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IEA SHC/ES Task 67/40

Compact Thermal Energy Storage – Materials within Components within Systems



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The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.



Summary

The IEA's combined ES Task 40 and SHC Task 67 focused on the advancement of compact thermal energy storage (CTES) technologies through the investigation and improvement of Phase Change Materials (PCM) and Thermochemical Materials (TCM). This international collaboration aimed to address the growing demand for energy efficient thermal storage solutions in various applications, including residential, industrial and district heating systems.

The objectives of the joint task included the establishment of reliable methods for material characterisation, the development of innovative composite materials and the establishment of standardised guidelines for the integration of CTES in energy systems. Activities included carrying out interlaboratory tests to refine measurement protocols, developing a comprehensive materials database and improving material stability under service conditions. Work was also carried out to find methods to determine the state of charge (SoC) of thermal storage systems and to understand degradation mechanisms affecting PCM and TCM to ensure durability and improved performance.

Key results highlighted advances in tailored materials development, such as composite designs that improve thermal conductivity, energy density and system compatibility. Through international collaboration, significant progress has been made in standardising test methods and improving material performance for practical applications.

In summary, the combined efforts of ES Task 40 and SHC Task 67 have filled critical gaps in knowledge and practice, contributing to scalable and efficient CTES solutions. Future work will focus on refining material databases, extending test protocols to new materials and supporting the transfer of project results into market-ready technologies.

Zusammenfassung

Die kombinierte ES Task 40 und SHC Task 67 der Internationalen Energieagentur konzentrierte sich auf die Weiterentwicklung von Technologien zur kompakten thermischen Energiespeicherung (CTES) durch die Untersuchung und Verbesserung von Phasenwechselmaterialien (PCM) und thermochemischen Materialien (TCM). Diese internationale Zusammenarbeit zielte darauf ab, die wachsende Nachfrage nach energieeffizienten thermischen Speicherlösungen in verschiedenen Anwendungen, einschließlich Wohn-, Industrie- und Fernwärmesystemen, zu befriedigen.

Zu den Zielen der gemeinsamen Aufgabe gehörten die Festlegung zuverlässiger Methoden zur Materialcharakterisierung, die Entwicklung innovativer Verbundwerkstoffe und die Erstellung standardisierter Leitlinien für die Integration von CTES in Energiesysteme. Zu den Aktivitäten gehörten die Durchführung von Ringversuchen zur Verfeinerung von Messprotokollen, die Entwicklung einer umfassenden Materialdatenbank und die Verbesserung der Materialstabilität unter Betriebsbedingungen. Außerdem wurden Methoden zur Bestimmung des Ladezustands (SoC) von Wärmespeichersystemen und zum Verständnis der Degradationsmechanismen von PCM und TCM entwickelt, um die Haltbarkeit und die Leistung zu verbessern.

Zu den wichtigsten Ergebnissen gehören Fortschritte bei der Entwicklung maßgeschneiderter Materialien, wie z. B. Verbundkonstruktionen, die die Wärmeleitfähigkeit, Energiedichte und Systemkompatibilität verbessern. Durch internationale Zusammenarbeit wurden bedeutende Fortschritte bei der Standardisierung von Testmethoden und der Verbesserung der Materialeistung für praktische Anwendungen erzielt.

Zusammenfassend lässt sich sagen, dass die kombinierten Bemühungen von ES Task 40 und SHC Task 67 kritische Wissens- und Praxislücken geschlossen und zu skalierbaren und effizienten CTES-Lösungen beigetragen haben. Die künftige Arbeit wird sich auf die Verfeinerung von Materialdatenbanken, die Ausweitung von Testprotokollen auf neue Materialien und die Unterstützung des Transfers von Projektergebnissen in marktreife Technologien konzentrieren.



Résumé

Les tâches ES Task 40 et SHC Task 67 de l'Agence internationale de l'énergie se sont concentrées sur l'avancement des technologies de stockage compact de l'énergie thermique (CTES) grâce à l'étude et à l'amélioration des matériaux à changement de phase (PCM) et des matériaux thermochimiques (TCM). Cette collaboration internationale visait à répondre à la demande croissante de solutions de stockage thermique efficaces sur le plan énergétique dans diverses applications, notamment les systèmes résidentiels, industriels et de chauffage urbain.

Les objectifs de la tâche commune comprenaient l'établissement de méthodes fiables pour la caractérisation des matériaux, le développement de matériaux composites innovants et l'établissement de lignes directrices normalisées pour l'intégration des CTES dans les systèmes énergétiques. Les activités comprenaient la réalisation d'essais interlaboratoires pour affiner les protocoles de mesure, le développement d'une base de données complète sur les matériaux et l'amélioration de la stabilité des matériaux dans les conditions de service. Des travaux ont également été menés pour trouver des méthodes permettant de déterminer l'état de charge (SoC) des systèmes de stockage thermique et pour comprendre les mécanismes de dégradation affectant la PCM et la TCM afin de garantir la durabilité et l'amélioration des performances.

Les principaux résultats ont mis en évidence les progrès réalisés dans le développement de matériaux sur mesure, tels que les matériaux composites qui améliorent la conductivité thermique, la densité énergétique et la compatibilité des systèmes. Grâce à la collaboration internationale, des progrès significatifs ont été réalisés dans la normalisation des méthodes d'essai et l'amélioration des performances des matériaux pour des applications pratiques.

In summary, the combined efforts of ES Task 40 and SHC Task 67 have filled critical gaps in knowledge and practice, contributing to scalable and efficient CTES solutions. Future work will focus on refining material databases, extending test protocols to new materials and supporting the transfer of project results into market-ready technologies.



Main findings («Take-Home Messages»)

Main Findings ("Take-Home Messages")

1. **Advancements in Material Characterization:** The development of standardized protocols for characterizing Phase Change Materials (PCM) and Thermochemical Materials (TCM) has significantly improved the reliability and reproducibility of testing. The creation of a comprehensive material database ensures accessibility and supports future research.
2. **State-of-Charge (SoC) Determination:** Techniques for determining the SoC of CTES systems were refined, including novel approaches that integrate measurement methods with modeling. This advancement enhances real-time energy management, supporting the integration of thermal storage into digitalized energy systems.
3. **Material Stability and Durability:** Detailed studies identified degradation mechanisms affecting PCM and TCM under operational and accelerated conditions. Insights from these investigations led to recommendations for stability testing and strategies to mitigate degradation, ensuring long-term material performance.
4. **System Integration and Design Optimization:** The interaction between materials and components was studied to optimize the design of CTES systems. This research produced guidelines for integrating thermal storage into energy systems, ensuring compatibility and efficiency at both component and system levels.



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List of abbreviations

AIT:	Austrian Institute of Technology
ASHRAE:	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CEA:	Commissariat à l'énergie atomique et aux énergies alternatives (France)
CIEMAT:	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Spain)
CIC EnergiGUNE:	Cooperative Research Center on Energy Materials (Spain)
CNRS:	Centre National de la Recherche Scientifique (France)
CTES:	Compact Thermal Energy Storage
DLR:	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
DSC:	Differential Scanning Calorimetry
DTU:	Technical University of Denmark
ES:	Energy Storage
FAIR:	Findable, Accessible, Interoperable, and Reusable
FHOÖ:	University of Applied Sciences Upper Austria
HSLU:	Lucerne University of Applied Sciences and Arts (Switzerland)
HTF:	Heat Transfer Fluid
IEA:	International Energy Agency
INSA:	Institut National des Sciences Appliquées (France)
KPI:	Key Performance Indicator
LOCIE:	Laboratory of Optimisation of the Design and Engineering of the Environment (France)
LFA:	Laser Flash Analysis
MPC:	Model Predictive Control
NRCan:	Natural Resources Canada
PCM:	Phase Change Material
RRT:	Round-Robin Tests
SFOE	Swiss Federal Office of Energy
SHC:	Solar Heating and Cooling
SoC:	State of Charge
TCM:	Thermochemical Material
TES:	Thermal Energy Storage
TNO:	Netherlands Organisation for Applied Scientific Research
TPS:	Transient Plane Source
UA:	Heat Transfer Coefficient-Area Product
VDI:	Verein Deutscher Ingenieure (Association of German Engineers)
ZAE Bayern:	Bavarian Center for Applied Energy Research (Germany)
SFOE	Swiss Federal Office of Energy



1 Introduction

The combined efforts of the International Energy Agency's (IEA's) Energy Storage (ES) Task 40 and Solar Heating and Cooling (SHC) Task 67 address the growing need for efficient Compact Thermal Energy Storage (CTES) systems. These tasks, operating from July 1, 2021, to June 30, 2024, focused on enhancing the performance and application potential of Phase Change Materials (PCM) and Thermochemical Materials (TCM), which are key to achieving higher energy efficiency and integration of renewable energy in diverse applications, including residential, industrial, and district heating systems.

The primary goal was to advance the state of knowledge on CTES materials by focusing on improving material characterization, understanding degradation mechanisms, refining state-of-charge (SoC) determination techniques, and fostering effective integration of CTES components into energy systems. By combining expertise in materials science, system engineering, and application testing, the project provided a comprehensive approach to developing innovative, reliable, and scalable solutions.

The approach was structured across five interconnected subtasks, each led by experts in the field:

1. Subtask A: Material Characterization

- **Leader:** Daniel Lager (AIT, Austria)

Focused on developing standardized testing protocols and expanding the material database to ensure reproducibility and accessibility.

2. Subtask B: Material Development

- **Leader:** Stefania Doppiu (CIC EnergiGUNE, Spain)

Targeted the creation of advanced material composites to optimize energy storage density and thermal performance.

3. Subtask C: State of Charge (SoC) Determination

- **Leaders:** Gerald Englmaier (DTU, Denmark) and Reda Djebbar (NRCAN, Canada)

Addressed the challenge of determining the state of charge through novel measurement techniques and validation in standalone and integrated systems.

4. Subtask D: Stability and Durability of CTES Materials

- **Leader:** Christoph Rathgeber (ZAE Bayern, Germany)

Investigated material stability under operational and accelerated conditions to map degradation mechanisms and develop testing recommendations.

5. Subtask E: Material-Component Interaction and System Integration

- **Leaders:** Ana Lázaro (University of Zaragoza, Spain), Andreas König-Haagen (University of the Basque Country, Spain), and Benjamin Fumey (HSLU, Switzerland)

Focused on designing components and systems to improve performance and enable seamless integration of CTES technologies.

These efforts have strengthened the platform for progress in the development of materials with higher energy density, better thermal conductivity and improved stability, as well as advanced techniques for SoC measurement and system control. The results of the project not only pave the way for scalable applications, but also strengthen the foundation for achieving global energy efficiency and decarbonisation goals through improved thermal storage technologies.



2 Approach, method, results and discussion

2.1 Task Participants

Austria

- **AIT:** Daniel Lager
- **AEE Intec:** Wim van Helden
- **University of Applied Sciences Upper Austria (FHOÖ):** Gayaneh Issayan, Bernhard Zettl
- **TU Wien:** Peter Weinberger, Jakob Smith

Canada

- **NRCan:** Reda Djebbar, Lia Kouchachvili, Thomas Manser, Dylan Bardy
- **Dalhousie University:** Dominic Groulx
- **University of Ottawa:** Handan Tezel
- **Neothermal Energy Storage Inc.:** Louis Desgrosseilliers

Denmark

- **DTU:** Gerald Englmaier, Jianhua Fan
- **Aalborg University:** Alireza Afshari, Evdoxia Paroutoglu, Allesandro Maccarini

France

- **CEA:** Grégory Largiller
- **Université Savoie Mont Blanc:** Nolwenn Le Pierrès, Michel Ondarts, Jonathan Outin, Élise Berut
- **CNRS:** Jérôme Soto
- **INSA Lyon:** Frédéric Kuznik, Kévy Johanes
- **LOCIE Laboratory:** Élise Berut
- **University of Nantes:** Lingai Luo

Germany

- **ZAE Bayern:** Christoph Rathgeber, Andreas Hauer, Henri Schmit
- **Fraunhofer ISE:** Stefan Gschwander, Franziska Klünder
- **TU Munich:** Leander Morgenstern, Florian Kersch
- **DLR:** Andrea Gutierrez, Maike Johnson

Italy

- **CNR:** Vincenza Brancato, Andrea Frazzica
- **University of Messina:** Luigi Calabrese, Candida Milone, Elpida Piperopoulos

Netherlands

- **TU Eindhoven:** Henk Huinink
- **TNO:** Ruud Cuypers, Jochem Jongerius
- **University of Twente:** Mina Shahi



Norway

- **SINTEF**: Galina Simonsen, Fride Vullum-Bruer, Alexis Sevault, Asmira Delic

Spain

- **CIC EnergiGUNE**: Stefania Doppiu, Ángel Serrano, Elena Palomo, Eduardo José García-Suarez
- **University of Zaragoza**: Ana Lázaro
- **University of Barcelona**: Inés Fernández, Camila Barreneche
- **University of Lleida**: Luisa F. Cabeza, Gabriel Zsembinszki, Emiliano Borri, David Verez
- **CIEMAT**: Rocio Bayón

Switzerland

- **HSLU**: Benjamin Fumey, Rebecca Ravotti

United Kingdom

- **University of Birmingham**: Yulong Ding, Helena Navarro
- **Swansea University**: Jonathon Elvins, Jack Reynolds
- **University of Warwick**: Bob Critoph, Sai Saran Yagnamurthy

United States

- **US Department of Energy (DoE)**: Sven Mumme, Sumanjeet Kaur

2.2 IEA Task homepages

The IEA oversees two collaborative programs focusing on Compact Thermal Energy Storage (CTES):

- **IEA Solar Heating and Cooling (SHC) Programme**: [IEA-SHC-Task 67](#)
- **IEA Energy Storage (ES) Programme**: [IEA-ES-Task 40](#)

Extensive information on the task activities can be found under these pages.

2.3 Task Meetings

1. Kick-Off Meeting

- **Location**: Vitoria-Gasteiz, Spain
- **Date**: October 27–29, 2021
- **Participants**: 53 (24 onsite, 29 online)

2. Second Meeting

- **Location**: Graz, Austria
- **Date**: April 4–5, 2022
- **Participants**: 38 onsite

3. Third Meeting

- **Location**: Kassel, Germany
- **Date**: September 29–30, 2022
- **Participants**: 41 onsite



4. Fourth Meeting

- **Location:** Halifax, Canada
- **Date:** April 24–26, 2023
- **Participants:** 37 (30 onsite, 7 online)

5. Fifth Meeting

- **Location:** Lyon, France
- **Date:** October 2–4, 2023
- **Participants:** 35 (29 onsite, 6 online)

6. Final Meeting

- **Location:** Lucerne, Switzerland
- **Date:** April 22–24, 2024
- **Participants:** 34 (28 onsite, 6 online)

2.4 Subtask methods

The main objective of the Task is to advance CTES technologies and accelerate their market introduction through international collaboration between experts in materials research, component development, system integration and industry. Key objectives include understanding the factors influencing storage density and performance degradation in CTES materials, developing reliable and reproducible characterisation methods, developing effective techniques for determining the state of charge (SoC), and expanding the knowledge base for designing optimised heat exchangers and reactors tailored to CTES technologies.

The following descriptions of the subtask methodologies are summaries of the official task reports available on the task homepages provided.

2.4.1. Subtask A: Material Characterization and Database (Round Robin Tests)

Introduction and Objectives

Subtask A under Task 67/Task 40 aimed to advance the characterization and database development of CTES materials, specifically PCM and TCM. The objectives included creating standardized measurement procedures, conducting round-robin tests (RRT) for reliability, and enhancing the CTES materials database to support the wider research community.

Standardized Measurement Procedures and Round Robin Tests (RRT)

The standardized measurement efforts focused on the critical material properties: thermal conductivity, thermal diffusivity, specific heat capacity, enthalpy changes, density, and viscosity. Each property was addressed through RRTs involving international collaboration and the use of diverse equipment and methodologies. These efforts helped identify variability across laboratories and improve measurement protocols.

Thermal conductivity and diffusivity measurements were conducted using paraffin from Merck as the reference material in round-robin tests (RRTs). Techniques such as Laser Flash Analysis (LFA), Hot Wire (HW), and Transient Plane Source (TPS) were employed. However, discrepancies arose due to equipment-specific settings and variations in sample preparation methods. To mitigate these issues, solutions such as controlled cooling and detailed procedural adjustments were proposed to enhance standardization and comparability of results.

The availability of suitable equipment poses a significant challenge to developing a standardized measurement protocol. To address this, procedures were categorized by equipment type, including LFA,



TPS, HW, and other steady-state methods. Ensuring accurate comparisons requires careful consideration of both experimental and systematic uncertainties. In some instances, reported uncertainties were smaller than the instrument error due to insufficient replicates, neglecting equipment error, or inadequate sample testing. Future actions to address these issues include increasing the number of replicates, testing diverse samples under consistent conditions, accounting for equipment errors using independent standards, and performing statistical analyses to evaluate different instruments and techniques. Additionally, expanding investigations into other PCM and testing TCM will further strengthen the research outcomes.

Specific Heat Capacity was studied using Anhydrous strontium bromide (SrBr_2), its hexahydrate form ($\text{SrBr}_2 \cdot 6\text{H}_2\text{O}$), and synthetic zeolite Z-13X were analyzed using Differential Scanning Calorimetry (DSC). The tests yielded reliable and consistent data for SrBr_2 and Z-13X, while results for $\text{SrBr}_2 \cdot 6\text{H}_2\text{O}$ showed significant inconsistencies due to issues related to sample hydration. These findings emphasize the need for refined preparation methods and standardized procedures for testing hydrated materials.

In the first round-robin test for SrBr_2 , eight participants contributed, resulting in a robust dataset suitable for statistical analysis. The results demonstrated strong comparability among participants, with a favorable z-score indicating satisfactory performance. Conversely, measurements for SrBr_2 hydrates revealed notable deviations, likely due to differences in hydration states during testing, underscoring the need for enhanced standardization in sample preparation.

For the zeolite 13X round-robin test, only three participants submitted data, likely due to the test's late initiation. Nevertheless, the procedure and results were comparable, with participants achieving low z-scores, reflecting consistent performance. Future efforts should prioritize addressing the impact of water content in hydrated or sorption materials and expanding measurement routines to include higher-temperature applications, which remain underexplored.

Enthalpy changes were investigated using zeolite 13X and water vapor with a simplified isobaric adsorption/desorption procedure. While results from some laboratories demonstrated high replicability, variations in conditions and instrumentation highlighted the challenges of aligning methodologies across different facilities. Limited funding also restricted the participation and contribution of certain partners, further complicating progress. Despite these obstacles, the initial results showed reasonable agreement among those able to complete the tests, even with different apparatuses, marking a promising first step toward standardization.

Future efforts will aim to increase the number of laboratories involved in the testing campaign and ensure the use of diverse apparatuses under a unified simplified protocol. Once validated, this methodology could be expanded to accommodate a broader range of conditions and materials, helping to establish a standardized approach for sorption enthalpy measurement. Such a framework would foster consistency and collaboration within the scientific community, advancing the reliability and applicability of these measurements.

Density and viscosity measurements revealed important insights and areas for improvement. Liquid-phase density measurements showed consistent results, requiring no changes to existing procedures. However, solid-phase density measurements exhibited significant variations, prompting the development of a procedure based on the Archimedes principle. This new method was shared with participants, but results based on its implementation have not yet been reported, making it a potential focus for future studies to evaluate its effectiveness.

For viscosity, the current procedure demonstrated good reproducibility for molten paraffins, including octadecane, RT70, and the paraffin detailed in this report. To further enhance understanding, it is recommended to expand testing to include other PCM families using the same protocol. Additionally, there is a need to investigate materials with non-Newtonian behaviors, such as PCM slurries, to determine if the existing measurement method requires adaptation for these specific materials.



CTES Materials Database Development

The development of the new version of the CTES materials database, "thermalmaterials.org," focuses on improving accessibility, usability, and integration within the broader framework of materials data platforms. This initiative underwent four key phases, involving system, external interface, and non-functional requirements. A major goal is to enable users to efficiently submit measurement data, access relevant information, and navigate the database with ease. Enhancements include support for diverse data types, such as material class filters, degradation process descriptions, chemical formulas, and molecular weights. Additionally, the database now accommodates detailed documentation for measurements not adhering to DSC standards and emphasizes contributions from users, including references to their related projects and research.

The database interface has been restructured to provide a hierarchical format, enabling users to move from general overviews to specific datasets, measurements, and plots. A new "Compare and Explore" section allows simultaneous plotting of multiple datasets. Features like filters, switches, and predefined plot formats further enhance usability. Specific procedures for uploading TCM measurements have been added to ensure consistency. Integration with external platforms through hyperlinks, aligning with FAIR data principles, strengthens the database's interoperability. The communication interface has been enhanced to include automated, customizable email newsletters for users.

The updated database is expected to streamline access to a wealth of PCM and TCM data, fostering collaboration and advancing research. It provides a more structured approach to organizing, visualizing, and comparing data, enabling scientists to draw meaningful insights and share findings effectively. With these enhancements, "thermalmaterials.org" is set to become a vital resource for the energy storage research community, promoting standardized methods and facilitating integration with similar platforms. Further steps involve expanding adoption of the database and exploring additional features to maintain its relevance and usability.

Conclusion

Subtask A successfully laid the groundwork for advancing material characterization and database development for CTES. By conducting comprehensive round-robin tests (RRTs) for thermal properties and addressing challenges in density, viscosity, and sorption enthalpy measurements, the task demonstrated the potential for standardized procedures to ensure consistent and accurate results. Additionally, significant progress was made in defining requirements for a robust CTES materials database, aiming to enhance accessibility, usability, and collaboration within the research community. However, constraints such as equipment variability, sample preparation inconsistencies, and budgetary limitations hindered complete implementation. Future efforts should focus on refining methodologies, expanding collaborative participation, and streamlining database development to bridge the remaining gaps and foster innovation.

Key Messages

1. **Standardized Methodologies Are Crucial:** The development of standardized procedures for measuring thermal conductivity, diffusivity, and specific heat capacity proved essential in achieving reliable and comparable data across different laboratories.
2. **Challenges in Measurement Highlight Areas for Improvement:** Variability in equipment, sample preparation, and environmental conditions impacted the consistency of results, particularly for hydrated materials and solid-phase density. Addressing these issues is vital for advancing material characterization.
3. **Collaborative Testing Strengthens Outcomes:** Round-robin tests involving multiple institutions provided valuable insights into procedural refinements and equipment performance, underscoring the importance of collaborative efforts in overcoming technical challenges.

2.4.2. Subtask B: CTES Material Improvement



Introduction and Objectives

The advancement of CTES materials plays a pivotal role in improving the efficiency and affordability of thermal energy storage systems. Enhancing materials to meet application-specific needs is essential for optimizing energy storage performance, system integration, and durability. Subtask B focused on strategies to develop new materials and refine existing ones, addressing challenges in energy density, thermal conductivity, and material compatibility.

Improving CTES materials involves distinct approaches based on the type of material, whether PCM or TCM. For PCM, efforts center on maximizing latent heat storage, mitigating supercooling, and ensuring compatibility with heat transfer fluids. For TCM, the priorities include enhancing reaction enthalpy, improving thermal conductivity, and achieving consistent process reversibility. The subtask underscored the importance of aligning material properties, such as energy density and operational temperatures, with the demands of specific applications to maximize performance.

The objectives included creating low-cost, sustainable, and non-toxic materials while exploring both single-component innovations and multi-component composites for enhanced storage capacity. The evaluation of synthesis and processing methods was critical for understanding their impact on economic and environmental performance. Additionally, advancements in composite designs and encapsulation techniques aimed to enhance heat and mass transfer properties, supporting better integration of CTES materials into practical applications.

Key Strategies and Research Activities

Subtask B pursued a comprehensive mapping of materials, identifying research pathways and optimization strategies for PCM and TCM. The strategies were categorized into three main areas: tailoring energy density and working temperatures, enhancing heat and mass transfer, and improving system integration. The results were achieved through collaboration among approximately 20 research institutions.

Tailoring energy density and working temperatures was a primary focus in material development efforts. Researchers explored composite materials that incorporated active substances such as salt hydrates, zeolites, and aluminophosphates. These composites aimed to facilitate phase transitions or chemical reactions within specific temperature ranges, thereby optimizing energy density and ensuring stability. Examples included hosting TCMs in porous matrices and creating hybrid systems that combined PCMs and TCMs. By fine-tuning the chemical composition and structure, these materials achieved targeted thermodynamic properties, addressing the unique demands of various thermal energy storage (TES) applications.

Enhancing heat and mass transfer properties was another significant goal. Techniques included incorporating highly conductive materials, such as foams or fibers, to improve thermal conductivity. Active materials were also infiltrated into conductive matrices or encapsulated, minimizing the proportion of inert materials that could detract from energy density. These methods ensured more efficient heat transfer processes and supported better thermal performance over time. Such approaches were particularly critical in applications requiring rapid thermal response or significant temperature gradients.

System integration was streamlined through the use of shape-stabilized and encapsulated materials. Encapsulation, for instance, allowed direct contact between PCMs and heat transfer fluids, eliminating the need for intermediary heat exchangers. This simplification reduced system complexity and costs, making TES technologies more practical and scalable. These advances enabled seamless integration of improved materials into existing systems, enhancing the overall feasibility of TES applications in energy storage and distribution networks.

Collaboration among participating institutions played a crucial role in advancing these objectives. Researchers shared insights into material behaviors, explored diverse pathways for optimization, and discussed challenges such as stability under various operating conditions. This joint effort laid the groundwork for developing standardized guidelines for material enhancement, particularly in quantifying how improvements impact TES systems. Although some planned activities, like constructing Ragone plots to evaluate power versus energy trade-offs, could not be fully realized due to resource constraints,



these discussions highlighted the importance of aligning material development with application-specific needs. The work emphasized the potential of interdisciplinary efforts to overcome challenges and drive innovations in thermal energy storage technologies.

Subtask B made substantial progress in advancing CTES materials but also revealed several challenges in aligning material improvements with TES system performance. Key issues included difficulties in quantifying how material enhancements impact overall system efficiency, defining development guidelines tailored to specific applications, and managing trade-offs between boosting energy density and ensuring material durability. Addressing these challenges required collaborative brainstorming across subtasks to link material properties to system-level outcomes through Key Performance Indicators (KPIs). Discussions emphasized the importance of encapsulated materials that maintain thermal efficiency and compatibility with heat transfer fluids. Tools like Ragone plots were proposed to evaluate critical material properties, such as energy density and power output, within specific application contexts.

The subtask identified significant outcomes that set the stage for future advancements. Promising composites for PCM and TCM with tailored thermodynamic and physical properties were highlighted. Methodologies to evaluate and predict material performance under defined conditions were developed, alongside a collaborative framework to align research and development efforts with system-level requirements. These achievements underscored the importance of systematic material optimization strategies in enhancing the scalability and efficiency of CTES technologies.

Looking ahead, Subtask B recommended focusing on advanced encapsulation techniques and shape stabilization to improve material integration into TES systems. The use of tools like Ragone plots should be expanded to guide optimization efforts by providing clear metrics on energy and power trade-offs. To address remaining questions, joint research initiatives were proposed to explore the broader impact of material properties on system performance. These steps are crucial for aligning material innovations with the evolving demands of TES applications and ensuring their practical adoption.

Conclusions

The development of optimized CTES materials is vital for achieving cost-effective, efficient TES systems. Subtask B demonstrated how innovative strategies can lead to materials with improved properties, contributing to the scalability and applicability of TES technologies. Despite progress, challenges remain, particularly in establishing guidelines for material improvement and quantifying their impact on TES systems. Continued collaboration and targeted research are essential to address these gaps and advance the field.

Key Messages

1. The development of high-performance TES materials is crucial for the widespread adoption of efficient, cost-effective TES systems.
2. Establishing guidelines for material improvement is critical to aligning development efforts with system requirements.
3. Novel strategies for TCM enhancement, such as composite designs and encapsulation, are emerging, complementing traditional PCM optimization approaches.
4. The use of KPIs and tools like Ragone plots provides a pathway to assess and improve material properties in the context of system-level performance.
5. Despite ongoing research, many questions remain open, underscoring the need for sustained efforts in material development and integration strategies.

This summary encapsulates Subtask B's achievements, challenges, and future directions, showcasing its contribution to advancing CTES materials and TES technologies.

2.4.3. Subtask C: State of Charge – SoC Determination



Introduction and Objectives

Subtask C was dedicated to identifying and promoting effective methods for determining the State of Charge (SoC) in CTES systems, specifically those utilizing PCM and TCM. Reliable SoC determination is critical for optimizing energy storage system performance, facilitating precise control, improving efficiency, and supporting the digital transformation of energy infrastructure.

The subtask encompassed three primary areas of focus: gathering existing SoC determination methods, validating these techniques through experimental and numerical approaches, and aligning them with real-world application requirements. The efforts were centered on measuring the relative enthalpy contributions of active materials, such as PCM and TCM, which are responsible for the energy storage capacity, while excluding the passive sensible storage capacities of the system. SoC was defined as the percentage ratio of residual or accumulated energy to the system's maximum energy capacity. Due to the extensive nature of energy capacity evaluation, methods were required that could assess either bulk material properties or localized measurements to accurately determine the overall system SoC.

Methodologies for State of Charge (SoC) Determination

Techniques for determining the State of Charge (SoC) in thermal energy storage systems are organized across three development levels, reflecting the progression from fundamental research to practical application. At the material level, methods focus on intrinsic properties of PCM and TCM, such as thermal, acoustic, optical, or electrical responses. These foundational techniques are typically suited for early-stage research. At the component level, material-level measurements are integrated into subsystems, offering calibrated data for bulk or localized SoC determination. Finally, at the system control level, these methods are fully implemented into operational systems, incorporating advanced control mechanisms like model predictive control (MPC) and "digital twins" for real-time management.

PCM SoC Determination Techniques

Determining SoC in PCM systems primarily involves measuring phase transitions and latent heat contributions. One common approach combines temperature monitoring with heat flux calculations to estimate the phase fraction and associated energy storage. Optical methods, such as light transmission or digital imaging, are used to track phase boundaries, though their reliance on transparent containers limits practical applications. Acoustic wave methods, particularly time-of-flight measurements, show promise but face challenges like scattering and path dependency. Electrical conductivity and capacitance techniques exploit differences in electrical properties between solid and liquid phases, offering high sensitivity, especially for ionic PCMs like salt hydrates. Flow cell methods are adapted for PCM slurries, using turbidity sensors to dynamically monitor phase fractions. For PCMs with complex behaviors, such as sodium acetate trihydrate, binary mixture solubility approaches model phase equilibria based on temperature, effectively addressing systems with supercooling.

TCM SoC Determination Techniques

SoC determination in TCM systems must address the complexities of reaction kinetics and equilibrium dynamics. Techniques include monitoring mass or volume changes of sorbates, which, while straightforward, are often intrusive and unsuitable for large-scale systems. Enthalpy balance methods calculate SoC by measuring heat flow, requiring accurate heat loss modeling and predefined reference states. Temperature and vapor pressure correlations leverage equilibrium properties to estimate SoC but are most effective under steady-state conditions. Capacitive sensors measure changes in dielectric properties during sorption processes, offering non-intrusive monitoring with significant potential for materials like zeolites. Additionally, spectroscopic analysis, such as UV-Vis spectroscopy, identifies chemical composition changes in TCMs through material color shifts, providing indirect yet insightful SoC measurements.

Applications and Case Studies

Subtask C emphasized real-world applications of SoC techniques, focusing on system integration and control. Key examples included:



- **Neothermal Energy Storage (Canada):** Developed a PCM storage system using sodium acetate trihydrate, integrating local temperature sensors for control in residential heating systems.
- **DTU's "Cool-Data" Project (Denmark):** Used PCM temperature data to create a digital twin for optimizing server room cooling systems. The approach demonstrated the utility of data-driven models in improving system performance.
- **SINTEF Energy (Norway):** Integrated SoC techniques into a PCM-based heat pump system, enabling ancillary services like flexible grid operation and waste heat recovery.
- **ZAE Bayern (Germany):** Implemented temperature-based control for a solar heating and cooling system with PCM storage, demonstrating combined short- and long-term energy storage benefits.

Conclusion

Subtask C emphasized the critical role of State of Charge (SoC) determination for advancing CTES technologies using PCM and TCM. Reliable SoC determination not only enables optimized operation and control of thermal storage systems but also supports integration into modern, digitalized energy systems. This is particularly important for enhancing flexibility, efficiency, and supply security in heating and cooling applications.

The research identified a spectrum of innovative techniques across three development levels: material characterization, component integration, and system control. For PCMs, methods such as bulk temperature monitoring combined with heat flux measurements were prevalent, while novel approaches, including chamber pressure and electrical resistance measurements, showed promise for tracking overall phase transitions. For TCMs, sorbate content measurement and non-intrusive methods were explored to address the complexities of chemical reactions and high-temperature storage.

A key outcome was the recognition of SoC as a component-level property reliant on material bulk response. This foundation is vital for designing modular and adaptable detection systems, ensuring scalability across diverse storage geometries and applications. SoC determination also contributes significantly to system-level innovations, such as model predictive control (MPC) and digital twin development, enabling precise energy management and ancillary services.

The findings underline the need for interdisciplinary collaboration between material scientists and system engineers to develop practical, reliable sensor solutions. Future efforts should focus on bridging laboratory-scale innovations with real-world system applications, fostering partnerships with industrial stakeholders to address economic and scalability challenges.

Key Messages

1. Reliable SoC determination is essential for optimizing thermal energy storage systems, particularly in digitized energy infrastructures.
2. Temperature and heat flux measurement remain the most widely used techniques for PCM SoC determination, while novel methods like capacitance and spectroscopic analysis show potential.
3. For TCM, methods like enthalpy balance and capacitive sensors offer promising pathways for non-intrusive SoC monitoring.
4. SoC determination techniques play a critical role in enabling ancillary services, improving system flexibility, and integrating renewable energy into heating and cooling networks.
5. Future research should address the scalability and economic feasibility of SoC techniques to advance their adoption in commercial CTES applications.

2.4.4. Subtask D: Stability of PCM and TCM

Introduction and Objectives

The stability of CTES materials, including PCM and TCM, is critical for their effective deployment and commercialization. Stability refers to a material's ability to retain its essential properties, such as enthalpy, temperature, and chemical composition, within acceptable limits under specified testing



conditions. These conditions may span controlled laboratory environments and real-world applications, where degradation mechanisms such as chemical decomposition in PCM or structural deterioration in TCM often influence performance.

Previous studies, including those from Annex 33, emphasize the importance of evaluating PCM stability under practical application conditions. These findings reveal that material stability is closely tied to specific testing scenarios, making generalized conclusions about material performance inadequate. Although existing research provides substantial data on degradation, it often lacks structured methodologies and comprehensive documentation of experimental parameters, leading to challenges in reproducibility and broader applicability.

Current research highlights three notable approaches to understanding PCM stability. The first involves compiling data on material properties before and after testing using various methods, offering a broad view of stability under different conditions. The second introduces a validation framework tailored to specific applications, with an emphasis on accelerated testing to predict long-term behavior, as demonstrated through studies on D-mannitol. The third adopts a systematic method to identify degradation mechanisms and customize testing protocols for targeted applications. Together, these approaches underscore the necessity of aligning testing methods with application-specific requirements and degradation processes.

Subtask D of Task 40 builds on these insights to deepen understanding of PCM and TCM stability. Its objectives focus on mapping degradation mechanisms across CTES material classes and devising practical recommendations for stability testing. These efforts emphasize developing straightforward experimental methods and leveraging accelerated degradation techniques to streamline evaluations. By addressing existing gaps in identifying degradation mechanisms and harmonizing testing procedures with material-specific characteristics, Subtask D aims to deliver actionable guidelines for application-oriented stability assessments.

A diverse group of Task experts contributed to this work, showcasing extensive experience with various materials, including paraffins, fatty acids, salt hydrates, zeolites, and salt hydrate composites. Their efforts reflect a comprehensive understanding of testing conditions and experimental boundaries. Testing approaches were specifically tailored to material types, with PCM evaluations using techniques such as differential scanning calorimetry (DSC), thermal cycling, and climate chamber testing. For TCM, stability assessments involved gravimetric analysis, dynamic water sorption analyzers, and cycling under controlled temperature and humidity conditions. These methodologies highlight the critical interplay between material-specific properties, degradation mechanisms, and testing environments, underscoring the importance of targeted strategies to ensure long-term stability and functionality of CTES materials.

Mapping CTES Material Degradation

The mapping of CTES material degradation provides a structured framework to visualize the interplay between test conditions, degradation mechanisms, and their effects on materials and storage systems. This approach aims to facilitate a comprehensive understanding of CTES material stability by sorting and connecting these factors, enabling better insights into degradation causes, measurable properties, and strategies for mitigation and accelerated testing.

Several visualization techniques were proposed and refined during Task 40 to structure the discussion on material stability. Initial approaches included templates that categorized material behaviors, measurable changes, and underlying causes of degradation. Experts contributed feedback and examples, filling templates for specific materials such as salt hydrates (TCM) and D-mannitol (PCM). These templates linked degradation mechanisms to relevant experimental methods and provided conclusions on stability under specific conditions.

A more advanced visualization approach developed by Ángel Serrano (CIC energiGUNE) further categorized degradation factors, mechanisms, material effects, and their impacts on thermal energy storage (TES) systems. This method enabled systematic rating of degradation severity and assessment of how application conditions influenced material performance. The tool also included recommendations for testing and mitigation, providing a clear pathway for addressing degradation challenges.



Examples from the final approach highlight degradation mappings for various materials, including organic plastic crystals, fatty esters, sodium acetate trihydrate mixtures (PCM), and zeolite pellets (TCM). These mappings illustrate degradation triggers such as temperature cycles, humidity, and chemical interactions, alongside their measurable impacts, such as reduced thermal conductivity or structural integrity. The approach emphasizes the importance of application-specific testing, as the severity of degradation often depends on storage system configurations and operating conditions.

The structured mapping methodology developed in Task 40 offers a robust tool for identifying degradation risks, guiding stability evaluations, and tailoring testing protocols to individual material properties and application needs. These efforts represent a significant step toward improving the durability and reliability of CTES materials in real-world applications.

Conclusion

The developed approach for mapping the degradation of CTES materials offers a detailed and structured representation of the degradation mechanisms and associated factors relevant to a specific material or material class. This mapping diagram effectively highlights how different types of degradation impact both the CTES material and the overall system performance.

The interconnections revealed by this approach underscore that a single effect on the material, such as a shift in transition temperature, can arise from multiple degradation mechanisms. Similarly, changes in storage performance often result from a combination of various material-level effects. Consequently, conducting stability tests under application-specific conditions requires a prior, clear understanding of the relationships between degradation factors, mechanisms, and their effects on material behavior and system performance.

This understanding, captured and communicated through the degradation mapping diagram, serves as a crucial tool for designing meaningful stability assessments and optimizing the testing process.

Key Messages

1. Collected Data Insights:

- Task 40 experts possess significant expertise in investigating CTES material stability.
- The developed mapping tools simplify visualization and understanding of degradation mechanisms.
- Accelerated testing methods were identified to expedite stability investigations.

2. Deliverable Insights:

- CTES material stability depends on the material type and testing conditions.
- Addressing degradation at the material level is critical to mitigate performance issues at the system level.
- Operating conditions can often be optimized to prevent material degradation.

2.4.5. Subtask E: Effective Component Performance with Innovative Materials

Introduction and Objectives

Subtask E focused on improving the performance of thermal energy storage (TES) systems through innovative material-component interactions and standardized evaluation methods. The primary goal is to establish uniform performance indicators and methodologies for comparing PCM energy storage and TCM energy storage systems under varying conditions. These efforts aimed to support the development and commercialization of TES technologies, enabling effective system optimization and real-world applicability.

By defining standardized procedures and innovative performance mapping techniques, Subtask E aimed to create tools that enhance material-component interaction analysis, enable accurate comparisons across systems, and guide the optimization of TES technologies for diverse applications.



Methods for Evaluating Component Performance

Performance Indicators and Analysis Techniques for PCM energy storage systems

Three key methodologies were developed to enable fair comparisons of PCM energy storage units by minimizing the influence of initial and boundary conditions:

- **Normalized Heat Transfer Rate vs. Capacity Flow Plots:** This method normalizes the heat transfer rate by volume and reference temperature differences and presents results as mean values in plots. The approach allows for comparisons across experiments and systems. For instance, the inclusion of an "infinite UA line" highlights the performance gap between ideal sensible storage and actual systems, aiding in identifying system limitations.
- **Three Sections Approach:** This technique divides the discharge power curve of a PCM energy storage system into sections using tangents at inflection points. It establishes a clear criterion for determining the end of the discharge process and enables a better understanding of the system's discharge dynamics compared to ideal sensible storage.
- **Constant Power Diagrams:** Developed under the VKTES project, this approach normalizes power curves and converts them into the energy domain, providing insights into the usable heat content under varying operational parameters. The method has been experimentally validated and is being incorporated into new guidelines (VDI 4657-2).

The UA (heat transfer coefficient-area product) approach combined experimental and analytical methods to assess the influence of material properties on performance. Using simplified equations, it was possible to estimate the discharge time of plate-type PCM energy storage units based on key parameters such as heat transfer surface area, thermal conductivity, and the melting temperature of the PCM.

Performance Indicators and Analysis Techniques for TCM energy storage systems

For sorption-based thermal energy storage systems, Subtask E focused on standardizing performance metrics and developing temperature-specific testing guidelines:

- **Performance Mapping:** A concentration vs. gross temperature lift diagram was developed to map performance based on material equilibrium lines. This method visualizes operational constraints and helps identify performance losses due to non-linear heat transfer characteristics. The approach is described in: *Applied Energy 335 (2023) 120755*
- **Temperature Guidelines:** Standardized test temperatures were proposed to reflect realistic building application conditions. Detailed description is found in: *Energies 2021, 14, 3754*
- **Realistic Application-Specific Performance Charts:** Based on the temperature guideline, performance charts were created to illustrate energy density and temperature requirements under realistic conditions. This method ensures results are comparable and meaningful for practical applications: Publication in progress.

Conclusion

Subtask E made significant strides in advancing the evaluation and optimization of TES systems by developing standardized performance indicators, innovative mapping techniques, and realistic testing guidelines. The work highlighted the importance of tailored evaluations for diverse applications, addressing challenges such as non-linear heat transfer relationships, inconsistent testing conditions, and the lack of comprehensive performance data.

Key achievements included:

- Normalized evaluation methods for PCM energy storage systems.
- A temperature-based testing protocol for sorption storage heat pumps.
- Performance mapping tools that connect material properties with system outcomes.



While substantial progress was made, challenges remain. Limited data sharing due to commercial sensitivities and varying engagement levels among participants highlight the need for improved collaboration and adherence to standardized methodologies. These efforts will be critical for the broader deployment of TES technologies and the realization of their potential in energy-efficient and decarbonized systems.

Key Messages

1. **Tailored Performance Evaluations:** TES system performance is highly application-specific, requiring detailed characterization of material properties and system configurations.
2. **Standardization as a Catalyst:** Uniform testing procedures and performance indicators are essential for meaningful comparisons and the widespread adoption of TES technologies.
3. **Material-Component Interactions:** Understanding and optimizing the interplay between materials and components are critical for enhancing system efficiency and scalability.
4. **Real-World Relevance:** Standardized test guidelines ensure that experimental results are applicable to practical scenarios, bridging the gap between laboratory research and real-world implementation.
5. **Collaboration and Data Sharing:** Increased collaboration and open data sharing among researchers and industry stakeholders are vital for overcoming existing barriers and advancing TES innovation.

3 Conclusions and outlook

The advancements achieved through the collaborative efforts of Subtasks A through E of IEA Technology Collaboration Platform (TCP) Energy Storage Task 40/67 have significantly contributed to the field of CTES. The multidisciplinary approach, encompassing material characterization, stability evaluation, system performance metrics, and innovative methods for state-of-charge determination, has provided a robust foundation for advancing both PCM and TCM for diverse energy applications.

Conclusion

1. **Material Characterization and Stability:** Comprehensive methodologies for characterizing the thermal, physical, and chemical properties of PCMs and TCMs have been established. Stability testing frameworks have been developed to address degradation mechanisms, enhancing our understanding of material behavior under real-world and accelerated conditions. This work is critical for improving the longevity and reliability of CTES materials.
2. **Performance Metrics and Standardization:** Standardized testing procedures and performance indicators were defined, enabling meaningful comparisons across different CTES systems. Novel techniques, such as normalized heat transfer and performance mapping, have bridged the gap between material behavior and system-level outcomes. These efforts ensure more accurate evaluations of thermal energy storage performance.
3. **Application-Specific Insights:** The integration of CTES into practical applications was a key focus, with guidelines for temperature-specific testing and energy density characterization providing actionable insights. The development of realistic application performance charts facilitates the design and optimization of systems for targeted use cases.
4. **Innovation in State-of-Charge Determination:** Advanced methodologies for SoC determination in both PCM and TCM systems have demonstrated the potential for more precise monitoring and control of CTES systems. These approaches improve system efficiency and pave the way for digitalization and integration into modern energy infrastructures.



Outlook

1. **Scaling and Commercialization:** The results of Task 40/67 provide a pathway for scaling CTES technologies from laboratory to market-ready solutions. Continued collaboration with industry partners will be essential to translate these findings into commercially viable products.
2. **Interdisciplinary Research:** Future efforts should emphasize interdisciplinary research to address the complex interactions between materials, components, and systems. This includes further integration of advanced simulation tools, material synthesis, and experimental validation.
3. **Broad Adoption of Standardized Procedures:** The adoption of standardized testing methods across the global research community is critical. Harmonized standards will enable more robust comparisons, accelerate innovation, and reduce barriers to adoption.
4. **Digitalization and System Integration:** The integration of CTES into digitized energy systems, including smart grids and predictive control systems, represents a promising area for future development. SoC determination and digital twins should be further refined to enhance system operability and reliability.
5. **Sustainability and Material Innovation:** Future research should prioritize the development of low-cost, sustainable, and non-toxic materials, alongside the exploration of advanced composites and novel encapsulation methods to improve thermal conductivity and stability.
6. **Collaboration and Dissemination:** To ensure impactful outcomes, ongoing collaboration among academia, industry, and policymakers is essential. Establishing platforms for knowledge sharing, joint publications, and innovation projects will amplify the impact of the work conducted under Task 40/67.

In conclusion, the efforts of Task 40/67 have laid a strong foundation for the advancement of CTES technologies, addressing critical challenges and providing innovative solutions for energy storage. With continued research, standardization, and collaboration, CTES is poised to play a pivotal role in the transition to sustainable and resilient energy systems worldwide.

4 Publications and other communications

Further information on the tasks can be found under:

- <https://task67.iea-shc.org>
- <https://iea-es.org/task-40/>