energy storage
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

Executive Summary

Task Manager ES TCP Task 43:

DI Christoph Rohringer

AEE – Institute for Sustainable Technologies

Austria

energy storage

MAIN AUTHORS (ALPHABETICAL ORDER)

Alireza Afshari (Aalborg University, Denmark), Christoph Rohringer (AEE INTEC, Austria), Daniel Heidenthaler (FH Salzburg, Austria), Daniel Muschick (BEST – Bioenergy and Sustainable Technologies GmbH, Austria), David Ritter (Öko-Institut, Germany), John Grunewald (TU Dresden, Germany), Joscha Reber (TU Darmstadt, Germany), Manuel Andrés Chicote (University of Valladolid, Spain), Manuel Baumgartner (AEE INTEC, Austria), Matthias Kersken (Fraunhofer Institute for Building Physics IBP, Germany), Michael Moltinger (FH Salzburg, Austria), Pablo Hernandez-Cruz (University of the Basque Country, Spain), Shady Attia (University of Liège, Belgium), Thomas Friedrich (Innogration GmbH), Yang Xue (TU Darmstadt, Germany)

CONTRIBUTORS (ALPHABETICAL ORDER)

Aitor Erkoreka (University of the Basque Country, Spain), Alexander Engström (TermoDeck, UK), Andreas Wagner (Karlsruhe Institute of Technology, Germany), Bo Nørregaard Jørgensen (University of Southern Denmark), Claudia Dankl (VÖZ, Austria), Dirk Weiß (TU Dresden, Germany), Eric Matthes (Nanolope, Germany), Florien Möbius (Tragwerk Ingenieure, Germany), Hassan Mahach (IZES gGmbH, Germany), Joris Burger (Sto SE & Co. KGaA, Germany), Katja Tribulowsiki (TU Dresden, Germany), Karsten Rauber (IZES gGmbH, Germany), Kaya Dünzen (Öko-Institut, Germany), Matthias Pahn (Rheinland-Pfälzische Technische Universität), Maurice Plößer (Rheinland-Pfälzische Technische Universität, Germany), Markus Leeb (FH Salzburg, Austria), Maximilian Fürst (Clina Heiz- und Kühlelemente GmbH, Germany), Michael Gumhalter (AEE INTEC, Austria), Michael Müller (Hausservice Objektbewirtschaftungs GmbH, Austria), Michaela Meir (Inaventasolar, Norway), Paul Lampersberger (e7 energy innovation & engineering, Austria), Peter Holzer (IBR&I – Institute of Building Research & Innovation, Austria), Petra Mann (Karlsruhe Institute of Technology, Germany), Rene Basters (Rheinland-Pfälzische Technische Universität, Germany), Sebastian Fuchs (Tragwerk Ingenieure, Germany), Thomas Bednar (Tu Wien, Austria), Thomas Buchsteiner (TOWERN3000, Austria), Thomas Gröschke (Bauprojekt Dresden GmbH, Germany), Thomas Ramschak (TOWERN3000, Austria), Walter Becke (AEE INTEC, Austria), Zheng Grace Ma (University of Southern Denmark)

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

Abbreviation Meaning

ISO	International Organization for Standardization
KDI	Key Design Indicator
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).

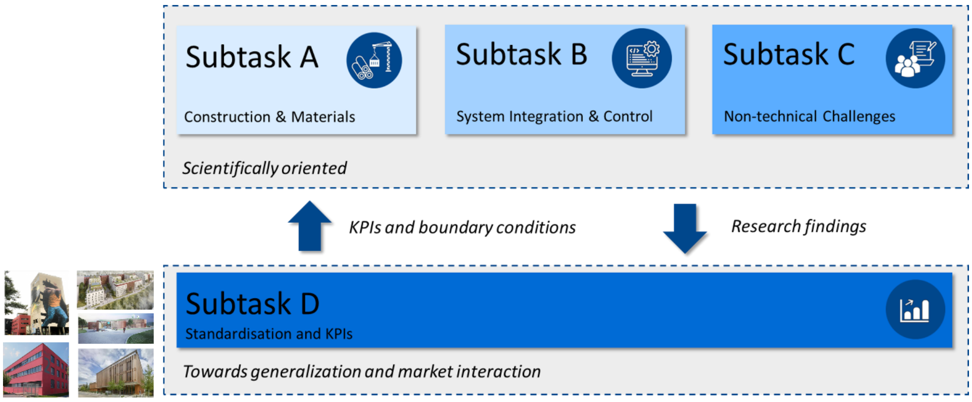

Figure 2: Overview of the 4 Subtasks of Task 43, including their relation to each other and how information flows between them. Source: AEE INTEC

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, Table 2 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/m^2 initial charging, 1.5–2.5 kWh/m^2 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.