degree of control sophistication involves explicitly using TABS as an active energy storage medium rather than merely a comfort system. In this context, the building mass becomes analogous to a thermal battery. Active pre-heating or pre-cooling enables shifting electrical loads, increasing self-consumption of photovoltaic electricity, or participating in grid flexibility markets. However, active management introduces a second control objective beyond temperature regulation: deliberate demand shifting through either modifying feed temperature or modifying mass flow rate for heating and cooling circuits.

Both strategies are constrained. Feed temperature adjustments must avoid excessive surface temperatures that could compromise comfort or cause condensation and mold formation. Mass flow modulation may reduce available storage capacity if not properly coordinated. When integrating heat pumps, PV systems, or dynamic electricity pricing, the optimization problem becomes significantly more complex. Controllers must handle both continuous variables (temperature, flow rate) and discrete decisions (heat pump on/off states). Mathematically, this leads to mixed-integer nonlinear programming (MINLP) problems, which are computationally demanding. To maintain real-time feasibility, simplification strategies such as linearization or reduced-order thermal storage models can transform the problem into mixed-integer linear programming (MILP) formulations. These approaches balance model fidelity with computational tractability.

Active storage management unlocks the full flexibility potential of TABS—but only if computational feasibility and data quality are ensured.

Conclusion and recommendations

Control complexity should always match the intended flexibility objective and storage duration. For basic comfort applications, ad-hoc measurement-based strategies are sufficient and robust. For intraday flexibility or integration of renewable forecasts, predictive control approaches provide significant benefits. For active demand shifting and portfolio-level optimization, advanced MPC combined with storage management is most effective.

However, increased control sophistication comes with higher implementation effort, greater data requirements, and increased computational demands. Control strategies should not be selected based on theoretical optimality alone, but on practical feasibility, data availability, and stakeholder objectives. When appropriately matched to the system's physical characteristics and use case, TABS control can transform passive thermal mass into a strategic flexibility asset within future grid-interactive buildings.

5.4.5 Detailed design of thermally activated building systems

The actual design of Thermally Activated Building Systems (TABS) represents the critical transition from theoretical flexibility potential to reliable real-world performance. While earlier sections of this report have discussed storage capacity estimation, KPI selection, and control strategies, these elements can only unfold their intended impact if the physical system is properly designed from the outset. TABS are fundamentally different from conventional HVAC components. They are not mechanical devices added to a building at a later stage; rather, they are structural energy elements embedded directly into the concrete mass of slabs, walls, or foundations. Because TABS are structurally integrated systems, their design requires early and coordinated collaboration between architects, structural engineers, HVAC planners, control specialists, and energy system designers. Slab thickness, pipe spacing, depth of embedment, reinforcement layout, insulation layers, and the interaction with ventilation and shading systems all influence the resulting thermal behavior. These parameters define not only comfort performance but also the available flexibility potential. Late-stage adjustments are difficult or impossible once the concrete is cast; therefore, design decisions must be robust and well-founded.

A central starting point in TABS design is the estimation of usable thermal storage capacity. The designer must determine whether the building mass supports hourly balancing, intraday shifting, multi-day smoothing, or longer storage durations as outlined in the previous sections. Simplified dimensioning methods allow practitioners to assess first-order storage potential based on slab geometry, material properties, and anticipated load profiles. Hydraulic design is equally critical. Pipe spacing, loop lengths, and manifold configuration determine achievable power density and response time. Closer pipe spacing increases power transfer but also construction effort and cost. Deeper embedment increases storage inertia but slows response. The designer must balance thermal power, storage duration, comfort constraints, and economic feasibility. Furthermore, uniform distribution is essential to avoid thermal hotspots and ensure even surface temperatures. Comfort considerations must remain central throughout the design process. TABS operate with relatively small temperature differences between supply fluid and room air. While this enhances efficiency and reduces drafts compared to forced-air systems, surface temperature limits must be respected. In cooling mode, condensation risks must be addressed through dew point monitoring and coordinated ventilation control. In heating mode, excessive radiant temperatures must be avoided to maintain thermal comfort. These aspects highlight again that structural design, control strategy, and HVAC integration cannot be separated.

At this point, it is important to emphasize that comprehensive and field-tested guidance for TABS design already exists. Rather than duplicating these resources, Task 43 deliberately builds upon them. The Austrian planning guideline "Energy-storage concrete – Thermal Component Activation", published by the Austrian Cement Association (VÖZ), provides a highly detailed and practice-oriented framework for implementing TABS (Friembichler, Handler, Krec, & Kuster, 2017), download link in English: https://zement.at/wp-content/uploads/Planning_guide_Energy_storage_concrete.pdf. The document covers structural integration, hydraulic dimensioning, comfort limits, planning workflows, commissioning considerations, and case examples. It represents accumulated practical experience and has been validated in numerous real projects, see

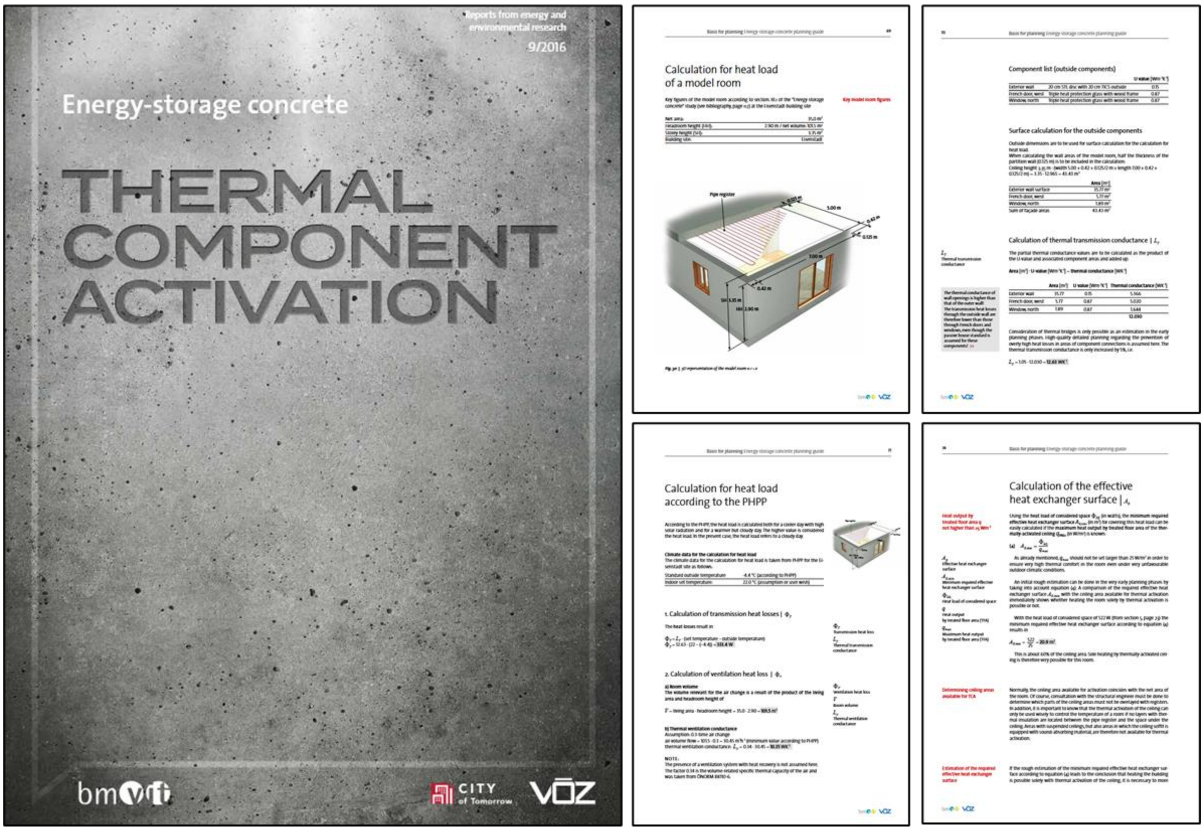


Figure 91: Cover and exemplary pages of the Austrian TABS planning guideline "Energy-storage concrete – Thermal Component Activation", published by the Austrian Cement Association (VÖZ). Source: (Felix Friembichler, 2016). Download link in English: https://zement.at/wp-content/uploads/Planning_guide_Energy_storage_concrete.pdf

For practitioners seeking to implement TABS in a robust and technically sound manner, this planning guide should be regarded as a primary reference document. It complements the flexibility-oriented insights of Task 43 by providing concrete design procedures, construction details, and calculation methodologies. In essence, Task 43 extends the established structural and HVAC design principles of TABS toward grid-interactive and flexibility-enabled operation through this report, while the VÖZ guideline ensures technical reliability and implementation feasibility of the TABS base technology.

5.5 Real scale implementations as showcase for TABS versatility

The original intention behind the collection of demonstration factsheets within Task 43 was to highlight the wide range of building types that can be equipped with Thermally Activated Building Systems (TABS) and to illustrate the flexibility potential inherent in such buildings. The goal was not only to document technical implementations, but also to showcase the architectural and functional diversity in which TABS can be successfully applied — from residential and office buildings to educational and mixed-use developments. By doing so, Task 43 aimed to make visible the adaptability of TABS across different climatic contexts, use cases, and design approaches. The submitted factsheets are skewed towards the countries of the core contributors of Task 43, namely Austria and Germany. The showcased buildings effectively demonstrate the architectural design freedom and application versatility that TABS enable. The selected examples underline that TABS are not confined to a specific building typology or scale but can be integrated into a broad spectrum of building concepts while maintaining high comfort standards and energy efficiency. The full factsheets can be found in Appendix 2, section 7.2, an overview is presented in Figure 92.

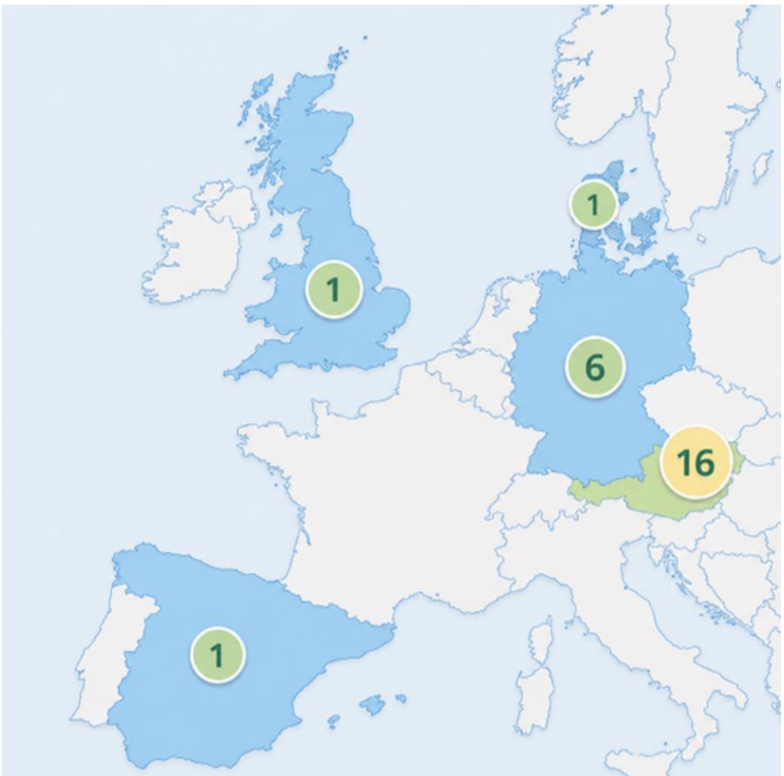


Figure 92: Overview of the geographical spread of the Task 43 factsheets. The detailed factsheets can be found in Appendix 2, section 7.2. Source: AEE INTEC, generated with AI.

However, a particularly noteworthy finding emerged from this review is, that out of the 25 documented buildings, only two currently operate in an energy-flexible manner. This observation highlights a significant gap between the technical storage potential embedded in TABS-equipped buildings and the actual implementation of flexible operation strategies. It underscores the importance of Task 43 in advancing knowledge exchange, raising awareness, and strengthening visibility of energy-flexible building operation within the construction and HVAC industries. To augment its own findings with those of other research projects, Task 43 also engaged in an exchange with UC Berkely, which implemented a radiant systems map that highlights radiant building heating systems including TABS across the globe. The individual buildings are presented in an online map format and are publicly accessible via an online link (https://radiant.cbe.berkeley.edu/resources, click " Interactive map for radiant system buildings"). The Task 43 factsheet buildings will be integrated into this platform as well to foster cross collaboration.

Figure 93: Screenshot of the "interactive map for radiant system buildings" from the UC Berkely. Yellow and Orange pins indicated TABS implementations. Source: https://radiant.cbe.berkeley.edu/resources

6 Impact and outreach

Throughout its three-year runtime, IEA ES TCP Task 43 actively exchanged with adjacent international networks and stakeholder communities to (i) avoid duplication, (ii) align terminology and evaluation approaches, and (iii) accelerate uptake of thermally activated building systems TABS as building-scale, multi-energy-carrier storage interacting with electricity and thermal networks.

A central collaboration was established with the IEA EBC TCP, in particular EBC Annex 82 and EBC Annex 84. Both annex operating agents were already involved during the Task definition phase and received regular updates on Task 43 scope and progress. Dedicated online meetings were used to identify synergies, clarify overlap, and implement concrete scope adjustments, with the intent of maintaining continuous exchange of methods and results.

This cooperation also materialised in joint events. The 3rd Task 43 meeting (Graz, Austria; hybrid; 8–9 April 2024) included invited contributions from international experts and a joint on-site workshop with the EBC Annex 84 community, enabling direct cross-fertilisation between TABS-focused work and broader demand-management research in thermal networks. In the same week, Task 43 contributed to the ISEC 2024 conference in Graz, including the workshop "Flexibility and Load Management for Energy Grids: The Hidden Potential of Buildings", presented alongside EBC Annex 84, explicitly targeting scientifically trained audiences beyond the immediate TABS expert community.

Task 43 also targeted scientific conferences, peer-reviewed journals, industry workshops and webinars for capacity building and increase of its outreach capabilities. In total, Task 43 achieved 16 scientific conference contributions, 5 publications in non-scientific journals and 4 peer-reviewed paper submissions in the journals "Smart Energy", "Springer Nature Energy Informatics" and "Energy and Buildings". Stakeholder engagement activities included one international Webinar and 4 industry workshops. Attended conferences with dedicated Task 43 presentations include 9th SES in Kopenhagen, the ISEC 2024 in Graz, the Enerstock 2024 in Lyon, the 34th Symposium Solar Heat in Germany and many others. Task 43 also hosted an entire session at the energy informatics academy conference 2025 in Malaysia, including the ongoing management and review of a Springer Nature Special collection on "Thermal Storage and Flexibility in Buildings: Digitalization, Control and Market Integration of Activated building mass" in the Journal "Energy Informatics" by the Task 43 leadership (link to the collection: https://link.springer.com/collections/aecdaghddj). To further broaden the audience of its results Task 43 conducted the 35th ES TCP On-Seminar in close cooperation with the ES TCP secretariat, allowing high level speakers from the Task group to present their solutions and findings. Within Subtask C – Non-technical challenges, also a peer reviewed publication was prepared in a transnational effort by the Task 43 participants. Key results of Subtask C are based on this original work, the paper itself is currently under review and is expected to be published in Summer 2026 in a special collection of "Springer Nature Energy Informatics".

On the national and stakeholder side, Task 43 engaged with the German funding coordination ecosystem via Projektträger Jülich (PtJ) (including exchange with the "Thermischer Verbund" initiative and associated projects), and with industry and implementation actors such as the Austrian Association of Cement Industries (VÖZ). VÖZ contributed national lighthouse examples and pointed to existing TABS planning guidance ("Energiespeicher Beton: Thermische Bauteilaktivierung"). Also, Task 43 supported in preparing and conducting the two final workshops of the Austrian Monitoring study "BTTAB", reaching 75+ participants from Austrian ministry, industry and academia in total.

Finally, Task 43 connected to the international standardisation and evaluation community through the IEA's EGRD workshop on "Developments in demonstrations, tests and standardization" (21–22 Nov 2024, Denmark), and through engagement with European standardisation activities (e.g., CEN/CENELEC workshop activity around thermal energy storage system integration).

7 Appendices

7.1 Appendix 1 Literature

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7.2 Appendix 2 Demo Factsheets

Available here: https://iea-es.org/task-43/

7.3 Appendix 3 Model Factsheets

Available here: https://iea-es.org/task-43/