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Danish participation in IEA ECES Annex 30

‘Thermal Energy Storage’

Final report

Danish Technological Institute

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Danish participation in IEA ECES Annex 30 ‘Thermal Energy Storage’

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1. Project details

Project title	Danish participation in IEA ECES Annex 30 'Thermal Energy Storage'
Project identification (program abbrev. and file)	64015-0639
Name of the programme which has funded the project	EUDP 2015
Project managing company/institution (name and address)	**Danish Technological Institute** Kongsvang Allé 29 DK-8000 Aarhus C CVR 56976116 Contact: Lars Reinholdt, lre@teknologisk.dk
Project partners	**PlanEnergi A/S** Jyllandsgade 1 DK-9520 Skørping Contact: Morten Vang Jensen, mvj@planenergi.dk **DTU, Mechanical Engineering** Nils Koppels Allé Bygning 403, rum 110 DK-2800 Kgs. Lyngby Contact: Brian Elmegaard, be@mek.dtu.dk
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2. Short description of project objective and results

Dansk

Effektive termiske energilagre vil indgå som en central teknologi i fremtidens fleksible energisystem med fluktuerende vedvarende energikilder. Projektet dækker Dansk deltagelse i *IEA ECES Annex 30 'Thermal Energy Storage'*, der har haft det overordnede formål at udvikle metoder til at karakterisere og vurdere termiske lagersystemers tekniske og økonomiske ydeevne.

Ud over ovennævnte metodeudvikling har hjemtagning af international viden på området samt præsentation af danske resultater over for den internationale branche og forskningsverden været centrale. De udviklede metoder samt projektets samlede resultater præsenteres i rapporten *Applications of thermal energy storage in the energy transition: benchmarks and developments*[1]*.*

English

Effective thermal energy storage will be a central technology in the future flexible energy systems having fluctuating sustainable energy supply. The objective of the project has been the Danish participation in *IEA ECES Annex 30 'Thermal Energy Storage' in which* methodologies have been developed to characterize and evaluate the thermal energy storage systems' technical and economic capacity.

In addition to the above-mentioned development of methodology, the acquisition of international knowledge in the field and the presentation of the Danish expertise and results to the international industry and research world have been central. The developed methodologies and the overall results of the project are presented in the report *Applications of thermal energy storage in the energy transition: benchmarks and developments*[1].

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[1] *Applications of thermal energy storage in the energy transition – benchmarks and developments* is the final report of the international project IEA ECES Annex 30 "Thermal energy storage for cost-effective energy management and CO2 mitigation". The present report contains extracts from the final main report of the international project about Annex 30. The full international report is enclosed in Annex 1.

3. Preface

The Danish project group with the project partners Danish Technological Institute, PlanEnergi A/S, and DTU, Mechanical Engineering, has participated actively in the international IEA Annex 30-project ‘IEA ECES Annex 30 Thermal Energy Storage’ – including in the work and preparation of the final report of this international project.

The final report of the international project ‘IEA ECES Annex 30 Thermal Energy Storage’ is enclosed in Annex 1 of the present report.

The present report presents the main findings of the international work. With respect for the work done in the International Annex 30 project, the Danish EUDP Project Group has chosen to present the full Executive Summary from the International Report. However, a Danish project summary that highlights the most important results seen in a Danish context is also presented. Furthermore, a full English conclusion from the international report is presented in the present report. The section 'Introduction' shows what the full international report contains.

The present report can be read independently. For more detailed information, please see the international final Report for International Annex 30 work (enclosed in Annex 1).

4. Dansk projektresumé

Teknologier til termisk energilagring, TES *(thermal energy storage),* har en unik position i energisektoren og udgør en vigtig del af fremtidens fleksible energisystem.

Det internationale projekt IEA ECES Annex 30 ”Thermal energy storage for cost-effective energy management and CO_2 mitigation” omhandler kosteffektivisering af termiske energilagre samt udvikling af nøgleindikatorer (Key Performance Indikators, KPI) for sådanne lagre.

Teknologisk Institut har sammen med PlanEnergi og DTU Mek bidraget til dette projekt gennem det danske projekt *Dansk deltagelse i IEA ECES Annex 30 'Temisk Energilagring'.* I dette arbejde har de danske partnere bidraget med hjemtagning af international viden på området samt præsenteret den danske knowhow og resultater over for den internationale branche og forskningsverden. Projektets samlede danske og internationale resultater præsenteres i rapporten *Applications of thermal energy storage in the energy transition: benchmarks and developments*, se Annex 1.

Forskellige TES-systemer har forskellige egenskaber, der gør dem mere eller mindre egnede til en bestemt anvendelse, med det fælles overordnede mål at afkoble produktion og forbrug af termisk energi. Dette betyder dog, at selvom TES-systemer kan anvendes på mange forskellige måder, vil der altid være proceskrav, der skal opfyldes, og betingelser, der ikke kan ses bort fra i forskellige anvendelser. Der findes altså ikke en *one-size-fits-all*-version af et termisk energilagringssystem, som blot kan justeres, således at det egner sig til alle anvendelser.

De grundlæggende principper for energilagring har været kendt og til dels anvendt i mere end et århundrede – såvel i boliger som i industrien. Teknologierne er veletablerede i deres respektive sektorer og har bidraget til en effektiv og bekvem anvendelse af varme og kulde på mange måder. Samtidig er der nye måder at anvende termisk lagring på, som nu begynder at blive udnyttet, samt nye teknologier, som anvendes på nye og innovative måder.

I øjeblikket finder de klassiske teknologier nye anvendelser på kraftværker, i fjernvarmeanlæg og i industrielle processer med en lang række fordele til følge – bl.a. energieffektivitet i processer, øget anvendelse af vedvarende energi og omkostningsbesparelser. Derudover har den teknologiske udvikling åbnet nye døre inden for velkendte anvendelser. Som f.eks. den omkostningseffektive lagring i smeltende salte i akkumuleringstanke, latent varmelagring (ved høje temperaturer) til højeffektniveauer samt termokemiske reaktioner, der kan lagre uden varmetab.

Udviklingen af energisystemet har endvidere ført til nye muligheder at anvende varme på. Det bliver stadig mere anerkendt, at termisk energilagring er en teknologi, der åbner op for nye potentialer på tværs af sektorer. At styrke samspillet mellem el- og varmesektoren ses som en vigtig del af de fremtidige løsninger.

I arbejdet med Annex 30 belyses de fordele, som integrerede TES-systemer kan bringe i forskellige anvendelser. Efterhånden som der kommer en bedre forståelse for de fordele, der er ved at anvende forskellige typer lagringsteknologier, vil implementeringen af teknologierne blive mere avanceret for at sikre en mere kosteffektiv udrulning af VE-teknologier og deraf følgende CO_2-reduktion.

I Annex 30 er der arbejdet på at fremme implementeringen af TES-systemer. Der er udviklet en analysemetode til lagringsintegration, udviklet nøgleindikatorer for sådanne lagre samt indsamlet og analyseret casestudier vedrørende TES-systemer, der er integreret i industrielle processer – herunder fjernvarme. De casestudier, der præsenteres i hovedrapporten for Annex 30 – *Applications of thermal energy storage in the energy transition: benchmarks and developments* – skal ikke ses som en udtømmende præsentation af hver sektor eller teknologi. Formålet med Annex 30-arbejdet har været at udvælge interessante og informative cases, som fremhæver nøgleegenskaberne ved termisk energilagring.

Formålet med ovennævnte rapport er:

- At præsentere det metodiske arbejde, der er gennemført i Annex 30 vedrørende procesanalyse, parametre for TES-systemer og nøgleindikatorer for sådanne lagre.
- At give et overblik over de nyeste benchmarks i nogle af de fire mest relevante sektorer, der anvender termisk energilagring – nemlig fjernvarme, erhvervsbyggeri, industrielle processer og kraftværker.
- At give et billede af det teknologiudviklingsarbejde, som deltagerne i Annex 30 har gennemført i ovennævnte sektorer.
- At præsentere, hvad der teknisk og økonomisk karakteriserer hver af de fire sektorer.
- At undersøge og afklare de vigtigste forskelle i anvendelserne.

I rapporten præsenteres fire sektorer, som anvender termisk energilagring – **fjernvarme, erhvervsbyggeri, industrielle processer og kraftværker**. Ud over at være fire af de mest relevante sektorer for integration af TES-systemer er disse anvendelsesområder også velrepræsenterede blandt deltagerne i det internationale Annex 30-netværk. Derfor har det været muligt at få adgang til state-of-the-art-eksempler og lovende udviklinger inden for de fire sektorer.

Fjernvarme

En stor del af det danske arbejde har været inden for dette område med fokus på vand som lagermedie. I projektet er der udvalgt en række eksempler (benchmarks) på termisk energilagring i fjernvarme for at fremhæve sektorens mangfoldighed. Eksemplerne omfatter damvarmelager, tryksat og trykfri varmtvandslagring samt sæsonbestemt varmtvandslagring. Da fjernvarme allerede er et veludviklet anvendelsesområde for termisk lagring, præsenteres der i rapporten kun to eksempler, som p.t. er under udvikling.

Inden for fjernvarme er der to primære anvendelsesområder: bufferlagring i kortere eller længere tid og sæsonlagring. Generelt er konventionelle designs af første type blevet implementeret i en lang række lande, mens anvendelsen af damvarmelagre er et ret dansk fænomen.

I et bufferlager anvendes både tryksatte og trykfrie varmtvandstanke. TES-systemer kan bruges i kombination med et kraftvarmeanlæg eller andre fjernvarmeprocesenheder for at tilføje fleksibilitet i driften. Bufferlagrene leverer en række fælles fordele – herunder en forbedret ydeevne og udnyttelse af kraftvarmeanlægget, et optimeret samspil med elmarkedet, en besparelse i fossile brændstoffer, en reduktion af CO_2-emissioner, en reduceret produktionskapacitet samt en samlet forøgelse af fjernvarmenetværkets stabilitet.

Ved sæsonlagring er damvarmelagre og store varmtvandstanke i fokus. Disse muliggør en større anvendelse af vedvarende energi, når overskydende varmeproduktion lagres i de varmere måneder. Dette giver et samlet lavere omkostning til varmeproduktionen for fjernvarmenettet.

Erhvervsbyggeri

Sektoren for erhvervsbyggeri er et område i vækst, hvor man har set en lang række etablerede teknologier anvendt, som leverer både buffer- og sæsonlagring. Nye teknologier til bufferlagring og procesenhedsoptimering benytter latent varme ved lav temperatur/ PCM's (faseskiftende materialer).

Selvom termisk energilagring endnu ikke er særligt udbredt i denne sektor, er der gode eksempler på veletablerede teknologier. Benchmark-eksemplerne, der fremhæves i rapporten, bruger alle den latente varme, der er forbundet med at lagre termisk energi – enten dagligt eller sæsonbetonet. Forskning og udvikling inden for denne sektor lægger vægt på lavtemperatur PCM fra 4 °C til 80 °C. Materialet er her som oftest et salthydrat. Disse systemer anvender enten makroindkapslede faseskiftende materialer (PCMs) eller pladevarmevekslere.

I disse nye eksempler anvendes termisk energilagring til at reducere effektbehovet til køling og/eller opvarmning, hvilket muliggør en reduktion af udstyr og dets kapacitet samt en driftsfordel for visse procesenheder (kraftvarmeproduktion, chillere osv.).

Industrielle processer

Termisk energilagring i industrielle processer er et noget anderledes anvendelsesområde. Til trods for mere end 100 års erfaring findes der meget få typiske eksempler på integrerede lagringssystemer. Alligevel involverer de fleste anvendelser udnyttelse af spildvarme og bufferlagring. I modsætning til andre sektorer, hvor der fokuseres på én type lagerteknologi (i fjernvarme på sensible lagringssystemer, i erhvervsbyggeri på latente lagringssystemer), er udviklingsarbejdet i industrielle processer fokuseret på både sensible, latente og termokemiske lagringssystemer. Der findes således ikke en standardløsning til termiske lagring i industrielle processer, og moderne og nye anvendelser af termisk energilagring i industrielle processer er derfor det mest mangfoldige anvendelsesområde.

Bortset fra benchmark-eksemplerne findes der ingen standardintegrationer af termiske energilagringssystemer i industrielle processer, og en lang række forskellige lagertyper er blevet implementeret. Fra sensibel lagring i faste stoffer (bulkmaterialer eller mursten) over gasformige varmeoverføringsmedier ved høje temperaturer og sensibel lagring i væsker (vand, olie, salt) til sensible hybridlagre, der kombinerer faste stoffer og flydende væsker. Derudover er også latente varmelagre og termokemiske lagre blevet anvendt i industrielle processer. På baggrund af mangfoldigheden i teknologier fremhæver evalueringen i rapporten kun nogle specifikke eksempler, der understreger brugen af termiske energilagringssystemer i industrielle processer.

Ikke desto mindre er der stadig nogle fælles træk og fordele ved de mange forskellige anvendte systemer. Anvendelsen af et bestemt TES-system er fuldt ud afhængigt af anlæggets specifikke proceskrav, og det er sjældent, at en detaljeret integration kopieres fra et anlæg til et andet. De termiske kilder er ofte en form for spildvarme, som enten anvendes på stedet eller transporteres til et varmeaftag – ofte i en helt anden sektor.

I industrielle processer kan de termiske energilagringssystemer bl.a. medvirke til at reducere anvendelsen af backupsystemer, at forvarme procesvand, at kompensere for udsving i de tilgængelige varmekilder, at genvinde spildvarme ved forskellige temperaturområder, at reducere anvendelsen af fossile brændstoffer, sænke opstartstider samt til at forøge procesfleksibiliteten.

Kraftværkssektoren

I kraftværkssektoren er der specifikke og velkendte anvendelser af TES-systemer – som fx Concentrated Solar Power (CSP). Blandt de mest almindelige teknologier er smeltet salt (både i direkte og indirekte konfigurationer) og dampakkumulatorer. I termiske kraftværker er lagringstemperaturerne typisk høje for at sikre høj virkningsgrad, og kapaciteterne er store.

Den mest almindelige anvendelse inden for kraftværkssektoren er lagring af termisk energi ved koncentrering af solenergi (CSP), hvilket har været almindelig praksis i de seneste ti år, hvor TES sikrer kraftproduktion om natten og stabiliserer driften – fx i skyet vejr. To lagertanke med smeltet salt i en direkte lagringskonfiguration er for tiden den mest almindelige metode til termisk energilagring ved CSP.

I Annex 30 er der udvalgt en række FoU-cases, som fremhæver de fremskridt, der gøres inden for termiske energilagringssystemer til kraftværker.

Ligesom i de industrielle processer findes der inden for specifikke kraftværkskonfigurationer en bred vifte af anvendelser – som fx energilagring i form af trykluft (CAES - Compressed Air Energy Storage) og procesfleksibilitet i kraftværker med kombinerede cyklusser. Men der findes også eksempler, der har et bredere og mere standardiseret potentiale med integrationsmuligheder, som ikke er begrænset til deres specifikke anvendelser (fx akkumuleringstank med fyldmateriale og termokemisk lagring til koncentrering af solenergi). Med hensyn til sidstnævnte vurderes det, at en betydelig teknologioverførsel vil kunne forekomme på tværs af kraftværkskonfigurationer og endog sektorer, når teknologierne engang får kommerciel status.

Termisk energilagring i kraftværker medfører en række fordele – herunder lastfordeling, lavere omkostningsniveau til elektricitetsproduktion, forbedret effektivitet for kraftværket, reduktion af anvendelsen af fossile brændstoffer samt en kortvarig kompensation for udsving i efterspørgslen og ved afbrydelser i produktionen.

Sammenligning på tværs af sektorer

På baggrund af de betydelige forskelle mellem anvendelser inden for de forskellige sektorer er det udfordrende at lave sammenligninger på tværs af sektorer. Der kan dog drages nogle konklusioner på baggrund af de evalueringer, der er foretaget i arbejdet med Annex 30. Disse konklusioner er hovedsageligt observationer, og de fremhæver nogle fakta, der for de flestes vedkommende allerede er kendte – som fx at sensible lagre gennemsnitligt er billigere.

Ikke desto mindre viser resultaterne fra Annex 30-arbejdet, at mange af de fordele, der er forbundet med de forskellige anvendelser, allerede i dag deles på tværs af sektorer, og at anvendelsen af TES-systemer i de forskellige sektorer allerede har bidraget til at reducere CO_2-emissioner, til at øge procesfleksibiliteten og energieffektiviteten – og mest relevant for industrien – til at reducere omkostningerne. Resultaterne, der præsenteres i rapporten, indeholder en lang liste over benchmarks og over udviklingen i de termiske energilagringssystemer, der leverer reelle fordele i dag.

Metoderne samt tilgangen til teknologivurderingen, der er blevet udviklet i Annex 30, kan bruges til at styre den fremtidige udvikling og integration af termiske lagre. Arbejdet er derfor et vigtigt første skridt på vejen mod generelle termiske energilagringsløsninger, som kan tilpasses til en bredere vifte af anvendelser.

5. Extracts from the international Annex 30 report

5.1. Introduction

Thermal energy storage (TES) technologies have significant potential to improve energy management across a wide variety of sectors. Along with enhancing the use of heat at various temperature levels, the emergence of a focus on sector coupling has also underlined the technical potential for TES systems to enable the efficient management of electrical energy. The benefits delivered by integrated TES systems are manifold – energy efficiency, process flexibility, and increased shares of renewable energy use highlight just several of the services provided by these technologies.

There is no shortage of application fields in which TES systems provide useful services. Beginning with applications in the lower-temperature region, district heating processes use TES units for seasonal and buffer storage. In the non-residential building sector, heat is managed both for domestic hot water production and space heating. Industrial processes use thermal energy storage primarily for waste heat recovery and process efficiency. Power plant applications, particularly those in concentrating solar power, use TES systems to improve dispatchability and increase operational efficiency of process units. In automobile applications, TES systems are seeing developmental work in waste heat recovery and thermal management.

The technical potential can be activated by a wide selection of TES technologies that have inherent characteristics that designate them as more or less suitable for an application. Nevertheless, there are three distinct storage principles that differ in the fundamental way they storage thermal energy:

- sensible heat storage (SHS) raises or lowers the temperature of a liquid or solid storage medium,
- latent heat storage (LHS) uses the energy absorbed or released at constant temperature during the phase change of a material and
- thermochemical storage (TCS) either stores energy as the heat of reaction in reversible reactions or in sorption processes.

Some of these technologies have already been integrated into commercial applications in various forms, yet others remain at lower stages of development. In order to compose a full picture of the application fields, both selected benchmarks (i.e. commercialized technologies) and TES systems in development will be discussed and evaluated in this report.

Also taken into consideration are the main types of integration of thermal energy storage systems: retrofit and greenfield. Retrofit applications examine an existing process where the storage system must be designed to fit the needs of an already dimensioned and built process. The challenge is in designing a storage system that fulfils the process requirements[2]. In a greenfield analysis, the storage parameters are designed from the very beginning in parallel with the rest of the process. While no two projects are the same, it is noteworthy that the fundamental principles of the integration remain consistent and as such, a ground-up engineering of the system is not required and best practices can be employed.

Considering the diverse applications available and the various characteristics of the TES technologies themselves, it is clear that there is no single application that is suitable for a specific TES system, or vice versa. It follows that detailed analyses are necessary to properly characterize the process into which the storage system is being integrated, the TES system itself and the integration in general i.e. the key performance indicators of the application. The Annex 30 network has thus developed a methodology that systematically addresses these points in a thermal energy storage integration.

Chapter 1 introduces the methodological work. It is split into the following subchapters and outlines the methodological procedures of Annex 30 in detail. Beginning with guidelines for process analysis, the methodology also proposes a definition of the system boundary for TES systems, definitions of technical parameters for TES systems, economic parameters and a procedure for identification of key performance indicators from a stakeholder perspective.

Chapters 2-6 examine the aforementioned application fields in detail, wherein the methodological work from Chapter 1 has been applied to a series of 22 real-world case studies.

Each of these chapters proceeds as follows:

- Benchmarks of the application are described to provide history and context for future discussions. These sections give an overview of the general state of the art in each sector and highlight several examples of TES systems in these applications.
- Cases of TES systems in development are presented to which the methodological work was applied. The case studies describe the process (with process diagram and identified TES system boundary), the TES systems (operational strategies, dimensions etc.) and on the final page, abridged analysis results are shown in a fact sheet format that includes relevant integration aspects of the process, values calculated from the technical parameter definitions and the key performance indicator (KPI) methodology results.
- Finally, each complete application field undergoes an evaluation that highlights key characteristics, trends, benefits delivered by TES systems and an overview of KPI.

Chapter 7 presents an overall evaluation of all application fields that highlights commonalities and differences as well as provides a look at the general state of development of TES systems in these applications.

Chapter 8 summarizes the discussions that have taken place in this report and presents conclusions for the work going forward. Specifically, it introduces how the methodological work from Annex 30 can be further applied to advance the integration of thermal energy storage systems in a global context.

5.2. Executive summary

Thermal energy storage technologies occupy a unique position in the energy sector. On the one hand, the basic principles of storing heat have been understood for well over a century and applied in domestic and industrial settings. This includes concepts as fundamental as hot water heaters or regenerator heat storages in steelmaking processes. These technologies are well-established within their respective sectors and have contributed to the efficient and convenient use of heat in many ways.

On the other hand, there are novel applications of thermal storage that are beginning to be exploited and new technologies that are being applied in innovative ways. The story begins with classical technologies that are currently finding new uses in power plants, district heating grids and industrial processes in order to provide a wide range of benefits. These include energy efficiency in processes, increased use of renewable energy and cost savings. In addition to this, there have been technological developments that are opening new doors within well-known applications. Some suitable examples are the cost-effective storage of molten salts in a thermocline, high-temperature latent heat storage for high power levels and thermochemical reactions that can store heat loss-free.

The evolution of the energy system has furthermore led to new possibilities for the usage of heat. It is beginning to be recognized that thermal energy storage is an enabling and cross-cutting technology that can unlock potentials in various sectors. By facilitating the coupling of the electricity and heat sectors, it is emerging as a key solution for the energy transition that improves thermal and electrical energy management in a flexible and reliable manner.

Annex 30 has worked to advance the implementation of thermal energy storage systems by developing an analysis methodology for storage integration, determining key performance indicators and collecting and analyzing case studies of TES systems integrated in processes.

This report has the following objectives:

- Present the methodological work conducted in Annex 30 regarding process analysis, thermal energy storage system parameters and key performance indicators.
- Concisely overview the state-of-the-art benchmarks in some of the most TES-relevant sectors: district heating, non-residential buildings, industrial processes and power plants.
- Depict technology development work by the Annex 30 participants in these same sectors.
- Present evaluations that technically and economically characterize each application field.
- Investigate and clarify key differences in the applications based on these evaluations.

Methodologies

As a diverse technology, different thermal energy storage (TES) systems have inherent characteristics that make them more or less suitable for an application. This variation means that while TES technologies are able to be deployed in many types of applications, there are process requirements that must be met and conditions that cannot be sacrificed in a certain integration. It follows that there is no "one-size-fits-all" version of a TES system that can be adjusted to suitability for any type of application. Additionally, due to the inherent diversity of processes, the engineering design required for integrating TES systems into processes can be complex and often presents a serious barrier for industrial partners considering these technologies. As introduced in [1], the interdependent relationship between TES and process is shown in Fig. ES1.

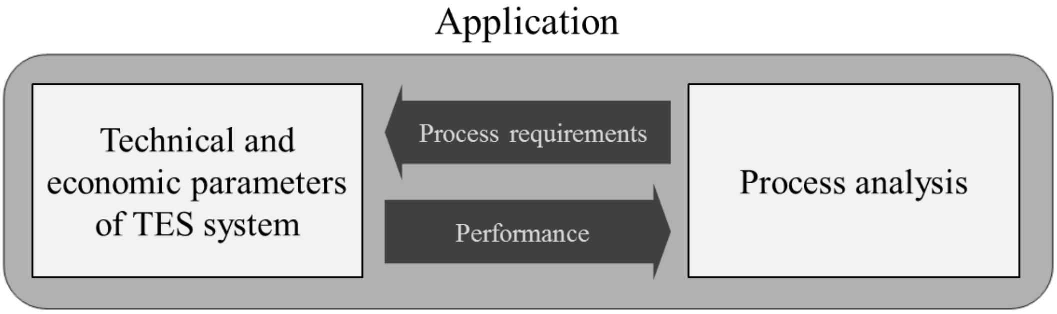


Fig. ES1. Interaction between the TES system parameters and process for a successful integration[1].

In the first section, a methodology has been developed that investigates the domains of TES system, process and application. The starting point is with a set of **process analysis guidelines** that can serve, on the one hand, as direction for researchers developing TES for industrial processes and upscaling from the laboratory setting. On the other hand, the guidelines can be a first step in assisting process customers or partners in assessing the necessity and depth of information required at the various steps of the evaluation and design.

The characterization of the TES system begins with the analysis levels of a thermal energy storage, resulting in definitions for the material, component, module and system levels. The system level particularly defines the **TES system boundary** as the "point of contact between the fluid streams and the heat source and heat sink". This effectively includes any process component that is used exclusively by the storage. Subsequently, definitions have been developed for **technical parameters of a TES system** covering nominal power, response time, system efficiency, auxiliary energy ratio, system storage capacity, minimum cycle length and partial load suitability. The economic methodologies applied in this report have been adopted from Annex 29 in ECES.

To evaluate the integration of a thermal energy storage system in a process, **key performance indicators (KPI**) are determined from storage system parameters that dictate performance and external factors that emerge from the integration. These are then prioritized based on the perspectives of various stakeholders to the integration.

Applications and Evaluations

There are four application fields investigated here: district heating, non-residential buildings, industrial processes and power plants. Along with being four of the most relevant sectors for integration of thermal energy storage systems, they were also well-represented by the participants in the Annex 30 network and as such, state-of-the-art and promising developments in these applications were readily available. The application field of vehicles is also touched, yet due to its nascent status and few examples of integrated systems, no evaluation has been conducted regarding this sector in this report.

Several benchmarks of TES in **district heating** were chosen to highlight the diversity of the sector. These include pit storage, pressurized and non-pressurized hot water storage and seasonal hot water storage. As district heating is a well-developed application field for thermal storage, only two cases in development are discussed. The district heating sector can be largely categorized into two types of thermal energy storage use: buffer storage and seasonal storage.

In buffer storages, both pressurized and non-pressurized hot water storage tanks are used. TES systems can be used in combination with a cogeneration plant or other DH process units to add flexibility in operation. These buffer storages deliver a number of common benefits, including an improved performance and utilization of the CHP plant, optimized electricity market participation, fossil fuel savings and CO_2 emissions reductions, reduced installed back-up capacity and an overall increase in stability of the DHC network.

For seasonal storages, pit storage and large-scale hot water storage tanks come into focus. These have the benefit of enabling a higher share of renewables when the storage is charged during the warmer months. This accompanies an overall lower cost of heat for the district heating network. A summary of this evaluation and presentation of the KPI for district heating can be found in the tables ES1 and ES2.

While thermal energy storage in the **non-residential building** sector has not yet seen widespread use, there are key examples of established technologies. The benchmarks highlighted in this report all utilize the latent heat of fusion of water (ice and snow) to store thermal energy either daily or seasonally.

Research and development in this sector put an emphasis on low-temperature PCM from 4 °C to 80 °C. This material is most commonly a salt hydrate. These systems use either macro-encapsulated PCM or flat-plate heat exchangers. Largely, there are two categories of R&D: at TRL 6-8, pilot systems have been installed in real environments. At TRL 4-5, new concepts are under development for heating of non-residential buildings.

In these new cases, TES is used for peak shaving of cooling or heating load that allows for energy use reductions, downsizing of equipment and an operational benefit for certain process units (cogeneration, thermal chiller etc.). A summary of this evaluation and presentation of the KPI for district heating can be found in the tables ES3 and ES4.

Thermal energy storage systems have been standard process components in the **industrial process** sector since the 19th century. Regenerator storages are benchmarks in steelmaking and glass manufacturing. Steam accumulators have also seen widespread use in industrial processes for buffering of steam.

Modern and novel uses of thermal energy storage in industrial processes represent the most diverse application field. Excluding the benchmarks, there are no standard integrations of TES technologies into industrial processes and there are various storage types that have been deployed. These include sensible storage in solids (bulk materials or bricks) for gaseous heat transfer fluids at high temperatures, sensible storage in liquids (water, oil, salt, bitumen) and hybrid sensible storages that combine solid and liquid phases. Additionally, latent heat storages have found use in industrial processes as well as thermochemical storages. Based on this diversity of technology, this evaluation can only highlight some specific examples that emphasize the utility of TES systems in industrial processes.

Nevertheless, some common benefits can still be discussed. The use of the TES system relies entirely on the specific process requirements and, according to current standards and information, rarely will any detailed integration be replicated. As such, there are no standard TES storages for industrial processes, unlike in district heating and to some extent, non-residential buildings and power plants. The thermal sources are often some form of waste heat that is either used on-site or transported to a thermal sink, often in another sector entirely. The TES systems can

- reduce the use of backup systems,
- preheat components and
- compensate for fluctuations in available heat sources.

Thermal energy storages in industrial processes deliver a broad range of benefits including waste heat recovery at various temperature ranges, reduction in the use of fossil fuels and increase in process flexibility. The benchmarks and KPI results are found in tables ES5 and ES6.

The most common benchmark in the **power plant** sector is the storage of thermal energy in concentrating solar power (CSP), which has been a common industry practice for the past ten years. At the time of writing, there are 12 GWh of thermal energy storage installed in CSP applications worldwide.

Two-tank molten salt in a direct storage configuration is currently the most common method of thermal energy storage in CSP. Nevertheless, indirect storage in two-tank molten salts and steam accumulators round out the commercialized technological options for this application field, as shown in Table ES7.

Within Annex 30, several R&D cases were chosen that highlight the progress being made in TES for power plant applications. Almost exclusively consisting of regenerator-type storages, high capacities (>20 MWh) and temperatures (>290 °C) are the norm for either storing heat for later electricity generation or buffering for power plant flexibility.

As in industrial processes, a diverse array of applications within specific power plant configurations can be found (e.g. TES for A-CAES power plants, process flexibility in combined cycle power plants), yet there are cases that have a broader, more standardized potential with integration possibilities not restricted to their specific applications (e.g. thermocline with filler material, thermochemical storage for CSP). Regarding the latter, it is conceivable that significant technology transfer could occur across power plant configurations and even sectors once the technologies reach a commercial status.

Thermal energy storage in power plants delivers a number of benefits including power dispatchability, lower levelized cost of electricity, overall power plant efficiency, reduction of fossil fuels and short-term compensation of demand fluctuation and generation interruptions.

Important note: the cases presented in this report should be understood as a non-exhaustive representation of each sector or technology. The goal of the Annex 30 network was to select interesting and informative cases that highlight key characteristics of thermal energy storage.

DISTRICT HEATING EVALUATION

Table ES1. ***Non-exhaustive selection of relevant system parameters for storage in district heating.***

	Buffer storage		Seasonal storage	
	Pressurized	**Non-pressurized**	**Pit storage**	**Tank storage**
T_{min} (ºC)	60 – 70	60 – 70	10 – 12	15
T_{max} (ºC)	140 – 180	98	80 – 90	90
CAPEX (€/kWh)	20 – 25	6 – 20	as low as 0.4	1.8
Volume (m^3)	1000 – 6000	1000 – 50,000	60,000 – 200,000	6000
ESC_{sys}	Up to 850 MWh	Up to 2 GWh	5 – 15 GWh	ca. 500 MWh
Cycle freq.	1/day to 1/week		1-2/year	1-2/year
Efficiency	99%		< 81%	81%

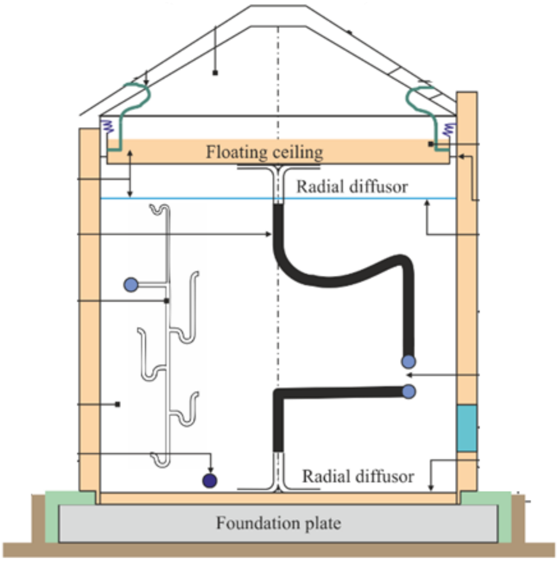


Table ES2. Key performance indicators for district heating.

Stakeholder:	**District heating company**	**Consumer or End-User**
KPI 1:	Max/min temperatures	Cost of delivered heat
KPI 2:	Storage capacity	CO_2 emissions reductions
KPI 3:	Charging/discharging power	
KPI 4:	CAPEX	
KPI 5:	Network stability	

NON-RESIDENTIAL BUILDINGS EVALUATION

Table ES3. Non-exhaustive selection of relevant system parameters for storage in non-residential buildings.

	Cold storage	Heat storage
T_{min}	-7 … 7 ºC	20 ºC
T_{max}	7 … 18 ºC	80 ºC
CAPEX	0.8 … 3.3 €/kWh	ca. 103 €/kWh
ESC_{sys}	0.3 … 11 MWh (R&D) 0.49 … 10 GWh (Benchmarks)	
Cycle freq.	1/day to 1/year (seasonal)	
$ReTi_{sys}$	Immediate to 1-2 minutes	

Table ES4. Key performance indicators for non-residential buildings.

Stake-holder:	Building owner	Energy utility
KPI 1:	Net economic benefit (peak shaving, equipment downsizing)	Net economic benefit
KPI 2:	Net environmental benefit	Net environmental benefit
KPI 3:	Operational benefit for certain process units / flexibility	Higher flexibility in process operation
KPI 4:	Reliability	Improved grid stability

INDUSTRIAL PROCESSES EVALUATION

Table ES5. Non-exhaustive selection of relevant system parameters for benchmarks in industrial processes.

	Regenerator (steelmaking)	Regenerator (glass production)	Steam Accumulator
Temperatures	1250 … 1400 ºC	300 … 1400 °C	150 … 230 ºC
ESC	140 MWh	10	up to 30 MWh
Nominal Power	140 MW	30	variable
CAPEX	15 … 40 € kWh	N/A	70 … 300 €/kWh
Cycle freq.	2/hour … 1/3 hours	3/hour	several/day

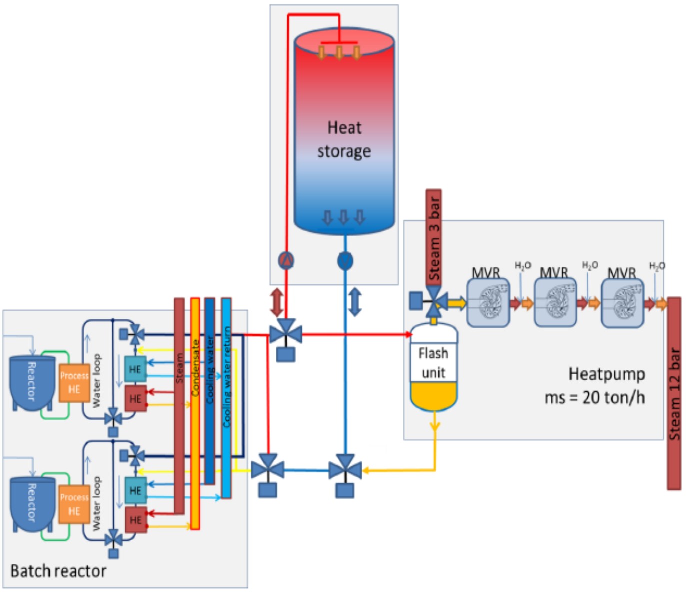


Table ES6. Key performance indicators for industrial processes.

Stakeholder:	Process owner	Energy utility	Industrial customer
KPI 1:	Economic benefit (waste heat usage)	Industrial process flexibility (grid balancing)	Environmental benefit
KPI 2:	Environmental benefit	Net economic benefit	Product cost reduction
KPI 3:	Discharging power	Net environmental benefit	
KPI 4:	Process flexibility and reliability	Higher flexibility in process operation	
KPI 5:	Storage capacity		

POWER PLANTS EVALUATION

Table ES7. Non-exhaustive selection of commercialized TES options for power plants.

	2-tank molten salt Direct	2-tank molten salt Indirect	Steam accumulator
Temp.	290 – 565 ºC	290 – 390 ºC	250 – 300 ºC
CAPEX	20 – 40 €/kWh	N/A	N/A
ESC	~ 6 GWh (Atacama)	~ 4 GWh (Solana)	3 – 5 MWh per tank <100 MWh (Khi Solar 1)
Cycling	1/day	1/day	multiple times per day

Table ES8. Selection of technologies in development for TES in power plants.

	Molten Salt Thermocline	CSP with TCS	Regen. combined cycle (DLR)	Regen. combined cycle (TUM)	Regen. A-CAES
TRL	3 – 5	3 – 5	2 – 4	2 – 3	2 – 4
Storage type	sensible	TCS	sensible	sensible	sensible
Temp. (°C)	290 – 560	550 – 600	400 – 600	400 – 600	400 – 600
ESC (MWh)	2800	15 kWh (lab) ~750 MWh (real)	3000	20	340
P_{nom} (MW)	235	5 kW (lab) ~250 MW (real)	250	100	34
Efficiency	> 98%	~97% (real)	> 95%	> 95%	> 98%
CAPEX (€/kWh)	18 €/kWh	N/A	N/A	N/A	80 €/kWh
Cycle frequency	1/day	1/day	1/day	1/day	1/day

Table ES9. Key performance indicators for power plants.

Stakeholder:	**Power plant**	**Energy utility**
KPI 1:	Economic incentive (LCOE reduction)	Dispatchability
KPI 2:	CO_2 emissions reductions	CO_2 emissions reductions
KPI 3:	Storage capacity	
KPI 4:	Discharging power	
KPI 5:	Dispatchability	
KPI 6:	Optimization for power block components	

6. Project objectives

The purpose of Annex 30 has been to identify and evaluate the potential for implementing the TES as a transverse technology to:

- Obtain bigger energy efficiency and process integration
- Obtain bigger system flexibility
- Obtain bigger exploitation of sustainable heat and refrigeration resources
- Contribute to evening out the load and stabilizing the electrical net.

Both sensible, latent and thermoelectrical technologies have be researched.

The main objective has been to develop a methodology to characterize and evaluate the thermal energy storage systems capacity both technically and economically within the industry, in power plants, in industry buildings and in district heating. The method has been tested on a number of existing thermoelectric storages to find the best and most cost-effective integration of TES.

Annex 30 had the main objective of encouraging the implementation of thermal energy storage systems and evaluating their potential in a variety of applications with respect to cost-effective energy management and CO_2 mitigation.

The objectives of Annex 30 have been achieved through five work packages:

1. **Definition of requirement**
   The conditions of the storage system are determined in terms of temperature levels, heat transfer medium, charge and discharge characteristics, capacity, interaction with the energy system etc. The results from this work package will provide the basis for Work Packages 2 to 4.

2. **Effective Storage Density**
   Different storage materials and methods are investigated.

3. **Key Performance Indicators**
   To evaluate the integration of a thermal energy storage system in a process, key performance indicators (KPI) are determined based on storage system parameters that dictate performance and external factors that emerge from the integration. The Key Performance Indicators are then prioritized based on the perspectives of various stakeholders to the integration. The Key Performance Indicators are identified based on inputs from the industry and a literature study.

4. **Cost Calculation**
   Available price information is collected. This information is subsequently used in models for economic evaluation of TES systems such as 'Top-down' and 'Bottom-up' in order to minimize the cost.

5. **Application – Case studies**
   Knowledge about existing storages is gathered among the participants in Annex 30 and the industry – including knowledge about the requirements to these storages. The results from the Work Packages 2-4 will then be applied to these data.

7. Project results and dissemination of results

In the project *Danish participation in IEA ECES Annex 30 'Thermal Energy Storage',* the development of a methodology for storage integration, the determination of key performance indicators and collection and analysis of case studies of TES systems integrated in processes have been central.

There are some conclusions that can be drawn from the work with Annex 30, e.g. the well-known fact that sensible storages are cheaper on average.

Thermal energy storage in power plants delivers a number of benefits including power dispatchability, lower levelized cost of electricity, overall power plant efficiency, reduction of fossil fuels and short-term compensation of demand fluctuation and generation interruptions.

The results of the Annex 30 work show that many of these benefits are indeed shared between sectors. It highlights the fact that TES systems are already operational in the different sectors and have been successful in reducing CO_2 emissions, providing process flexibility, increasing energy efficiency, and, most relevant for industry, reducing costs. The results of the work comprise a long list of benchmarks and developments in thermal energy storage systems that are delivering real benefits today.

The Danish EUDP project group has primarily given input to work package 1 'Definition of requirement', work package 2 'Effective Storage Density', work package 3 'Key Performance Indicators', and work package 5 'Case studies'.

The methodology which is described in the final report is presented at https://www.eces-a30.org/publications/. The final report is also included in Annex 1.

In Danmark, the following main knowledge-sharing activities have been carried out in the project:

- The project was presented in 2016 and in 2018 at the annual conference 'Advanced Energy Storage' at Danish Technological Institute with approx. 60 participants both years.
- The Danish participation and work in Annex 30 have been presented internationally at Annex-meetings and workshops with external participants, e.g. in Tokyo in October 2016
- The project is presented at the website of Danish Technological Institute website www.dti.dk.

7.1. Utilization of project results

The methodologies as well as the approach for technology assessment developed within Annex 30 can be used to guide future development and integration of thermal storages. It is an important first step on the path towards generalized thermal energy storage solutions that can be adapted to a wide range of applications.

7.2. Project conclusion and perspective

This report has highlighted the diverse benefits that integrated TES systems can bring to different applications. As the advantages delivered by these systems become more well-understood, the deployment of these technologies will be advanced to ensure improved cost-effective energy management and CO_2 mitigation. To proceed toward this goal, Annex 30 has developed a comprehensive methodology for process integration of TES systems and applied it to a wide variety of benchmark and development case studies.

The methodology introduced in Chapter 1 of this report can be broken into five parts. The process analysis guidelines pave the way for a detailed evaluation of a process for integration of a TES system. Definitions on the analysis levels of a TES system provide clear boundaries for technology assessment. Furthermore, the technical parameter definitions ensure that different TES systems may be characterized in the same manner and that inter-technological comparisons are possible. The use of storage capacity costs provides a fundamental point when considering the investment costs of a thermal storage system. Finally, the methodology for key performance indicators identifies the critical storage parameters and benefits delivered by an integrated TES system. Inclusion of the stakeholder perspective provides a dynamic and overarching analysis of these important technologies.

Detailed investigations in Chapters 2-6 have uncovered some crucial characteristics within and important differences between the presented application fields:

District heating applications can be broken down into two main application-focuses: buffer storage and seasonal storage. Generally, conventional designs for both types are at a high TRL level and have seen deployment in a wide range of countries. R&D work focuses on improvements that address specific technical and economic issues but are not decisive on the affordability of the storage in many applications.

The non-residential buildings sector is a still-nascent field that has seen several established technologies delivering both buffer and seasonal storage solutions. Novel technologies for buffer storage and process unit optimization use low-temperature latent heat/PCM. Some systems are being tested in a real environment, others are earlier-stage concepts. Nevertheless, more elaborate technologies remain pre-commercial. R&D work focuses on material development, system design, and system integration into processes (schools, office buildings).

Thermal energy storage in industrial processes is a diverse application field. Despite benchmarks operational for over 100 years, there are very few typical examples of integrated storage systems. Despite this, most applications involve waste heat utilization, buffer storage or substitution of back-up systems. As opposed to other sectors that focus on one type of storage technology (district heating – sensible, non-residential buildings – latent), development work in industrial processes is focused on sensible, latent and thermochemical storage systems. R&D work involves all levels (material, component, process integration) to optimize functionality, reduce cost and maximize benefit of storage.

The power plant sector is one with specific, well-known uses of TES systems, such as in CSP. Among the most common technologies are molten salt (in both direct and indirect configurations) and steam accumulators. As is typical in thermal power plants, the storage temperatures are high and capacities are grid-scale. R&D work with regenerator-type storage systems is being pursued for buffer storage in cogeneration plants or in combination with compressed air energy storage. Furthermore, R&D work concerns the development of novel storage concepts for cost reduction, such as molten salt thermoclines with filler material or thermochemical storages for CSP.

Due to the substantial diversity between applications, cross-sectoral comparisons are challenging. There are some conclusions that can be drawn from the evaluation in Chapter 7, but they are largely observational and highlight some facts that are mostly already known (e.g. sensible storages are cheaper on average). There is, however, some technology transfer between applications that can be recognized – at 20.5 €/kWh, the pressurized water storage from industrial processes (pg. 72) falls notably in the range of the pressurized water storages for district heating (20-25 €/kWh). In these specific cases, it is possible to draw lines between sectors.

Nevertheless, the key performance indicator results show that many of these benefits are indeed shared between sectors. It highlights the fact that TES systems are already operational in these different sectors and have been successful in reducing CO2 emissions, providing process flexibility, increasing energy efficiency, delivering dispatchable power, and, most relevant for industry, reducing costs. The results presented in this report comprise a long list of benchmarks and developments in thermal energy storage systems that are delivering real benefits today.

The methodologies as well as the approach for technology assessment developed originally within Annex 30 can be used to guide future development and integration of thermal storages. It is an important first step on the path towards generalized thermal energy storage solutions that can be adapted to a wide range of applications.

In a Danish context, thermal energy storage will be crucial in the future to be able to exploit the full potential of the present and the future fluctuating sustainable energy sources where wind and sun form the foundation – a potential that will be even higher in the near future.

But in this context, it is relevant to discuss whether storage in its basic form (which by definition is decoupling of consumption and production) is a "nice to have" or a "need to have". In general, pit storage has been prevalent in district heating for many years in Denmark, where more than 300 large thermal storages based on water represent a considerable storage capacity. This has placed Denmark on the world map in terms of thermal storage, and many of the activities that have been initiated regarding storage have therefore naturally circled around the district heating area, e.g. many of the EUDP projects regarding storage in major energy systems.

In recent years, many other potential storage technologies have seen the light of day, and they have been investigated in various project contexts. For example, thermal storage using phase changing materials (PCM, such as sodium acetate that is used in smaller households presented by the Danish company Suntherm), and experiments with phase changing (melting) aluminum are also performed. Furthermore, experiments with large-scale energy storage in rocks are being carried out.

The use of energy storage in Denmark happens in two tracks:

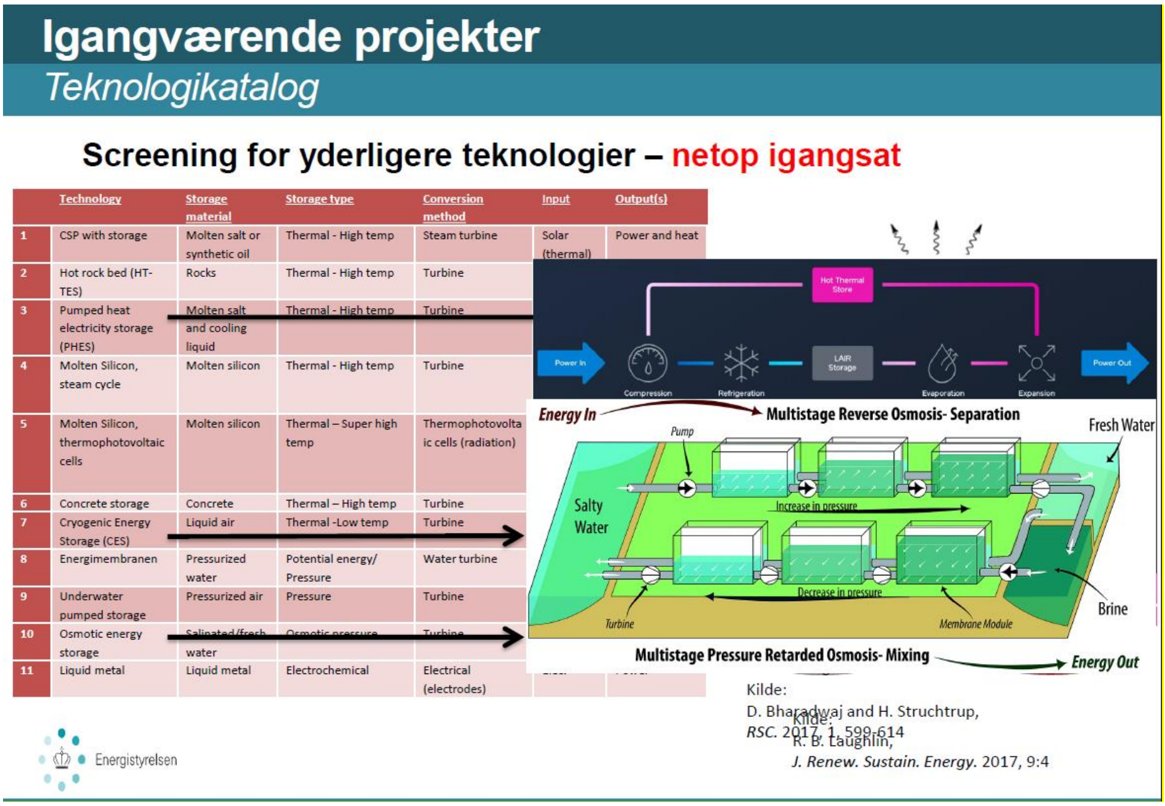
1) Electric storage in batteries

2) Thermal energy storage.

These two types of storage will be the buffer that is necessary to ensure economically viable renewable energy solutions. Both smaller storages in private households (both electric and small thermal storages, e.g. based on phase changing materials) and large storages in connection with district heating systems will ensure that we at (almost) any time can storage excess electricity. Here, the thermal energy storages will primarily be based on electric heaters and heat pumps, which is also underpinned by several national analyzes conducted by the Danish Energy Agency and the Danish TSO ‘Energinet’.

At the moment, the Danish technology catalogue ’Teknologikataloget’ is thoroughly revised. E.g. this work includes further screening for storage technologies (see Figure 1). This work has been initiated by the Danish Energy Agency. It will be interesting to evaluate whether storage – thermal as well as electrical – is economically viable, for example compared to an increase in electrical connections with Sweden, Norway, Germany and other countries. Since both thermal and electrical storage, by nature, are expensive to establish, the calculation may not always be favorable to storage technologies.

Therefore, a further development of thermal and electrical storage is important, because there is no doubt that storage is a necessity. But it is not clear to what extent storage should be introduced into the energy system to solve our balance challenges.



Igangværende projekter

Teknologikatalog

Screening for yderligere teknologier – netop igangsat

	Technology	Storage material	Storage type	Conversion method	Input	Output(s)
1	CSP with storage	Molten salt or synthetic oil	Thermal - High temp	Steam turbine	Solar (thermal)	Power and heat
2	Hot rock bed (HT-TES)	Rocks	Thermal - High temp	Turbine		
3	Pumped heat electricity storage (PHES)	Molten salt and cooling liquid	Thermal - High temp	Turbine		
4	Molten Silicon, steam cycle	Molten silicon	Thermal - High temp	Turbine		
5	Molten Silicon, thermophotovoltaic cells	Molten silicon	Thermal – Super high temp	Thermophotovoltaic cells (radiation)		
6	Concrete storage	Concrete	Thermal – High temp	Turbine		
7	Cryogenic Energy Storage (CES)	Liquid air	Thermal -Low temp	Turbine		
8	Energimembranen	Pressurized water	Potential energy/ Pressure	Water turbine		
9	Underwater pumped storage	Pressurized air	Pressure	Turbine		
10	Osmotic energy storage	Salinated/fresh water	Osmotic pressure	Turbine		
11	Liquid metal	Liquid metal	Electrochemical	Electrical (electrodes)		

Kilde:
D. Bharadwaj and H. Struchtrup,
RSC. 2017, 1, 599-614

Kilde:
R. B. Laughlin,
J. Renew. Sustain. Energy. 2017, 9:4

Energistyrelsen

Figure 1: Screening of technologies.

Source: Filip Gamborg, Danish Energy Agency, presentation at the conference ‘Advanced Energy Storage’, Danish Technological Institute, Aarhus, November 2018.

It is also expected that high temperature storage, in the future, will play a role. Especially in industrial processes, where high temperatures are needed, as well as in, for example, electricity generation in turbine plants, where high temperature storage of energy, e.g. in phase changing aluminum, can play an important role (carnot batteries).

In Denmark, thermal energy storage is already known in the public supply, where district heating typically has relatively large sensible thermal storages (water). Also, in this sector, phase changing materials could be relevant, since the district heating sector will be able to utilize fluctuating electricity prices at a completely different level in the future.

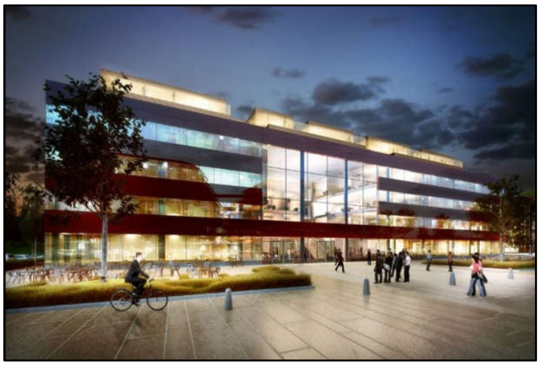
Of course, this development is also supported by the future scenarios where heat pumps play a central role in the supply of district heating.

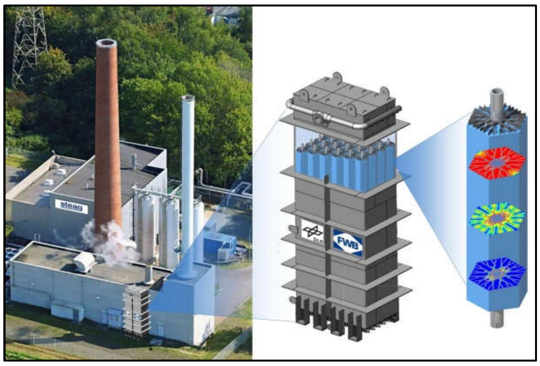
Annex 1

IEA-ECES (2018), “Applications of Thermal Energy Storage in the Energy Transition – Benchmarks and Developments”, [Gibb et al., German Aerospace Center (DLR)], IEA Technology Collaboration Programme on Energy Conservation through Energy Storage (IEA-ECES), 2018.

APPLICATIONS OF THERMAL ENERGY STORAGE IN THE ENERGY TRANSITION

BENCHMARKS AND DEVELOPMENTS





TES for Energy Management and CO_2 Mitigation

Public Report of IEA ECES Annex 30

September 2018

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ABOUT ECES ANNEX 30

ECES Annex 30 is a concluded project of the International Energy Agency's Technology Collaboration Programme "Energy Conservation through Energy Storage (ECES)". Officially active from July 2015 through June 2018, Annex 30 saw the participation of 16 countries, of which 23 institutions took part in a total of seven workshops.

Annex 30 had the main objective of encouraging the implementation of thermal energy storage systems and evaluating their potential in a variety of applications with respect to cost-effective energy management and CO_2 mitigation.

ECES facilitates integral research, development, implementation and integration of energy-storage technologies such as: electrical energy storage, thermal energy storage, distributed energy storage & borehole thermal energy storage.

More information can be found at the following links:

Annex 30	https://www.eces-a30.org
ECES	https://www.iea-eces.org
IEA-TCPs	https://www.iea.org/tcp/

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CONTENTS

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EXECUTIVE SUMMARY

Thermal energy storage technologies occupy a unique position in the energy sector. On the one hand, the basic principles of storing heat have been understood for well over a century and applied in domestic and industrial settings. This includes concepts as fundamental as hot water heaters or regenerator heat storages in steelmaking processes. These technologies are well-established within their respective sectors and have contributed to the efficient and convenient use of heat in many ways.

On the other hand, there are novel applications of thermal storage that are beginning to be exploited and new technologies that are being applied in innovative ways. The story begins with classical technologies that are currently finding new uses in power plants, district heating grids and industrial processes in order to provide a wide range of benefits. These include energy efficiency in processes, increased use of renewable energy and cost savings. In addition to this, there have been technological developments that are opening new doors within well-known applications. Some suitable examples are the cost-effective storage of molten salts in a thermocline, high-temperature latent heat storage for high power levels and thermochemical reactions that can store heat loss-free.

The evolution of the energy system has furthermore led to new possibilities for the usage of heat. It is beginning to be recognized that thermal energy storage is an enabling and cross-cutting technology that can unlock potentials in various sectors. By facilitating the coupling of the electricity and heat sectors, it is emerging as a key solution for the energy transition that improves thermal and electrical energy management in a flexible and reliable manner.

Annex 30 has worked to advance the implementation of thermal energy storage systems by developing an analysis methodology for storage integration, determining key performance indicators and collecting and analyzing case studies of TES systems integrated in processes.

This report has the following objectives:

- Present the methodological work conducted in Annex 30 regarding process analysis, thermal energy storage system parameters and key performance indicators.
- Concisely overview the state-of-the-art benchmarks in some of the most TES-relevant sectors: district heating, non-residential buildings, industrial processes and power plants.
- Depict technology development work by the Annex 30 participants in these same sectors.
- Present evaluations that technically and economically characterize each application field.
- Investigate and clarify key differences in the applications based on these evaluations.

Methodologies

As a diverse technology, different thermal energy storage (TES) systems have inherent characteristics that make them more or less suitable for an application. This variation means that while TES technologies are able to be deployed in many types of applications, there are process requirements that must be met and conditions that cannot be sacrificed in a certain integration. It follows that there is no "one-size-fits-all" version of a TES system that can be adjusted to suitability for any type of application. Additionally, due to the inherent diversity of processes, the engineering design required for integrating TES systems into processes can be complex and often presents a serious barrier for industrial partners considering these technologies. As introduced in [1], the interdependent relationship between TES and process is shown in Fig. ES1.

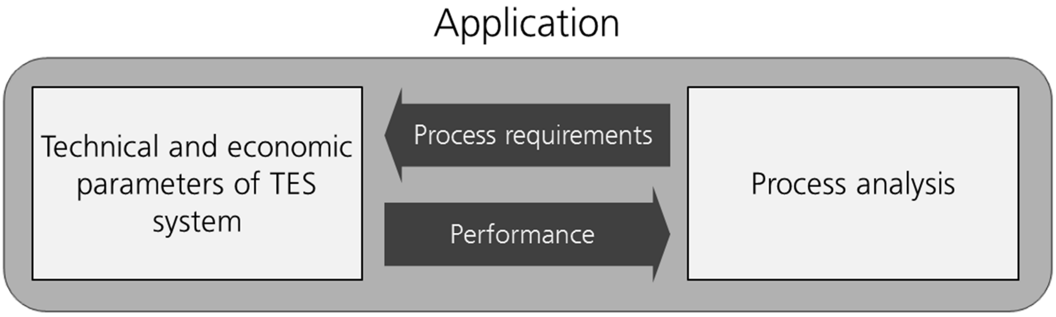


Fig. ES1. Interaction between the TES system parameters and process for a successful integration [1].

In the first section, a methodology has been developed that investigates the domains of TES system, process and application. The starting point is a set of **process analysis guidelines** that can serve, on the one hand, as direction for researchers developing TES for industrial processes and upscaling from the laboratory setting. On the other hand, the guidelines can be a first step in assisting process customers or partners in assessing the necessity and depth of information required at the various steps of the evaluation and design.

The characterization of the TES system begins with the analysis levels of a thermal energy storage, resulting in definitions for the material, component, module and system levels. The system level particularly defines the **TES system boundary** as the "point of contact between the fluid streams and the heat source and heat sink". This effectively includes any process component that is used exclusively by the storage. Subsequently, definitions have been developed for **technical parameters of a TES system** covering nominal power, response time, system efficiency, auxiliary energy ratio, system storage capacity, minimum cycle length and partial load suitability. The economic methodologies applied in this report have been adopted from Annex 29 in ECES.

To evaluate the integration of a thermal energy storage system in a process, **key performance indicators (KPI**) are determined from storage system parameters that dictate performance and external factors that emerge from the integration. These are then prioritized based on the perspectives of various stakeholders to the integration.

Applications and Evaluations

Four application fields investigated in this report: district heating, non-residential buildings, industrial processes and power plants. Along with being four of the most relevant sectors for integration of thermal energy storage systems, they were also well-represented by the participants in the Annex 30 network and as such, state-of-the-art and promising developments in these applications were readily available. The application field of vehicles is also touched, yet due to its nascent status and few examples of integrated systems, no evaluation has been conducted regarding this sector in this report.

Several benchmarks of TES in **district heating** (DH) were chosen to highlight the diversity of the sector. These include pit storage, pressurized and non-pressurized hot water storage and seasonal tank storage. As district heating is a well-developed application field for thermal storage, only two cases in development are discussed. The district heating sector can be largely categorized into two types of thermal energy storage use: buffer storage and seasonal storage.

In buffer storages, both pressurized and non-pressurized hot water storage tanks are used. TES systems can be used in combination with a cogeneration plant or other DH process units to add flexibility in operation. These buffer storages deliver a number of common benefits, including an improved performance and utilization of the CHP plant, optimized electricity market participation, fossil fuel savings and CO_2 emissions reductions, reduced installed back-up capacity and an overall increase in stability of the DH network.

For seasonal storages, pit storage and large-scale hot water storage tanks come into focus. These have the benefit of enabling a higher share of renewables when the storage is charged during the warmer months. This accompanies an overall lower cost of heat for the district heating network. A summary of this evaluation and presentation of the KPI for district heating can be found in the tables ES1 and ES2.

While thermal energy storage in the **non-residential building** sector has not yet seen widespread use, there are key examples of established technologies. The benchmarks highlighted in this report all utilize the latent heat of fusion of water (ice and snow) to store thermal energy either daily or seasonally.

Research and development in this sector sees an emphasis on low-temperature PCM from 4 °C to 80 °C. The material used is most commonly a salt hydrate or a paraffin. These systems use either macro-encapsulated PCM or flat-plate heat exchangers. Largely, there are two categories of R&D: at TRL 6-8, pilot systems have been installed in real environments. At TRL 4-5, new concepts are under development for heating of non-residential buildings.

In these new cases, TES is used for peak shaving of cooling or heating load that allows for energy use reductions, downsizing of equipment and an operational benefit for certain process units (cogeneration, thermal chiller etc.). A summary of this evaluation and presentation of the KPI for district heating can be found in the tables ES3 and ES4.

Thermal energy storage systems have been standard process components in the **industrial process** sector since the 19th century. Regenerator storages are benchmarks in steelmaking and glass manufacturing. Steam accumulators have also seen widespread use in industrial processes for buffering of steam.

Modern and novel uses of thermal energy storage in industrial processes represent the most diverse application field. Excluding the benchmarks, there is no standard integration of TES technologies into industrial processes and there are various storage types that have been deployed. Nevertheless, especially at high temperatures, there are several examples of innovative storage systems that have already reached technology readiness levels close to commercial applicability. These include sensible storage in solids (bulk materials or bricks) for gaseous heat transfer fluids at high temperatures, sensible storage in liquids (water, oil, salt, bitumen) and hybrid sensible storages that combine solid and liquid phases. Additionally, latent heat storages and thermochemical storages have also found use in industrial processes. Based on this diversity of technology, this evaluation can only highlight some specific examples that emphasize the utility of TES systems in industrial processes.

Nevertheless, some common benefits can still be discussed. The use of the TES system relies entirely on the specific process requirements and, according to current standards and information, rarely will any detailed integration be replicated. As such, there are no standard TES storages for industrial processes, unlike in district heating and to some extent, non-residential buildings and power plants. The thermal sources are often some form of waste heat that is either used on-site or transported to a thermal sink, often in another sector entirely. The TES systems can reduce the use of backup systems, preheat components and compensate for fluctuations in available heat sources.

Thermal energy storages in industrial processes deliver a broad range of benefits including waste heat recovery at various temperature ranges, reduction in the use of fossil fuels and increase in process flexibility. Currently, TES systems will in most cases be retrofit solutions to already-existing industrial processes being optimized in terms of output and quality of the product. The integration of a thermal energy storage as an additional process unit must not change the process itself and should at the same time be beneficial in terms of process flexibility and/or energy efficiency. Integrations of innovative thermal energy storage systems will therefore mostly be first-of-its-kind applications with high technical and economic risk. Until TES becomes a standard industrial process component for greenfield installations, financial support from funding agencies will be needed to overcome this hurdle, bring down storage costs and collect important operational experience in the industrial environment.

The benchmarks and KPI results are found in tables ES5 and ES6. It should also be noted that given the wide variety of thermal energy storage in industrial processes, it is not feasible to create generalized tables as can be found in tables ES1 and ES3. Furthermore, this report features nine of these cases and given this total, they have not been depicted in a single table as in Table ES8 and are represented in the text only.

The most common benchmark in the **power plant** sector is the storage of thermal energy in concentrating solar power (CSP), which has been a common industry practice for the past ten years. At the time of writing, there are 12 GWh of thermal energy storage installed in CSP applications worldwide.

Two-tank molten salt in a direct storage configuration is currently the most common method of thermal energy storage in CSP. Nevertheless, indirect storage in two-tank molten salts and steam accumulators round out the commercialized technological options for this application field, as shown in Table ES7.

Within Annex 30, several development cases were chosen that highlight the progress being made in TES for power plant applications. Consisting mainly of cases with regenerator-type storages and complemented by one with thermochemical storage, high capacities (>20 MWh) and temperatures (>290 °C) are the norm for either storing heat for later electricity generation or buffering for power plant flexibility. As in industrial processes, a diverse array of applications within specific power plant configurations can be found, such as thermal storage for adiabatic compressed air energy storages or thermal storage for process flexibility in combined cycle power plants. New technologies (thermochemical storage for CSP) and concepts (molten salt thermocline with filler material) are also in development.

Thermal energy storage in power plants delivers a number of benefits including power dispatchability, lower levelized cost of electricity, overall power plant efficiency, reduction of fossil fuels and short-term compensation of demand fluctuation and generation interruptions.

The key performance indicators in this report have been identified by the expert research community of Annex 30. Industry consultation will be an important step for further verifying the outcomes reported in the following pages.

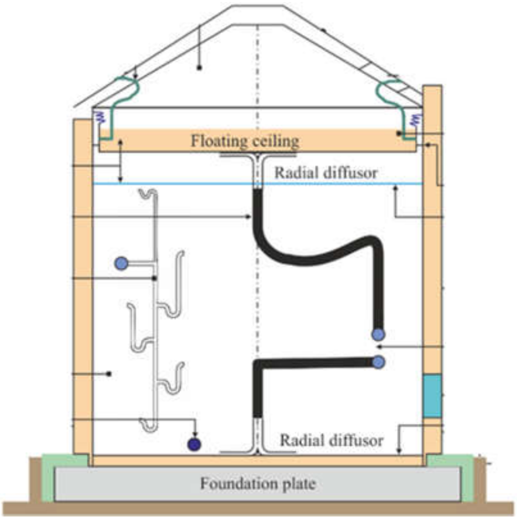
Important note: The cases presented in this report should be understood as a non-exhaustive representation of each sector or technology. The goal of the Annex 30 network was to select interesting and informative cases that highlight key characteristics of thermal energy storage.

DISTRICT HEATING EVALUATION

Table ES1. Non-exhaustive selection of relevant system parameters for storage in district heating.

	Buffer storage		**Seasonal storage**	
	Pressurized	**Non-pressurized**	**Pit storage**	**Tank storage**
T_{min} (°C)	60 – 70	60 – 70	10 – 12	15
T_{max} (°C)	140 – 180	98	80 – 90	90
Volume (m^3)	1000 – 6000	1000 – 50,000	60,000 – 200,000	6000
ESC_{sys} [1]	Up to 850 MWh	Up to 2 GWh	5 – 15 GWh	ca. 500 MWh
SCC_{real} [2] (€/kWh)	20 – 25	6 – 20	as low as 0.4	1.8
Cycle frequency	1/day to 1/week		1-2/year	1-2/year
Efficiency	99%		< 81%	81%

Hot water storage in Potsdam, Germany (City of Potsdam)



Overground thermal energy storage with floating ceiling (TU Chemnitz/OBSERW)

Table ES2. Key performance indicators for district heating.

Stakeholder:	**District heating company**	**Consumer or End-User**
KPI 1:	Max/min temperatures	Cost of delivered heat
KPI 2:	Storage capacity	CO_2 emissions reductions
KPI 3:	Charging/discharging power	
KPI 4:	CAPEX	
KPI 5:	Network stability	

Definitions found in Section 1.3:

[1] System storage capacity

[2] Storage capacity costs

NON-RESIDENTIAL BUILDINGS EVALUATION

Table ES3. Non-exhaustive selection of relevant system parameters for storage in non-residential buildings.

	Cold storage	Heat storage
T_{min} (°C)	-7 – 7	20
T_{max} (°C)	7 – 18	80
ESC_{sys} [1]	0.3 – 11 MWh (R&D) 0.49 – 10 GWh (Benchmarks)	
SCC_{real} [2] (€/kWh)	0.8 – 3.3	ca. 103 (PCM in R&D)
Cycle frequency	1/day to 1/year (seasonal)	
Response time	Immediate to 1-2 minutes	

Working lab office in Johanneberg Science Park (Akademiska Hus)

Storage bricks of phase change material (SINTEF Energy Research)

Table ES4. Key performance indicators for non-residential buildings.

Stakeholder:	Building owner	Energy utility
KPI 1:	Net economic benefit (peak shaving, equipment downsizing)	Net economic benefit
KPI 2:	Net environmental benefit	Net environmental benefit
KPI 3:	Operational benefit for certain process units / flexibility	Higher flexibility in process operation
KPI 4:	Reliability	Improved grid stability

Definitions found in Section 1.3:

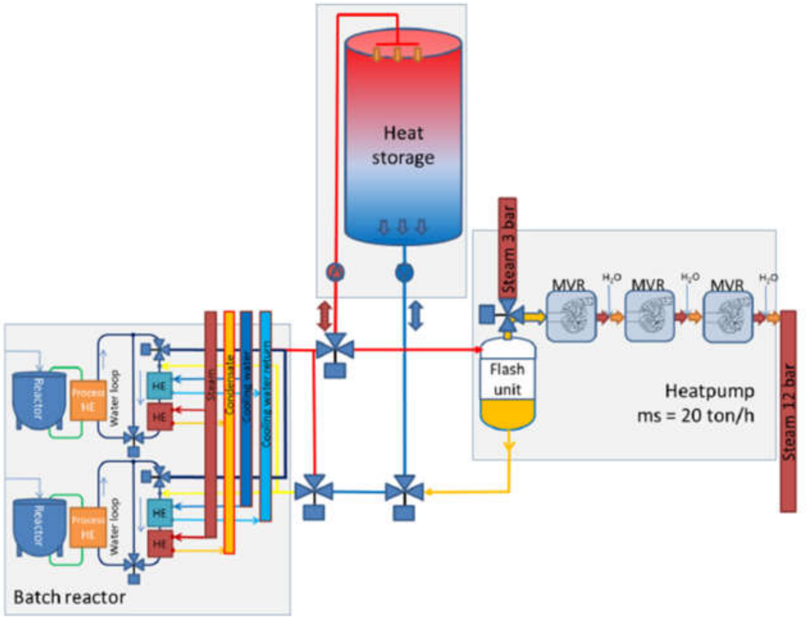
[1] System storage capacity

[2] Storage capacity costs

INDUSTRIAL PROCESSES EVALUATION

Table ES5. Non-exhaustive selection of relevant system parameters for benchmarks in industrial processes.

	Regenerator (steelmaking)	**Regenerator (glass production)**	**Steam Accumulator**
Temperatures (°C)	1250 – 1400	300 – 1400	150 – 230
ESC_{sys} [1] (MWh)	140	10	up to 30
P_{nom} [2] (MW)	140	30	variable
SCC_{real} [3] (€/kWh)	15 – 40	N/A	70 – 300
Cycle frequency	2/hour – 1/3 hours	3/hour	several/day



Thermal energy storage for waste heat recovery in a batch process (ECN, part of TNO)

Thermal energy storage testing unit (ZAE Bayern)

Table ES6. Key performance indicators for industrial processes.

Stakeholder:	**Process owner**	**Energy utility**	**Industrial customer**
KPI 1:	Economic benefit (waste heat usage)	Industrial process flexibility (grid balancing)	Environmental benefit
KPI 2:	Environmental benefit	Net economic benefit	Product cost reduction
KPI 3:	Discharging power	Net environmental benefit	
KPI 4:	Process flexibility and reliability	Higher flexibility in process operation	
KPI 5:	Storage capacity		

Definitions found in Section 1.3:

[1] System storage capacity

[2] Nominal power

[3] Storage capacity costs

POWER PLANTS EVALUATION

Table ES7. Non-exhaustive selection of commercialized TES options for power plants.

	2-tank molten salt Direct	**2-tank molten salt Indirect**	**Steam accumulator**
Temp. (°C)	290 – 565	290 – 390	250 – 300
ESC_{sys}[1]	~ 6 GWh (Atacama)	~ 4 GWh (Solana)	3 – 5 MWh per tank <100 MWh (KhiSolar1)
SCC_{real}[3] (€/kWh)	20 – 40	N/A	N/A
Cycle frequency	1/day	1/day	multiple times per day

Table ES8. Selection of technologies in development for TES in power plants.

	Molten Salt Thermocline	**CSP with TCS**	**Regen. combined cycle (DLR)**	**Regen. combined cycle (TUM)**	**Regen. A-CAES**
Storage type	sensible	thermochem.	sensible	sensible	sensible
Temp. (°C)	290 – 560	550 – 600	400 – 600	400 – 600	400 – 600
ESC_{sys}[1] (MWh)	2800	15 kWh (lab) ~750 MWh (real)	3000	20	340
P_{nom}[2] (MW)	235	5 kW (lab) ~250 MW (real)	250	100	34
Efficiency	> 98%	~97% (real)	> 95%	> 95%	> 98%
SCC_{real}[3] (€/kWh)	18	N/A	N/A	N/A	80
Cycle frequency	1/day	1/day	1/day	1/day	1/day

Table ES9. Key performance indicators for power plants.

Stakeholder:	**Power plant**	**Energy utility**
KPI 1:	Economic benefit (LCOE reduction)	Dispatchability
KPI 2:	CO_2 emissions reductions	CO_2 emissions reductions
KPI 3:	Storage capacity	
KPI 4:	Discharging power	
KPI 5:	Dispatchability	
KPI 6:	Optimization for power block components	

TCS: Thermochemical storage
CSP: Concentrating solar power

Definitions found in Section 1.3:
[1] System storage capacity
[2] Nominal power
[3] Storage capacity costs

Important note: The cases presented in this report should be understood as a non-exhaustive representation of each sector or technology. The goal of the Annex 30 network was to select interesting and informative cases that highlight key characteristics of thermal energy storage.

Introduction

Thermal energy storage (TES) technologies have significant potential to improve energy management across a wide variety of sectors. Along with enhancing the use of heat at various temperature levels, the emergence of a focus on sector coupling has also underlined the technical potential for TES systems to enable the efficient management of electrical energy. The benefits delivered by integrated TES systems are manifold – energy efficiency, process flexibility, and increased shares of renewable energy use highlight just several of the services provided by these technologies.

There is no shortage of application fields in which TES systems provide useful services. Beginning with applications in the lower-temperature region, district heating processes use TES units for seasonal and buffer storage. In the non-residential building sector, heat is managed both for domestic hot water production and space heating. Industrial processes use thermal energy storage primarily for waste heat recovery and process efficiency. Power plant applications, particularly those in concentrating solar power, use TES systems to improve dispatchability and increase operational efficiency of process units. In automobile applications, TES systems are seeing developmental work in waste heat recovery and thermal management.

The technical potential can be activated by a wide selection of TES technologies that have inherent characteristics that designate them as more or less suitable for an application. Nevertheless, there are three distinct storage principles that differ in the fundamental way they store thermal energy [2]:

- sensible heat storage (SHS) raises or lowers the temperature of a liquid or solid storage medium,
- latent heat storage (LHS) uses the energy absorbed or released at constant temperature during the phase change of a material and
- thermochemical storage (TCS) either stores energy as the heat of reaction in reversible reactions or in sorption processes.

Some of these technologies have already been integrated into commercial applications in various forms, yet others remain at lower stages of development. In order to compose a full picture of the application fields, both selected benchmarks (i.e. commercialized technologies) and TES systems in development will be discussed and evaluated in this report.

Also taken into consideration are the main types of integration of thermal energy storage systems: retrofit and greenfield. Retrofit applications examine an existing process where the storage system must be designed to fit the needs of an already dimensioned and built process. The challenge is in designing a storage system that fulfils the process requirements [1]. In a greenfield analysis, the storage parameters are designed from the very beginning in parallel with the rest of the process. While no two projects are the same, it is noteworthy that the fundamental principles of the integration remain consistent and as such, a ground-up engineering of the system is not required and best practices can be employed [1].

Considering the diverse applications available and the various characteristics of the TES technologies themselves, it is clear that there is no single application that is suitable for a specific TES system, or vice versa. It follows that detailed analyses are necessary to properly characterize the process into which the storage system is being integrated, the TES system itself and the integration in general i.e. the key performance indicators of the application. The Annex 30 network has thus developed a methodology that systematically addresses these points in a thermal energy storage integration.

Chapter 1 introduces the methodological work. It is split into the following subchapters and outlines the methodological procedures of Annex 30 in detail. Beginning with guidelines for process analysis, the methodology also proposes a definition of the system boundary for TES systems, definitions of technical parameters for TES systems, economic parameters and a procedure for identification of key performance indicators from a stakeholder perspective.

Chapters 2-6 examine the aforementioned application fields in detail, wherein the methodological work from Chapter 1 has been applied to a series of 22 application-oriented case studies from commercial and research projects.

Each of these chapters proceeds as follows:

- Benchmarks of the application are described to provide history and context for future discussions. These sections give an overview of the general state of the art in each sector and highlight several examples of TES systems in these applications.
- Cases of TES systems in development are presented to which the methodological work was applied. The case studies describe the process (with process diagram and identified TES system boundary), the TES systems (operational strategies, dimensions etc.) and on the final page, abridged analysis results are shown in a fact sheet format that includes relevant integration aspects of the process, values calculated from the technical parameter definitions and the key performance indicator (KPI) methodology results.
- Finally, each complete application field undergoes an evaluation that highlights key characteristics, trends, benefits delivered by TES systems and an overview of KPI.

Chapter 7 presents an overall evaluation of all application fields that highlights commonalities and differences as well as provides a look at the general state of development of TES systems in these applications.

Chapter 8 summarizes the discussions that inform this report and presents conclusions for the work going forward. Specifically it introduces how the methodological work from Annex 30 can be further applied to advance the integration of thermal energy storage systems in a global context.

1 Methodologies

1.1 Process analysis guidelines

The goal of Chapter 1.1 is the development of process analysis guidelines and the testing of these analysis steps with work conducted by researchers in Annex 30.

The goals of the guidelines are twofold. On the one hand, these guidelines can serve as direction for researchers developing TES for industrial processes and upscaling from the laboratory setting. On the other hand, the process analysis guidelines can be a first step in assisting process customers or partners in assessing the necessity and depth of information required at the various steps of the evaluation and design.

Referring to the structure of Annex 30, the combination of the process analysis conducted here and the storage unit analyses conducted in Chapter 1.2, 1.3 and 1.4 results in a combination of factors that can be used for evaluating the integration potential of a storage unit. This is analyzed in Chapter 1.5 *Key performance indicators*.

These guidelines have been developed with a focus on industrial processes and power plants, with an initial focus on retrofit applications, which was expanded to incorporate greenfield scenarios. Retrofit examines an existing process and the storage must be designed to fit the needs of this already dimensioned and built system. In a greenfield analysis, the storage parameters are designed with the rest of the system. This results in a different viewpoint while applying the process analysis guidelines. The information and values from the process analysis are used to design the storage system.

These guidelines can be used for processes other than industrial or power plants, but some adjustment may be necessary.

Design of thermal energy storage systems requires a detailed look at several types of process information. To this end, the first methodology in this report is a set of guidelines for process analysis for TES system integration. The guidelines follow a series of six steps that progressively collect and analyze process information that is relevant to integration of different storage technologies. These are shown in the flowchart comprising Fig. .

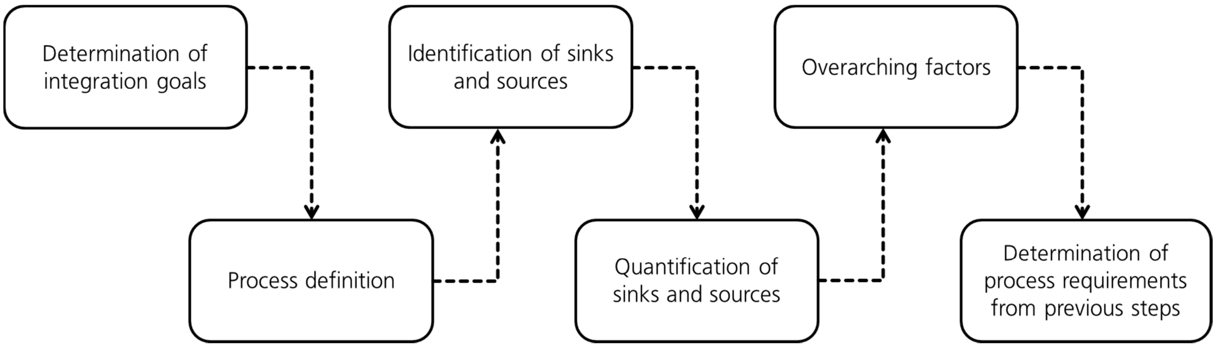


Fig. 1.1. Steps in the process analysis guidelines.

For the process analysis, different kinds of information are necessary or beneficial and as such, various types of information sources are required. Sometimes, however, the optimum information is not available and secondary sources have to be used. The information sources discussed within Annex 30 are listed in Table 1.1.

Table 1.1. Information sources for process data.

Measured transient data
Average system values
Database information
Fuel use extrapolation
Piping and instrumentation diagram analysis
Commercial information
Extrapolation from CO_2 emissions
Company experts
Industry experts

a. Determination of integration goals

To begin, the overall goal for the TES system integration needs to be identified. To some extent, the goal can first be determined through the analysis, especially in a retrofit system. In a greenfield design, it is possible that the goals can be more clearly quantified in advance. This is because the process may be designed for a certain number of solar hours of operation, for example, and all of the components will be designed for this. In a retrofit integration, it may only become clear through the process analysis how much more efficient a system can become, for example. To conclude this step, it is necessary to determine the expected goal of TES integration and the required results in achieving the goal.

b. Process and boundary definition

In order to analyze a process for storage integration, the process has to be defined or selected and the process boundaries for analysis clarified.

Process definition is a part of project preparation and/or research work, and typically entails a partner discussing process aspects with consultants or research institutions. If only parts of the process are analyzed, it helps to clarify this limitation regarding which specific process sections will be looked at.

In some cases, the introduction of a TES system makes further process optimization possible by cooperation of other systems, e.g. boiler and heat pump. In a retrofit application, this may only become clear through the process analysis.

At this step, possible future changes of the process characteristics (both source and sink) have to be addressed, as the return on the investment in a TES can be highly affected by this (e.g. change of operating temperatures, duration, power level etc.).

c. Identification of thermal sinks and sources

i. Thermal sinks

As the impact of a TES is often to replace heat needed for the process, the first step is to identify the thermal sinks. Focus should be on the overall goals of thermal energy storage integration.

This identification can be done via discussion with (industry) specialists, analysis of piping and instrumentation diagrams, process database analysis, estimation via extrapolation of fuel usage or measurement. The integration of a TES should consider the opportunity of exploring external thermal sinks, i.e., providing heat to nearby processes.

Typical sinks can be preheating or electricity generation, and as such can be external to original process boundaries. To conclude this partial step, it is necessary to identify what thermal sink(s) were selected, why they were selected and what sinks were considered overall.

ii. Thermal sources

As a second activity, thermal sources have to be identified. This has to be done based on the chosen heat sink (especially temperature level) as well as overall integration goals and uses similar information sources as the step identifying thermal sinks. This identification can be done via discussion with (industry) specialists, analysis of piping and instrumentation diagrams, process database analysis, estimation via extrapolation of fuel usage or measurement.

Typical sources can be waste heat or heat flows within the process. If there is no heat source found within a process, there is no need for a storage system. However, when also considering Power-to-Heat systems, excess electricity can also be seen as a heat source.

Information on both sinks and sources should be gathered in two steps – an initial estimation to preliminarily determine the benefit of pursuing more detailed information, followed by the more detailed information itself. Some of this information may be confidential.

To conclude this step, it is important to identify what sources were considered overall, what sources were selected and why each source was selected. As a final point, it should be clear whether the source can be used directly, or if a temperature upgrade is needed (e.g. heat pump, mixing or electrical heating) or conversion to electricity is required (Power-to-Heat-to-Power).

d. Quantification of thermal sinks and sources

Before evaluating the potential use of sinks and sources for TES integration, they must first be quantified. There are three major groups of parameters in this quantification – general factors, thermodynamics, and physical properties.

i. General factors

With the topic of general factors, an initial energy-based analysis can be completed, but should not yet consider temperature levels and other critical thermodynamic properties. The factors that need to be analyzed here are the following, and the answers are possibly more qualitative in nature. In the following steps, the answers would be more quantitative in nature.

- Availability: Are the sink and the source regularly available, is there a constant profile?
- Seasonal characteristics: Even for short-term storages, seasonal fluctuations in either source or sink may play a significant role in the supply or demand of energy.
- What overall energy level is available at the source? Is it required at the sink?

Here it is important to determine if the required or available thermal sources and sinks are compatible in terms of temperature levels and energy quantities. Similarly, it is useful to know if the sources and sinks have a comparable availability. A final key consideration is whether the sources and sinks are dispatchable in their profile, or if the TES system will have to be designed for supply or demand intermittency.

ii. Thermodynamics

Thermodynamic data can be analyzed independently of the physical factory or environment, though without consideration of the physical properties, a full analysis is not possible. Thermodynamic data are, however, most critical for the storage concept development.

The following distinctions are clarified for liquid/gaseous energy sources. If electricity is used as the energy source, the transient supply characteristics must be determined. The other parameters detailed here are then only necessary for the sink.

a) <u>Medium</u>

The medium of the source or sink influences the heat transfer rate, piping, types of containment and materials used and applicable storage concepts. In some cases, an additional heat transfer fluid will need to be introduced into the system as a heat transfer medium. It is important to determine the mediums for both thermal sink and thermal source. Possible heat transfer fluids discussed in Annex 30 are listed in Table 1.2.

Table 1.2. Heat transfer fluids.

Fluid	**Sink?**	**Source?**	**Additional?**
Thermal oil	X	X	X
Water (and water mixtures)	X	X	X
Air (Ambient)	X	X	X
Air (Flue gas)		X	
Steam	X	X	X
Molten salt	X	X	X
Molten metal	X	X	X
Refrigerants			X
Emulsions and slurries			X
Gases	X	X	X

b) Temperature levels and dynamic profiles

The temperature levels and dynamic profiles of the sink and the source are key for the development of a TES concept, its power level and its capacity (in combination with further characteristics). Information about the temperature level or temperature range can help establish the motivation and usefulness of storage integration. For detailed development, access to the dynamic temperature profiles is necessary. If electricity is used as the energy source, then the transient profiles of this availability are necessary as well.

The mass flow rates and the dynamic character of the source and sink are critical for the power level and capacity determination. The pressure, as well as the dynamic profile thereof, determines the phase of the heat transfer medium and therefore also the heat transfer characteristics. In addition, the material and containment aspects are directly affected by the pressure levels of the source, sink and possible intermediate heat transfer fluids. Determination of all of these properties is necessary before proceeding to the following step.

c) General Thermodynamics

The following issues regarding the heat transfer fluid, temperature gradients and cycle characteristics need to be clarified for the analysis of the given process for thermal energy storage integration. It is important to know if the heat transfer fluid between the source and the sink is the same. It is also significant whether the temperature gradients, temperature profiles or temperature levels are adjustable in any way. Further technical aspects regarding thermodynamics (e.g. condensation, corrosion, formation of toxins) should be considered at this stage.

In some systems, cycle length, i.e. the length of time energy is available for charging and needed for discharging a storage system, and cycle frequency, i.e. the rate or interval during which a storage system is cycled, are directly coupled to one another. In others, these characteristics are more independent of one another, depending on the source(s) and sink(s). There are also systems in which several sources or sinks are considered, resulting in a combination of cycle lengths and frequencies. If the sources and sinks operate independently, an evaluation of fully regular or irregular cycles is necessary – are full charging and discharging cycles likely, or is some kind of bypass and partial charge or discharge likely? To assist in addressing this potential combination of sources and sinks these characteristics, a series of questions is proposed as follows:

Questions

1. When the source and sink are connected via a storage system, what is the resulting cycle length? The cycle length here refers to the length of time energy is available for charging a storage system and for discharging a storage system if charging and discharging are conducted directly back-to-back. For example, in a CSP integration, consider 12h charge and 6h discharge: 18h cycle length.
2. Do multiple cycle lengths need to be considered (i.e. seasonal as well as daily)?

3. Are the source and sink operating in a regular or full cycle, and independently?
    a. Are full discharging and charging cycles possible?
    b. Is the source sometimes available at the same time that the sink has a demand? This would require either a closed loop or bypass over a possible storage, two storages or some other system solution.
4. When the source and sink are connected via a storage system, do multiple cycle frequencies need to the considered? How often would charging and/or discharging of the storage system occur, in theory? The cycle frequency in a continuously charging and discharging system is related to the cycle length. Taking the CSP storage above, the cycle frequency is 1/day.
5. When the source and sink are connected via a storage system, what is the maximum energy that can theoretically be transferred and/or saved?
6. What is the required response time of a storage system for charging? How quickly does a storage unit need to respond to charging requirements, in theory?
7. What is the required response time of a storage system for discharging? How quickly does a theoretical storage unit need to respond to discharging requirements?
8. Are charging/discharging times controlled by the system or result from less foreseeable factors?

iii. Physical plant/process properties

Some processes are so large that physical distance can be a critical factor but in small processes or integrating a storage system in an existing site, the same can be true. When analyzing a mobile storage system, the source and sink may not even be in the same area. The physical distance between the source, the sink and a possible location for the TES system can therefore directly affect the feasibility of the integration. Here it is important to determine what physical space is available for a TES system, what is the physical distance and obstacles between source and sink, what infrastructure for integration is already present and what is missing, and can the TES system be integrated without affecting the regular operation of the process.

e. Analysis of overarching factors

In the penultimate step, the overall process is considered and all information is related to the process, regardless of the TES system that may or may not be developed for integration. These issues are somewhat related to the research nature of the integration of storage units and the continuing development and changes in the policies and economics in different countries regarding energy efficiency. The topic can be grouped into three basic categories: company/type, legal/specific and economics.

For the company and process type, it is important to know how often the process exists in the world. Is it an established manufacturing process or a relatively innovative energy management system? What is the life cycle/-span of the analyzed process? How does the company corporate culture and objectives relate to the storage development in terms of CO_2 emissions reductions, greenwashing, energy policy and energy reliability or flexibility?

Regarding the specific issues, the first point is whether the storage is integral to the process, i.e. if the process depends on the storage system operationally. This also applies if the storage is fully a serial part of the process. Still regarding the storage, it is important to know what development grade (TRL) is acceptable and what environmental or health restrictions (e.g. legionnaires/dioxins or permits for noise, emissions etc.) exist in the process.

Economically-speaking, any tax considerations should be taken into account as well as any clearly defined economic goal that is expected to be met with storage integration.

f. Summary and determination of process requirements from previous steps

In this step, the guideline summarizes the responses by determining whether the expected goal of the TES integration can be met and if the required results are feasible. To continue, if the process is considered suitable for TES in general, are there clear indications which storage concept or types are better suited to the process? On the other hand, any factors resulting in the unsuitability of a storage concepts for the process should be noted. The part of the process being analyzed may result in a certain storage technology type not being applicable or useful. As a final point, it should be determined if the integration of a TES system will make new improvements possible through the cooperation of other systems. In greenfield applications, the answer to this question may be more clear than in retrofit applications.

To conclude, the process requirements of a process for thermal energy storage integration can largely be outlined through the use of these process analysis guidelines.

1.2 Definitions of analysis levels for thermal energy storage

Annex 30 has investigated and prepared definitions for the different analysis levels of a TES system, i.e. detailing what constitutes the process, system, module, component and material. These definitions are an important step towards a complete understanding of the boundaries of a thermal energy storage system.

a. Process level

Definition:

Annex 30 considers as a process any series of actions that require heat sources and heat sinks to achieve a result. Application of TES systems to these processes is useful for increasing the utility or reducing the energy consumption and the greenhouse gas emissions.

Boundaries

Regarding Annex 30, the boundaries between the process and the TES systems are the point of contact between the fluid streams and the heat source and heat sink.

b. System level

Definition:

A system is a set of connected components that operate together. A system is defined by its purpose and the method it uses for fulfilling it. In the context of Annex 30 system refers to all the materials, components and modules, used exclusively by the TES device in order to perform its purpose of collecting, storing, and delivering heat. The approach of Annex 30 considers that the TES system is attached to a process, but it is independent of it.

Boundaries

The system boundary is the point of contact between the fluid streams and the heat source and heat sink. The system contains all the components and modules exclusively used by it.

c. Module level

Definition:

A module is a component or a set of components fulfilling a distinct and specific task inside the TES operation. According to the Annex 30 approach, the module level helps in structuring the analysis of a system. Grouping components in a module might be required in the calculation of system parameters. However, no parameters are defined for this level, as the modules are very specific for each TES system.

Boundaries:

A module involves one or more components. A module can contain the storage material. A module has a distinct task that is essential in the operation of the overall TES system. A module task might not be related to storage capacity of the system (i.e. pressurization module in molten salts TES).

d. Component level

Definition:

Components are the smallest parts of the TES, which in combination form the overall system.

Boundaries:

Components are single simple parts whose purpose is meaningless without the interaction with other components. According to the approach of Annex 30, the TES material is not a component, but it might be contained and integrated into one or more components. Components include all the fluid essential to system operation but not specifically used for thermal storage (i.e. heat transfer fluid). Insulation is considered a component. The components are elements and parts exclusively used by the TES system.

e. TES material level

Definition:

The TES material level involves exclusively the substances, mixture of substances, or reaction pairs that are the base of the thermal storage capacity of the system. The characteristics of the storage material define the technology family, the temperature level and the storage length of the studied system.

Boundaries:

The TES material level only includes the substances, mixtures of substances, or reaction pairs whose sole purpose is the thermal energy storage. The TES material excludes any other substance that could be key to the performance of the system, which might involve coatings, insulation, heat transfer fluids, structural materials, lubricants, etc.

f. Case study: molten salt TES for CSP

A molten salt TES for CSP is presented as an example of the use of analysis levels. The whole process is the concentrating solar power plant (CSP), whose objective is to produce electricity using the sun as energy source. Therefore, it only has one heat source, the solar field, and one heat sink, the power block.

The TES system, the molten salt system, is connected in parallel to the heat source and heat sink. This means that the process can operate by providing heat directly from the heat source to the heat sink to produce electricity. In this case, the system objective is to increase the utility factor of the process by storing the excess of production of the heat source to later release it to a demand in the heat sink.

The boundaries of the system are the connections of the heat transfer fluid piping that bypass the normal flow of the process from heat source to sink to the heat exchanger between the HTF and the molten salts.

The schematic of the process and system boundaries is shown in Fig. 1.2.

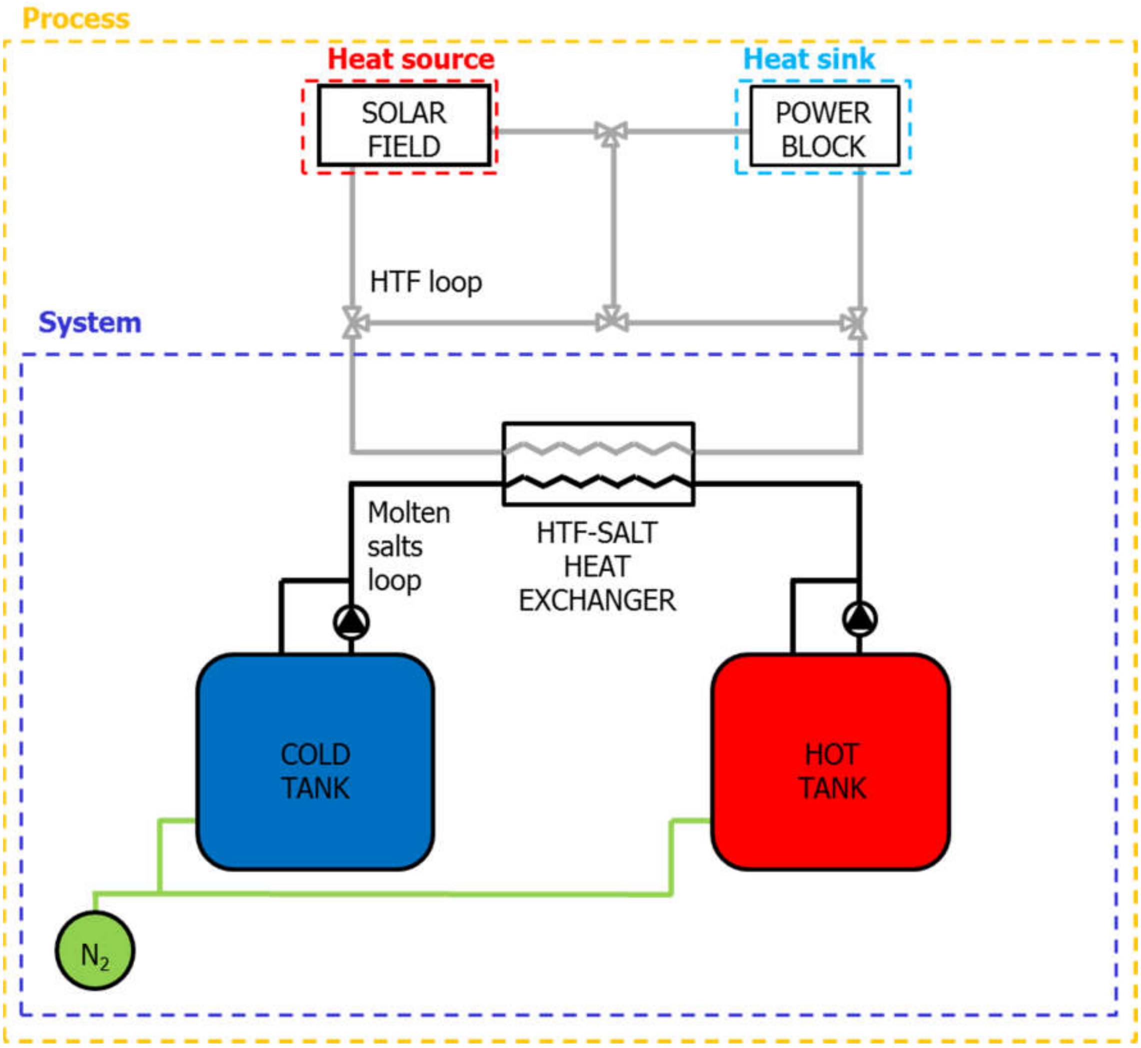


Fig. 1.2. Process and system level of a molten salt TES system for CSP.

The TES system has three modules, as shown in Fig. 1.3. The objective of the heat transfer module is to exchange heat from the HTF of the CSP and the molten salt, hence its main components are the heat exchanger and the molten salt pumps. It connects the two tanks of the heat storage module, whose purpose is to store the salt and to minimize the heat losses, avoiding the solidification of the salt. As the molten salt in contact with oxygen can cause corrosion of the components, the pressurisation module injects nitrogen into the tanks in order to reduce the amount of air. The summary of the main components of the system is presented in Fig. 1.4.

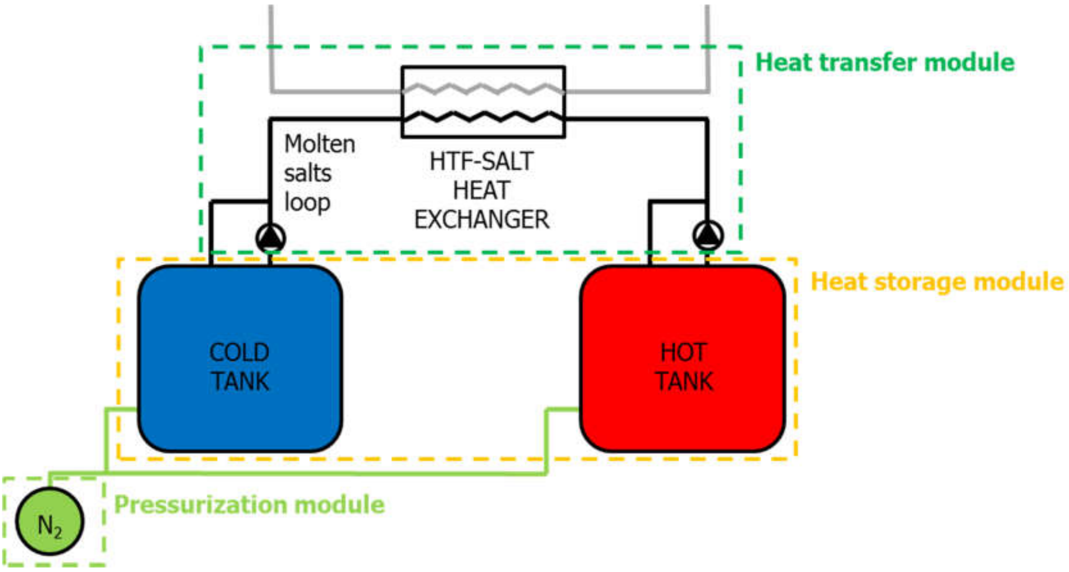


Fig. 1.3. Module level of molten salt TES system for CSP.

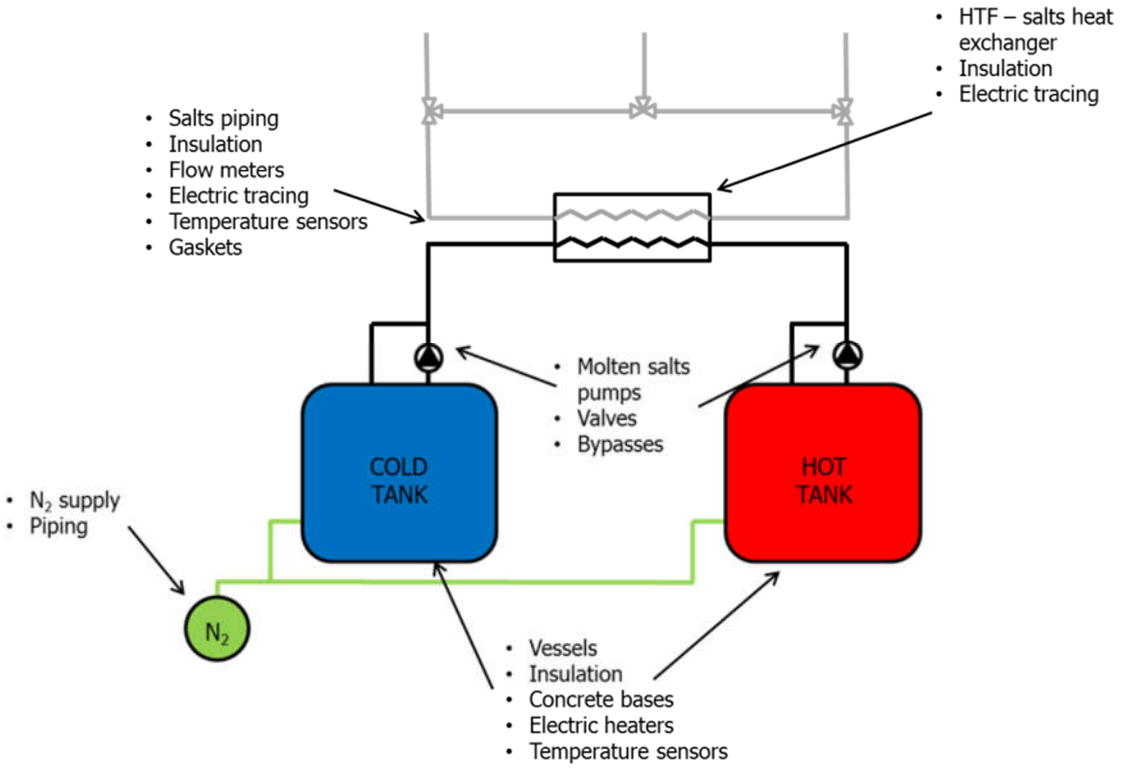


Fig. 1.4. Component level of a molten salt TES system for CSP.

1.3 Technical parameters for thermal energy storage systems

Along with the system boundary, technical parameters have been defined for a thermal energy storage system. These definitions can facilitate comparison across TES technologies and applications.

a. Nominal power ($P_{nom.sys}$)

Definition: The nominal power of a TES system is the design thermal power of the discharge. If relevant for the TES system, the nominal power of the charge can be indicated next to the discharge value, clearly stating which belongs to charge and which to discharge. Note that nominal power for discharge is required for the minimum cycle length calculation.

Presentation: The nominal power should be presented as follows:

$P_{nom.sys} = X$

$P_{nom.sys.charge} = Y$

where *X* and *Y* are the corresponding values for the discharge and charge, respectively.

Units: Power, [W].

b. Response time ($ReTi_{sys}$)

Definition: The response time ($ReTi_{sys}$) is the interval of time between the moments in which the discharge request is issued and the moment the TES system reaches the nominal power ($P_{nom.sys}$). Unless otherwise stated, $ReTi_{sys}$ regards discharging.

Alternatively:

- The response time ($ReTi_{sys}$) is the interval of time between the moments in which the discharge request is issued and the moment the TES system reaches the required output value of the critical parameter.
- The $ReTi_{sys}$ can additionally be given relating to nominal power during charging.

Presentation: The response time should be presented as follows:

$ReTi_{sys} = X$

$ReTi_{sys.charge} = Y$

Units: Time, [s] / [min] / [h] / [d].

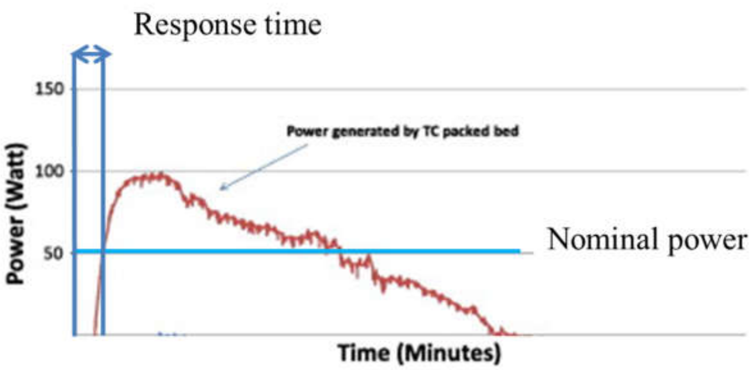


Fig. 1.5. Example of the $ReTi_{sys}$ in a real system.

c. Energy efficiency ($\varepsilon_{sys.xt}$)

Definition: The energy efficiency of the TES system ($\varepsilon_{sys.xt}$) is the ratio between the heat released to the heat sink(s) during discharging ($Q_{sys.discharge}$) and the energy absorbed by the system during charging as shown in Eq. 1. This last parameter considers the heat delivered by the heat source(s) to the system in charging ($Q_{sys.charge}$) and heat from the system components ($Q_{sys.aux}$). This last parameter only includes the heat intentionally generated by the components (i.e. electrical heaters, Peltier cell, etc.) not any heat generated indirectly by the operation of other components (joule effect on electric cables, friction of moving parts, etc.).

$$\varepsilon_{sys.xt} = \frac{|Q_{sys.discharge}|}{|Q_{sys.charge}| + |Q_{sys.aux}|} \qquad \text{Eq. 1}$$

where:

- $Q_{sys.discharge}$: Heat delivered to the heat sink(s) during discharging [J] or [kWh].
- $Q_{sys.charge}$: Heat absorbed from the heat source(s) during charging [J] or [kWh].
- $Q_{sys.aux}$: Heat from the system components [J] or [kWh].
- $\varepsilon_{sys.xt}$: System storage efficiency at a certain time period *x*, indicate units according to type of TES [%]:
    - Short term → hours [h]
    - Mid-term → days [d]
    - Long term → month [m]

The efficiency must not be calculated for the first charging-discharging cycle of the TES system (during commissioning). This is because at the beginning, the system undergoes a homogenization process that might affect the storage capacity. Therefore, the efficiency must only be calculated for nominal operating conditions.

Presentation: The efficiency must refer to the storage period between the charge and the discharge as follows:

$\varepsilon_{sys.xt} = Y$

where *Y* is the value obtained from Eq.1, 'x' is the storage period between the charge and the discharge, and 't' is the corresponding unit of time.

This parameter basically denotes the suitability of the insulation of the TES system, the waiting period between the charging and discharging processes, and to a lesser extent, the heat transfer rates during the discharging process.

Units: non-dimensional parameter.

d. Auxiliary energy ratio (Aux_{sys})

Definition: The auxiliary energy ratio (Aux_{sys}) expresses the ratio between the amount of auxiliary energy that is consumed during both charging and discharging and the amount of thermal energy released during discharging as shown in Eq. 2. The auxiliary energy (E_{aux}) is considered to be all the energy consumed by the components of the system that is not provided by the heat sources (i.e. electricity, gas, fuel, …). The auxiliary energy consumed by the system must be accounted for in all the phases of the cycle: standby, charge, storage, discharge.

$$Aux_{sys} = \frac{\sum E_{aux.sys}}{\left|Q_{sys.discharge}\right|} \qquad \text{Eq. 2}$$

where:

- $Q_{sys.discharge}$: Heat delivered during discharging [J_{th}] or [kWh_{th}].
- E_{aux}: Energy consumed by all the components of the system during the standby, charging, storage and discharging phases (full cycle of the TES system) [J].
- Aux_{sys}: Performance ratio [$J \cdot J_{th}^{-1}$] or [$kWh \cdot kWh_{th}^{-1}$].

Presentation: The auxiliary energy ratio should be accompanied by the share of each type of $E_{aux.sys}$, presenting the results as follows:

$Aux_{sys} = X$

where *X* is the value obtained from Eq. 2.

Units: non-dimensional parameter.

e. Energy storage capacity (ESC_{sys})

Definition: The energy storage capacity of the system (ESC_{sys}) calculates the total amount of heat that can be absorbed during charging under nominal conditions. The energy is mainly stored in the material; however, some set-ups may contain components in contact with the material, which inevitably heat up, hence storing sensible heat. Therefore, the ESC_{sys} takes into account the heat stored in the material and the heat stored in the components of the system.

While the components store heat, it is also true that the temperatures of the components in contact with the TES material might be difficult to determine, or might present temperature gradients. The key point for taking into account the storage capacity of a component is that its heat can be recovered and delivered during discharging. Therefore, the guidelines for determining which components must be taken into account are presented below:

- In case of TES in which the reaction pair is stored at ambient temperatures, such as long-term chemical and sorption TES, the components do not contribute to the energy storage capacity of the system.
- In all other cases:
    - If the material is not always stored in the same vessel, but moved from one vessel to another during charging/discharging, the components do not contribute to the energy storage capacity of the system (i.e. two tank molten salt storage).
    - If the material is always kept in the same vessel:
        - Consider components in direct contact, partially or totally immersed in the material.
        - Consider if the heat stored in the components can be recovered during discharging.
        - Consider if the temperature of the component might be at the same temperature of the material during storage intervals.
        - Disregard components placed between the material and the environment (i.e. vessel).
        - Consider components placed between the material and the heat transfer fluid for discharging (i.e. immersed heat exchangers).
        - Consider components completely immersed in the material despite not being directly in contact with it.

Once the list of components to take into account is ready, the ESC_{sys} is calculated with the following equation, which depends on the type of TES technology as it is explained below.

$$ESC_{sys} = ESC_{mat} + ESC_{comp} \qquad \text{Eq. 3}$$

where:

- ESC_{sys}: System energy storage capacity [J] or [kWh]
- ESC_{mat}: Storage material energy storage capacity [J] or [kWh]
- ESC_{sys}: Sum of components energy storage capacity [J] or [kWh]

The storage material energy storage capacity (ESC_{mat}) is calculated according to the type of TES technology:

i. ESC_{mat} for sensible heat TES

$$ESC_{mat.sens} = m_{mat} \cdot c_{p.mat} \cdot \Delta T_{sys} \qquad \text{Eq. 4}$$

where:

- $c_{p.mat}$: Specific heat of the material [$J \cdot kg^{-1} \cdot K^{-1}$].
- $m_{material}$: mass of the storage material [kg].
- ΔTsys: Design temperature difference of the system [K]. Obtained by the difference between the maximum and minimum uniform temperatures at which the material will be kept in the charged and discharged states.

ii. ESC$_{mat}$ for latent heat TES

$$ESC_{mat.lat} = \left(c_{p.mat.s} \cdot \Delta T_s + \Delta H_{pc} + c_{p.mat.l} \cdot \Delta T_l\right) \cdot m_{mat} \qquad \text{Eq. 5}$$

where:

- $c_{p.mat.s}$: Specific heat of the material in solid phase [$J \cdot kg^{-1} \cdot K^{-1}$].
- ΔT_s: Temperature difference of the material in the solid phase [K]. Difference measured between the minimum design temperature of the system and the minimum temperature of the phase change range.
- ΔH_{pc}: Enthalpy of phase change [$J \cdot kg^{-1}$]
- $c_{p.mat.l}$: Specific heat of the material in liquid phase [$J \cdot kg^{-1} \cdot K^{-1}$].
- ΔT_s: Temperature difference of the material in the solid phase [K]. Difference measured between the maximum design temperature of the system and the maximum temperature of the phase change range.
- $m_{material}$: mass of the material [kg].

iii. ESC$_{mat}$ for TES based on sorption and chemical reactions (thermochemical)

The energy storage capacity of TCM materials can be either calculated for short term storage systems according to Eq. 6, or without considering the sensible heat energy storage for long term storages kept at ambient temperature according to Eq. 7.

$$ESC_{mat.TCM} = \left(\frac{|\Delta H^0_{n\to m}| \cdot (n-m)}{M_n} \cdot (1-w) + c_{p.mat} \cdot \Delta T_{sys}\right) \cdot m_{mat} \qquad \text{Eq. 6}$$

$$ESC_{mat.TCM} = \frac{|\Delta H^0_{n\to m}| \cdot (n-m)}{M_n} \cdot (1-w) \cdot m_{mat} \qquad \text{Eq. 7}$$

where:

- $|\Delta H^0_{n\to m}|$: reaction enthalpy [$J \cdot mol^{-1}$]
- n: Hydration state of the highest hydrate.
- m: Hydration state of the lower hydrate.
- M_n: Molar mass of the highest hydrate [$kg \cdot mol^{-1}$]
- $m_{material}$: mass of the material in the highest hydrate state [kg].
- w: Mass fraction of additives or matrixes.

  - $c_{p.mat}$: Specific heat of the material. An average value may be necessary [$J \cdot kg^{-1} \cdot K^{-1}$]. Consider the additives or matrixes in the material.
  - ΔT_{sys}: Design temperature difference of the system [K]. Obtained by the difference between the maximum and minimum uniform temperatures at which the material will be kept in the charged and discharged states.

On the other hand, the storage capacity of the components (ESC_{comp}) is calculated as follows:

$$ESC_{comp} = \sum_{1}^{n} \left(c_{p.comp.i} \cdot m_{comp.i}\right) \cdot \Delta T_{sys} \qquad \text{Eq. 8}$$

where:

- $c_{p.comp}$: Specific heat of the component [$J \cdot kg^{-1} \cdot K^{-1}$]. An average value of the c_p of the component is taken into account, considering the value of the main material of the component, if it is composed of different parts.
- m_{comp}: mass of the component [kg].
- $\Delta Tsys$: Design temperature difference of the system [K]. Obtained by the difference between the maximum and minimum uniform temperatures at which the material will be kept in the charged and discharged states.

Presentation: The system energy storage capacity should be presented as follows:

$ESC_{sys}= X$

where *X* is the corresponding value according to Eq. 7.

Units: Energy, [J] or [kWh].

f. Minimum cycle length ($MinCy_{sys}$)

Definition: The minimum cycle length measures the shortest period of time required for completely charging and discharging the system at nominal conditions. It does not consider any storage or standby time. It gives information about the purpose of the storage system in terms of the length of the storage cycles (short term or long term).

The charging and discharging time can either be calculated considering the energy storage capacity of the system (ESC_{sys}) and the nominal power as shown in Eq. 8, or as a sum of the two cycle times, depending on the known quantities, see Eq. 9.:

$$MinCy_{sys} = \frac{ESC_{sys}}{P_{nom.sys.charge}} + \frac{ESC_{sys}}{P_{nom.sys}} \qquad \text{Eq. 9}$$

$$MinCy_{sys} = t_{charge} + t_{discharge} \qquad \text{Eq. 10}$$

where:

- $MinCy_{sys}$: Minimum cycle length [s] / [h] / [d].
- ESC_{sys}: System energy storage capacity [J] or [Wh].
- $P_{nom.sys.charge}$: Nominal power for charging [W].
- $P_{nom.sys}$: Nominal power for discharging [W].
- t_{charge} and $t_{discharge}$: time of charging or discharging cycle [t]

Presentation: The response time should be presented as follows:

$MinCy_{sys}= X$

Units: Time, [s] / [min] / [h] / [d].

g. Partial load suitability (PL_{sys})

Definition: The partial load suitability (PL_{sys}) is a qualitative indicator that denotes the suitability of a TES system to work under partial load operating conditions. This refers to the fact that an on-going charge or discharge can be interrupted, and either to continue it later on or to switch it to the other process after a period of time.

In order to evaluate the partial load suitability, the following statements have to be checked:

i. Charging/discharging can be stopped at any point before charging/discharging are completed without negatively impacting the system.
ii. The system can switch from charging to discharging at any charging state.
iii. The system can *swiftly* switch from charging to discharging at any charging state.
iv. The system can be stably maintained in a state between the charge and the discharge states.

Depending on the number of statements the system fulfils, it is classified as follows:

- Not suitable: the system fulfils one or zero statements.
- Partially suitable: the system fulfils two or three statements.
- Suitable: the system fulfils all four statements.

1.4 Economic parameters for thermal energy storage systems

Within the framework of Annex 30, previous work on economic parameters has been applied to the cases of thermal energy storage in development. In IEA SHC Task 42 / ECES Annex 29, a tool for economic evaluation of TES systems was developed wherein procedures for both top-down and bottom-up analysis were explained [3]. In analyzing from both perspectives, maximum acceptable storage capacity costs were found from top-down and realized storage costs were determined in the bottom-up manner. The latter approach is most interesting to Annex 30, as it provides a simple calculation method for evaluating installed storage systems. In calculating the realized storage capacity costs (SCC_{real}), the investment costs INC are divided by the storage capacity ESC_{sys}:

$$SCC_{real} = \frac{INC}{ESC_{sys}} \qquad \text{Eq. 11}$$

In some cases, TES systems are designed for power optimization and do not only focus only on storage capacity. This is when the realized storage power costs (SPC_{real}) become more relevant and have thus been defined as the investment costs INC divided by the nominal power $P_{nom.sys}$.

$$SPC_{real} = \frac{INC}{P_{nom.sys}} \qquad \text{Eq. 12}$$

Different TES technologies are differentiated by their respective material costs. Some systems, such as sensible storage in natural stones or thermochemical systems with limestone, utilize inexpensive storage materials that can be easily obtained and do not require elaborate containment or safety measures. Others, including 2-tank molten salt storage and latent heat storages, employ materials that occupy a much higher share of the overall TES system cost. With that in mind, Annex 30 has also investigated the “storage material cost ratio”, that is defined as the material costs divided by the CAPEX. This has also been previously investigated in 13 cases by Rathgeber et al. [3], however in Annex 30 a wider variety of storage technologies and applications are covered.

1.5 Key performance indicators

The previous subchapters have presented methodologies for a process analysis and definitions for the system boundary and technical parameters of thermal energy storage. The next step is to look at the benefits delivered by the integration of a TES system to the overall application. The effect of this integration is best characterized by looking at the performance of a TES system. An isolated system cannot be evaluated in terms of its performance, as it is still a process unit with a purpose that is unclear – there are not yet any requirements to fulfil. Once it is integrated in an application, its performance in terms of meeting the process requirements can be assessed. The critical point is that evaluation of storage performance is entirely dependent on the application into which it is being integrated. A detailed understanding of the process requirements and higher-level outcomes is required to identify performance indicators. Fig. 1.6 shows the procedure for identification of key performance indicators that will be described in the following subchapters.

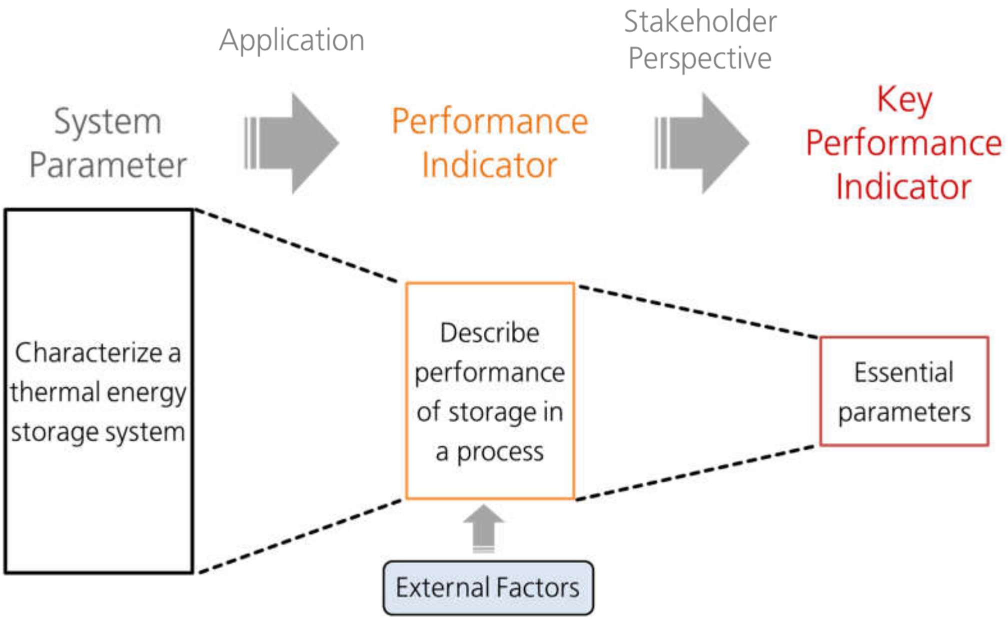


Fig. 1.6. The KPI funnel showing the transition from system parameter to KPI.

a. Performance indicators

Performance indicators can be derived directly from the process requirements. For example, a particular process may require a response time or a minimum power to be delivered from the TES system. These characteristics directly serve the process needs and define whether or not the storage system is suitable for the chosen application.

Nevertheless, the impact that a TES system may have on an application does not necessarily emerge from only the technical and economic parameters. As such, the definition also considers external factors that arise from outside the TES system, for which an understanding of the broader effects of the storage integration are necessary. This consideration could range from

- qualitative, process-specific factors such as process flexibility and energy efficiency to
- factors relevant to the local energy system, such as dispatchability or grid flexibility.

Further prospects for the category of external factors include a reduction in greenhouse gas emissions and renewable energy utilization, both of which are generally favorable from a policy-maker perspective. External factors are the overarching impacts of TES integration to the process and overall energy system that are not directly connected to storage system parameters.

b. Stakeholder perspective and key performance indicators

Performance of a technology can be defined by its ability to satisfy a specific need, however, the performance indicators are prioritized differently depending on the viewpoints of parties interested in the integration of the TES system. The final step in determining the key performance indicators is thus an analysis from various stakeholder perspectives. By introducing the concept of a stakeholder, it becomes possible to determine the most relevant performance indicators. The stakeholders selection process identifies the interests with the most potential to influence the integration or operation of the integrated TES system. They are the parties with the most invested in the integration. With these KPI identified, a stakeholder-based assessment can establish the benefits a specific TES system brings to an application.

The transition from system parameter to performance indicator to key performance indicator tightens the perspective from step to step, as shown in the KPI funnel in Fig. 1.6. At each step of the evaluation, a unique assessment of the TES system occurs. It follows that a KPI for technology assessment of TES is an internal (i.e. TES system-related parameters) or external (e.g. process benefits) property that demonstrates its ability to meet needs defined by stakeholders. With such a framework for KPI identification created, it is possible to assess the integration of TES systems from an extensive selection of perspectives to form a comprehensive and dynamic view on the integration of the technology.

c. Example of KPI methodology with Concentrating Solar Power

This methodology has been applied to a series of application cases in Chapters 2 - 6. However, for a clear explanation, it will be used in an example case on Concentrating Solar Power. To begin, system parameters (technical and economic) need to be identified. As described, there are a wide range of potential system parameters, so the left-hand side of Fig. 1.7 begins by showing an example selection, sourced from literature and the technical parameters defined in the previous subchapter.

The performance indicators are determined through the process requirements. As described in Gibb et al. [1], the most relevant system parameters in a CSP plant integration are ESC_{sys}, P_{nom}, TES Lifetime and $ReTi_{sys}$. Located below these in the middle box are the five most common benefits delivered by integrating storages into CSP plants, designated as external factors [1].

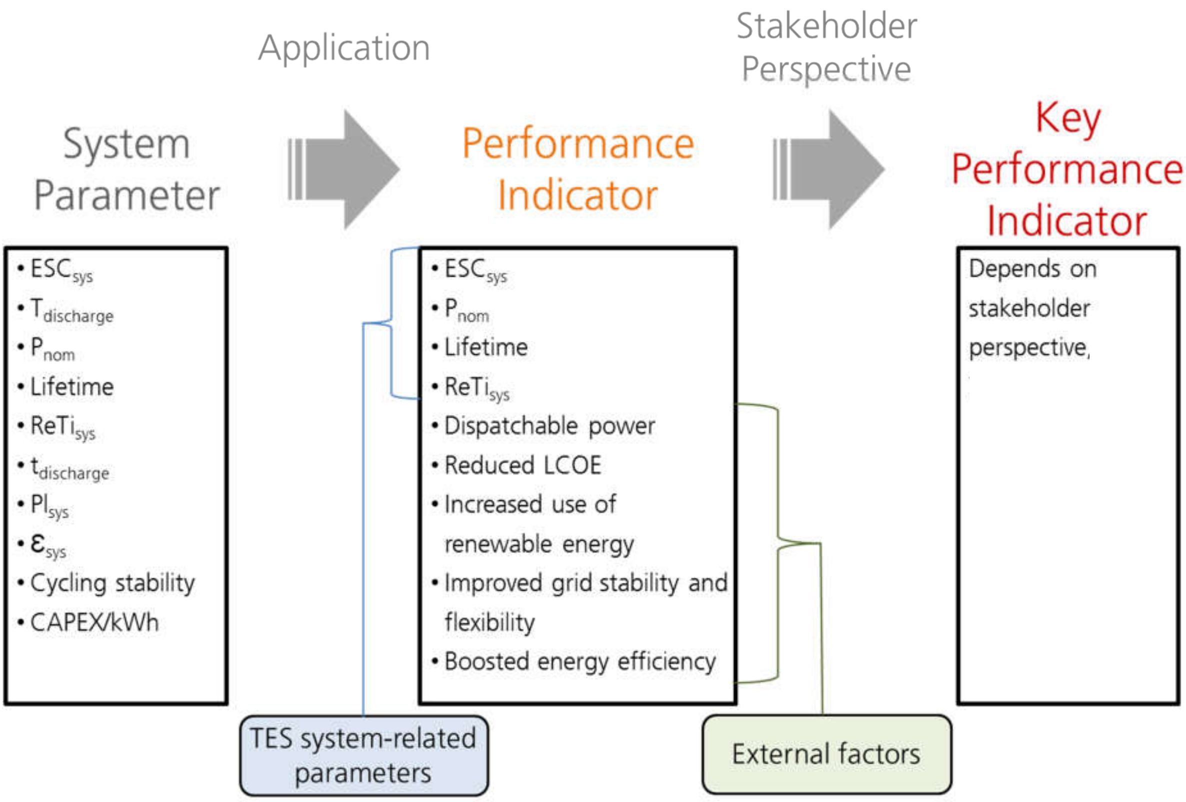


Fig. 1.7. System parameters and performance indicators in CSP.

Final determination of the KPI requires the selection of three main stakeholders, which is also based on Gibb et al [1]. The performance indicators are assigned to stakeholders in order to clarify their importance to the integration. This also highlights the main differences between various stakeholder perspectives and how these divergences in opinion can characterize the integration of a TES system. The results of this analysis are shown in Table 1.3. It is important to note that it is possible for multiple stakeholders to prioritize many of the same performance indicators. While this was not the result in this specific case, it can be observed in the upcoming chapters.

Table 1.3. KPI selection per stakeholder for integration of TES into a CSP plant.

KEY PERFORMANCE INDICATORS			
Stakeholder:	**CSP plant operator**	**Electric utility**	**Policy-maker**
KPI 1:	Storage capacity	Dispatchable power	CO_2 mitigation
KPI 2:	Power	Response time	Increased use of renewable energy
KPI 3:	Lifetime		Grid stability
KPI 4:	Reduced LCOE		
KPI 5:	Boosted energy efficiency (process)		

2 District heating

The following chapter examines the district heating application and its association to TES systems. Context is first given by a sectoral overview of district heating that describes the district heating process, followed by a look at the different types of TES systems that are used in this application. Detailed evaluations of TES benchmarks in district heating are then presented, one of which uses the complete methodology from Chapter 1. Thereafter, two cases in development are described and evaluated with the methodology. The chapter concludes with an evaluation of the district heating application based on the presented benchmarks and development cases. The contents of this chapter are shown in the table below.

Important note: the cases presented in this report should be understood as a non-exhaustive representation of each sector or technology. The goal of the Annex 30 network was to select interesting and informative cases that highlight key characteristics of thermal energy storage.

Image: © Dronninglund Fjernwarme

2.1 Benchmarks in district heating

Overview of district heating

District heating (DH) systems are used worldwide to distribute heat from one or more central heating sources to a variety of different costumer. As heating source cogeneration plants, renewable energy (geothermal, solar collectors, biomass) or waste heat are often used. Due to their specific capability to deliver heat on demand TES are often needed in DH systems. In general thermal storages can be integrated centralized or decentralized into the grid [4]. However this benchmark focuses on centralized large-scale thermal storages. DH systems use almost exclusively water as a heat transfer medium. Depending on the temperature level and design type, the storages can be pressurized. Particularly 1st and 2nd generation DH systems use steam or pressurized water as heat transfer medium whereas modern, 3rd generation DH systems (built before 1980) using hot water with a temperature level above 100°C. Future DH systems are expected to have even lower operating temperatures (< 70° C) [5,6].

Process description

DH systems consist of at least one heat source, a heat distribution network and at least one consumer. The goal is to be able to reliably supply the consumer with heat. In the case of a fluctuating heat sources, e.g. caused by a current-controlled operation of a cogeneration plant or fluctuating renewable energy, back-up systems are necessary. This could also be needed if the heat demand is fluctuating and the heat demand ca not be covered by the operating heat sources. In general the back-up systems are using fossil fuels with a lower overall efficiency.

Through the use of thermal energy storage, heat production and heat consumption can be decoupled. The heat source can be operated independently of the heat demand. Excess heat can be stored by the heat storage and used at a later time. Fluctuations on the heat demand side don’t need to be covered by heat source directly but by using the heat storage. By using thermal energy storages, DH systems are getting more flexible in terms of heat generation and consumption. On the one hand the consumption of fossil fuels of back-up systems can be reduced. On the other hand fluctuating heat sinks and sources can be integrated and used more efficiently (e.g. renewable energies).

In general the thermal energy storage is integrated directly into the network to reduce temperature losses. If the system is pressurized with high pressure the thermal storage cannot be integrated directly in general or technical devices for lowering the pressure are necessary [7].

Thermal energy storage in district heating

In general, TES systems used in DH systems are sensible heat storages. Water is used as thermal storage material in most cases except for borehole/aquifer underground storages and for pit storages with gravel or sand. Water is cheap, easy to handle and already used as heat transfer medium in DH systems. Depending on the character of the heat source, the storage can be categorized as long- (seasonal), mid- (days) or short-term (hours) storage. In addition, whether or not the storage is pressurized depends on the temperature and design of the DH system.

Depending on the application, a charging and/or discharging device to ensure a thermal stratification is needed for efficiency reasons. All district heating systems require a device for pressure maintenance (expansion and accommodation of volume changes) and in addition to the task of storing heat, storage systems are used in DH systems for this purpose.

Seasonal storages are used in general to store heat generated by solar collectors or waste heat during the summer time for covering heating demand during winter time. This means the numbers of charge and discharge cycles during a year and thus the total amount of stored thermal energy are low. For this reason an economical operation of seasonal storages must be cheap. That's why most seasonal storages are the simplest possible systems. This means large scale, non-pressurized systems (maximum temperature level below 98 °C). Common seasonal storage systems can be distinguished between tank thermal energy storage (TTES), pit thermal energy storage (PTES), borehole thermal energy storage (BTES) and aquifer thermal energy storage (ATES) shown in Fig. 2.1 [8].

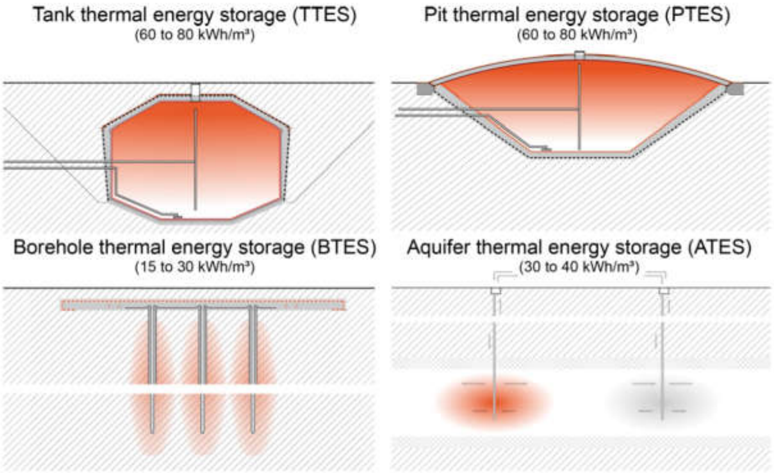


Fig. 2.1. Four seasonal sensible storage technologies [8].

In general, mid- and short-term storages are built to be used frequently (e.g. daily peak shaving, buffering nights or weekends). For this reason the numbers of charge and discharge cycles during a year and thus the total amount of stored thermal energy are higher. That's why short and mid-term storages can be realized with a smaller volume and operate pressurized if needed even if they more are expensive then seasonal storages. Unpressurized systems are usually built as above-ground flat bottom tanks (Fig. 2.2a). They combine large volumes with relatively low costs. They also can be built as two-zone storage systems for higher temperatures. Pressure vessels (Fig. 2.2b) allow much higher temperature levels and higher storage densities but often have low storage volumes, higher heat losses and investment costs. Depending on the pressure and storage capacity they are built as single or multiple vessels.

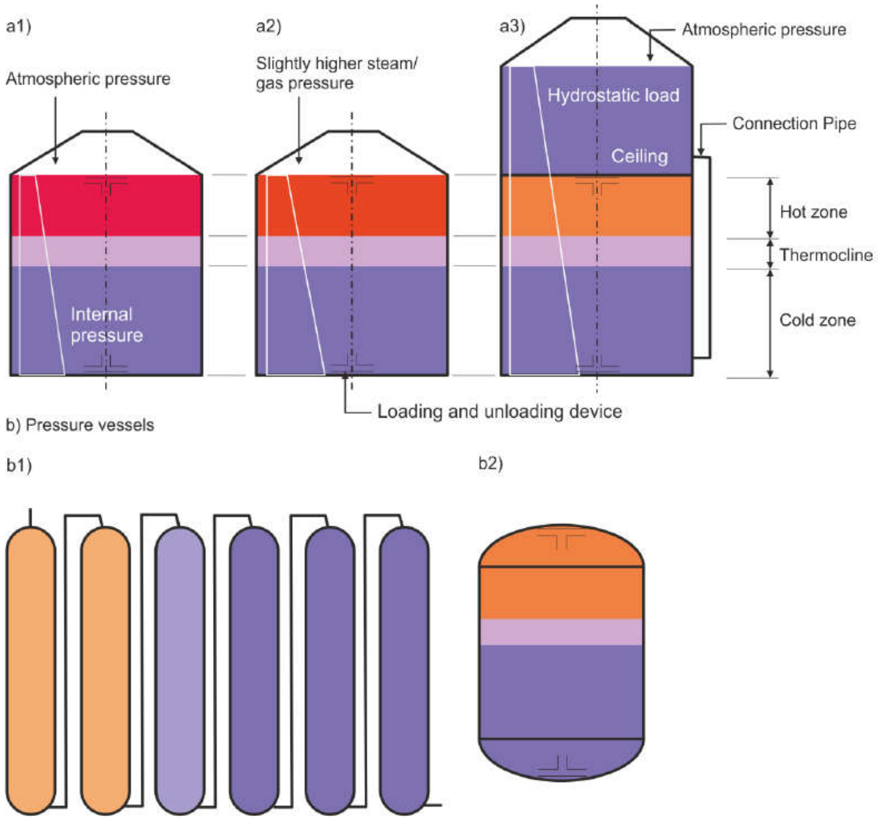


Fig. 2.2. Overview of conventional storage tank construction [7].

Over the past years, many storage systems have been built in different counties. Especially pressurized systems, two zone storage systems, above-ground flat bottom tank systems and large scale pit storage systems have been realized, especially in Germany and with examples in Austria. Mainly found in Denmark, large scale pit storage systems for seasonal storage of solar thermal energy have been installed as well.

Table 2.1. Selection of realized systems in the district heating application.

Name	**Loc.**	**Technology**	**Volume (m^3)**	**T_{low} (°C)**	**T_{high} (°C)**	**ESC_{sys} [MWh]**
Ulm	DE	Pressurized single tank	2500	70	130	140
Nuremberg	DE	Two-zone	33,000	60	113	1500
Chemnitz	DE	Two-zone	1000	40	108	40
Kiel	DE	Two-zone	42,000	60	115	1500
Ackermannbogen	DE	Non-pressurized single tank	5700	15	90	480
Leipzig	DE	Pressurized multi-tank	3000	N/A	140	225
Theiß	AT	Non-pressurized single tank	50,000	60	98	2000
Vienna, Simmering	AT	Pressurized two-tank	11,200	60	150	830
Turin, Marinetto	IT	Pressurized multi-tank	5000	N/A	120	N/A
Vojens	DK	Pit storage	200,000	N/A	80	N/A
Marstal	DK	Pit storage	75,000	10	85	6510
Dronninglund	DK	Pit storage	60,000	10	85	5400
Gram	DK	Pit storage	122,000	10	85	10,600

Dronninglund district heating system with pit thermal energy storage

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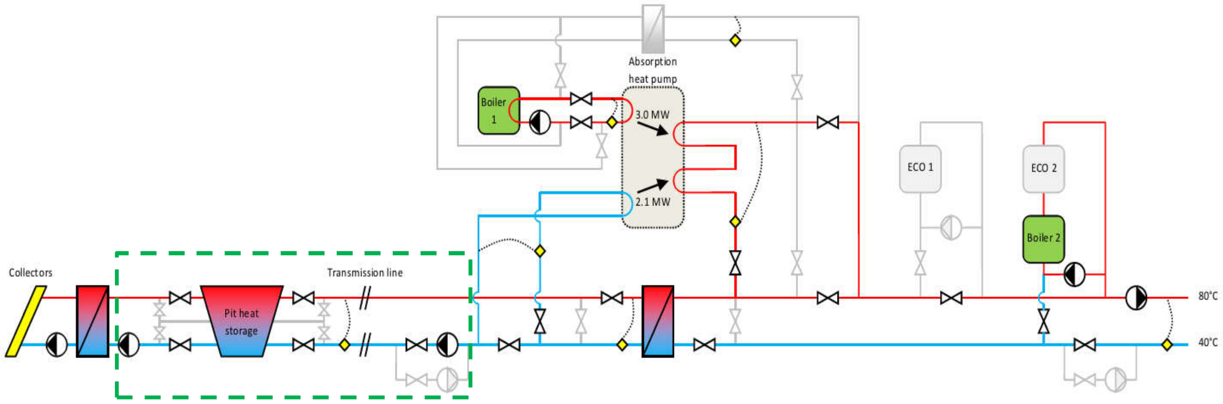

Fig. 2.3. Pit storage in combination with solar panels, heat pump and natural gas burner. The system boundary of the pit storage is shown in green.

Process Description

The objective of SUNSTORE is to optimize, design and implement a full scale demonstration plant with 35,000 m^2 solar thermal collectors, 60,000 m^3 pit heat storage and a heat pump that utilizes the storage as heat source for district heating. The commercial objectives for using a pit storage are to deliver heat at 50 €/MWh and keep the costs for the storage below 35 €/m^3. The storage and the large solar collector field has been designed from greenfield to run together and one will not function without the other.

Thermal Energy Storage System Description

The pit storage is built in a former open-pit gravel mine. The pit is designed like a upside-down pyramid. The walls of the pit storage is covered by sand with a welded HDPE-liner on top to seal the pit storage so the water does not sink into the ground. The in- and outlet pipes come into the storage through the bottom. The pipes ends at different heights (3 levels) which enables charging and discharging between the different layers depending on the conditions at the present time. The lid of the pit

Fig. 2.4. Pit storage with floating cover.

storage is a floating cover based on flexible insulation mats made of closed cell PE. Between the insulation and the top liner is a ventilation gap to be able to ventilate away water vapor in the cover. Along the edges of the storage the top liner is welded to the floating liner.

The storage operates as a seasonal storage and charges when there is a surplus of heat available from the solar panels. Discharging occurs when the demand exceeds the production from the solar panels, typically during night and the colder months of the year. See Fig. 2.4 for three years data of charging, discharging and energy content. Key technical parameters for the TES in Dronninglund for a 3 year period starting at the day in was taken into use is shown in Table 2.2. The difference in performance for the first three years and 2016 can be found in the fact that the facility takes 1-2 years of operation before it is running as dimensioned. This is due to heating of the gravel/dirt in the walls.

Table 2.2. Key figures for the pit storage during the first three years of operation .

Period	2016	2014 – 2016
Storage efficiency	81%	80%
No. of storage cycles	1.9	6.0
T-max/T-min	87 / 12°C	89 / 12°C
Heat capacity	5,200 MWh	5,400 MWh

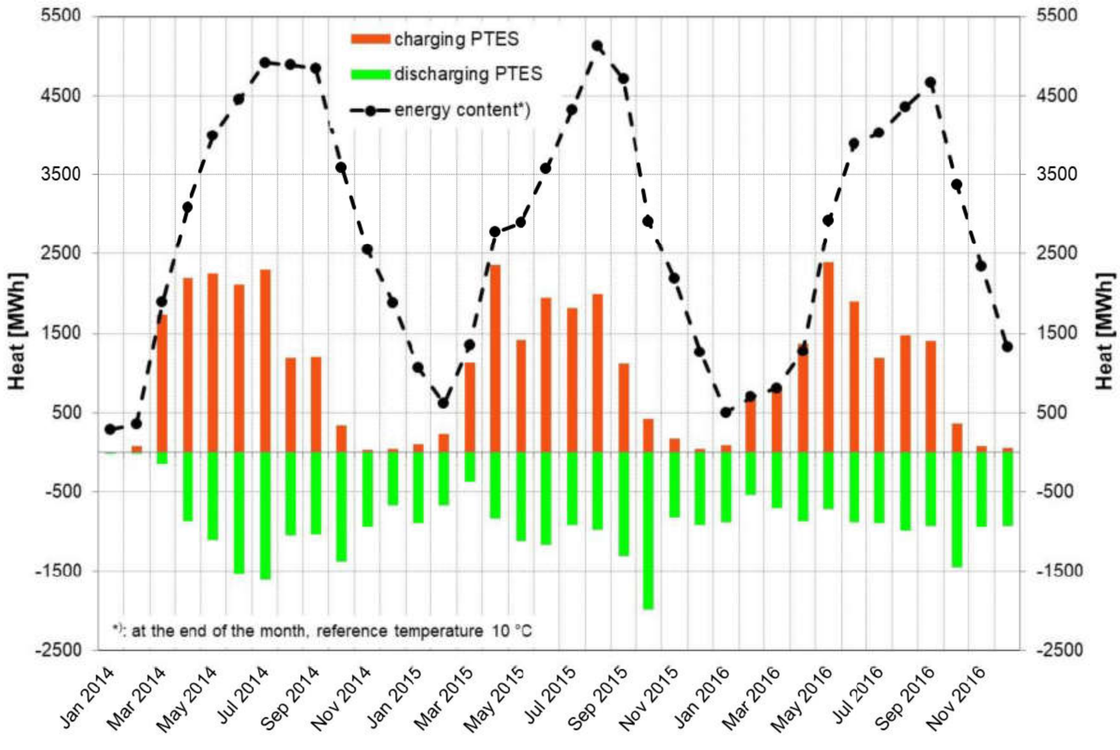

Fig. 2.5. Three years of operation showing the charging, discharging and total energy stored.

References

[9-11]

PROCESS DESCRIPTION

Analyzed process	Dronninglund district heating system consisting of natural gas boilers, natural gas cogeneration and absorption heat pump
Integration goal	Increased use of solar thermal heat to cover 50% of yearly district heating consumption
Thermal source(s)	Solar thermal unit
Thermal sink(s)	District heating network
Heat transfer fluid	Water mixtures
Cycle frequency	1-2 per year
Temperature range (°C)	T_{min} = 12 and T_{max} = 89

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION

Type of storage system		Sensible
Technology readiness level		9
Storage capacity	MWh	5400 (T_max = 89 and T_min =12)
Nominal power	MW	27 (maximum charge/discharge)
Response time of TES	minutes	3
Storage efficiency	%	0.81
Minimum cycle length of TES		17 days
Partial load suitability		Suitable
CAPEX per capacity	€/kWh	0.43
CAPEX per nominal power	€/kW	86
Storage material cost per CAPEX	%	7

KEY PERFORMANCE INDICATORS

Stakeholder:	**DH company**	**Consumer (end-user)**	**Policy maker**
KPI 1:	Max/min temperature	Life time	….. Cost of heat and fixed cost
KPI 2:	Power - Charging/ discharging	….. Cost of heat and fixed cost	
KPI 3:	Storage capacity		
KPI 4:	CAPEX / kWh		
KPI 5:	OPEX / kWh		

Pressurized hot water storage in Ulm, Germany

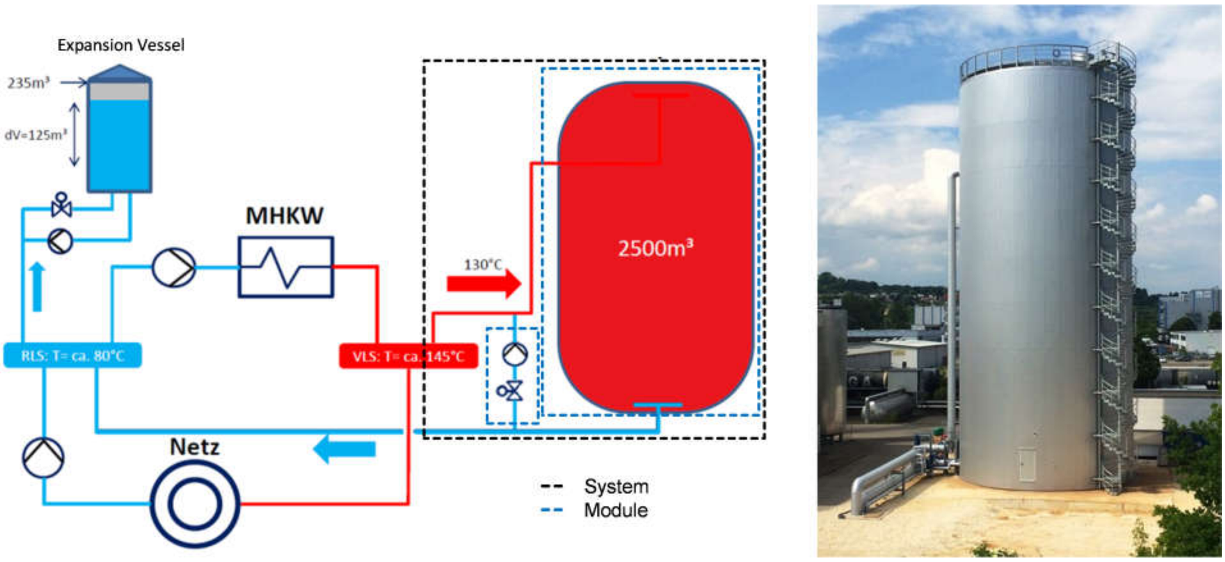

Fig. 2.6. Integration of sensible TES system into the district heating system located in Ulm, Germany [12].

PROCESS DESCRIPTION	
Analyzed process	District heating system
Integration goal	Saving backup energy costs, improving current-oriented operation of the MVA, improving participation in the balancing energy market.
Thermal source(s)	Heat from waste incineration plant (MVA)
Thermal sink(s)	Costumer district heating system (industrial and residential area)
Heat transfer fluid	Water
Cycle frequency	Once per day
Temperature range (°C)	70 - 130

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Sensible
Technology readiness level		TRL 8-9
Storage capacity	MWh	140 (2500 m³)
Nominal power discharging	MW	28
Response time of TES	minutes	N/A
Storage efficiency	%	N/A
CAPEX per capacity	€/kWh	21.4
CAPEX per nominal power	€/kW	107
Storage material cost per CAPEX	%	N/A

Non-pressurized hot water storage in Potsdam, Germany

Fig. 2.7. Thermal energy storage district heating system Potsdam, Germany [13].

PROCESS DESCRIPTION	
Analyzed process	District heating system, Non-Pressurized single vessel TES
Integration goal	Increasing flexibility of cogeneration plant, enables shut down of the cogeneration plant during weak load periods (e.g. weekend in summer), back-up system
Thermal source(s)	Heat cogeneration plant, excess renewable electricity
Thermal sink(s)	District heating system
Heat transfer fluid	Water
Cycle frequency	N/A
Temperature range (°C)	70 - 98

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Sensible
Technology readiness level		TRL 8-9
Storage capacity	MWh	1200 (41,000 m^3)
Nominal power discharging	MW	20
Response time of TES	minutes	N/A
Storage efficiency	%	N/A
CAPEX per capacity	€/kWh	9.7
CAPEX per nominal power	€/kW	580

References

[13,14]

Seasonal hot water storage at Ackermannbogen in Germany

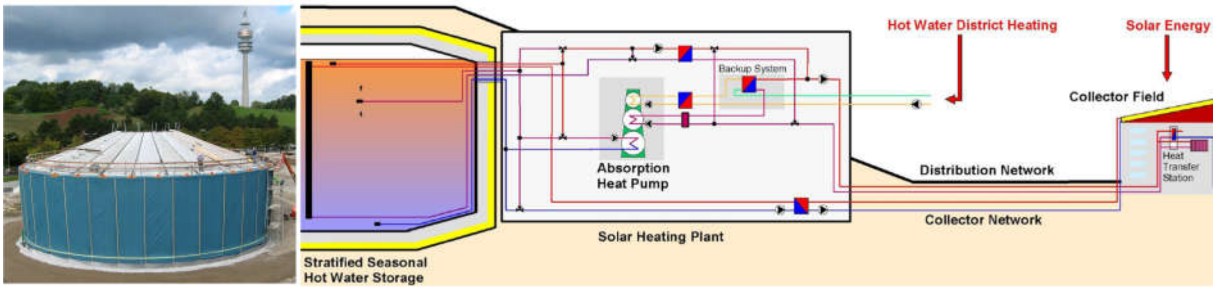

Fig. 2.8. District heating system Ackermannbogen in Munich, Germany.

PROCESS DESCRIPTION	
Analyzed process	District heating system/Absorption heat pump
Integration goal	Seasonal solar energy storage
Thermal source(s)	Solar thermal collectors
Thermal sink(s)	Customer district heating system (residential area)
Heat transfer fluid	Water
Cycle frequency	1-2 per year
Temperature range (°C)	15 - 90

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Sensible
Technology readiness level		TRL 7-8
Storage capacity	MWh	480 (6000 m³)
Nominal power discharging	MW	2
Response time of TES	minutes	N/A
Storage efficiency	%	81
CAPEX per capacity	€/kWh	1.8
CAPEX per nominal power	€/kW	428
Storage material cost per CAPEX	%	N/A

2.2 TES systems in development

Flat-bottomed water tank with floating ceiling for district heating

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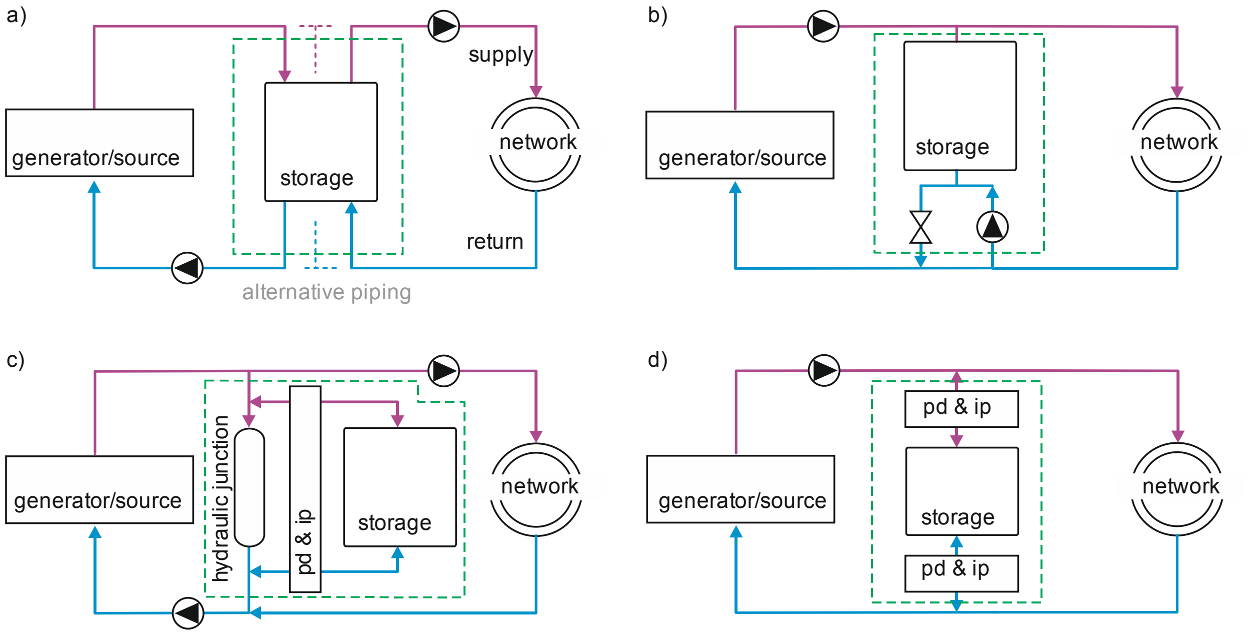

Fig. 2.9. Hydraulic integration of storages in district heating systems (system boundary in green).

<u>Process Description</u>

District heating with integrated TES systems has two main purposes: (i) decoupling of power and load in the network and (ii) system services, including pressurization, back-feeding etc. The benefits of TES integration are manifold and can be categorized into multiple groups:

Energetically, there is an increase of efficiency and utilization of the network. This is achieved by avoiding constant shutting down and restarting of generator units, increasing the running time of generator units and functioning at optimal operating points.

Operationally, TES integration allows for a better integration of renewable energy sources (solar thermal, biomass, geothermal, power-to-heat, etc.) and conventional energy sources such as cogeneration power plants. Also seen is an stabilization of system behavior, greater flexibility regarding merit order, network security and introduction of new products for the electricity market (regulation and balancing energy etc.).

Economically, the networks can take advantage of avoiding startup costs or high operating costs, lowering the fuel input, facilitating CHP operation according to electricity price, increasing technical lifetime and avoiding investment costs. In ecological terms, TES integrated in DHC leads to a reduction in greenhouse gas emissions, integration of renewable energy sources and improvement of the primary energy factor.

Thermal Energy Storage System Description

In TES for DHC, thermal stratification inside the storage is achieved by separating water with different temperatures through buoyancy. In a storage tank operating according to the displacement principle, a water exchange takes place by direct charging and discharging. Flat-bottomed tanks combine large volumes with relatively low costs, but a second zone (i.e. a higher fill level) is required and low-pressure steam or a protective gas in the attic is mandatory. This leads to higher heat losses, unfavorable thermal stratification and operation conditions, plus unused storage volume. A new storage design eliminates these disadvantages and a demo plant was built in cooperation with industrial partners as part of the OBSERW project.

The main novelty of the construction is an indoor, protected floating ceiling, with the upper loading device (e. g. a radial diffuser) attached directly to it. During charging of the tank a gravity current can occur directly at the ceiling and when discharging, hot water is sucked straight along the ceiling, which allows the full use of the warm zone. The aim is to operate the storage with a maximum temperature of 98 °C. A flexible sealing and the pressure compensation pipe ensure volume and pressure compensation in both storage and attic. The floating ceiling avoids a gas input into the storage water and thus avoids corrosion in the system. For the construction of the ceiling, bolted and sealed segments are provided which can be easily filled with a blow-in thermal insulation material. Compared to other constructions, the thermal insulation is located directly on the hot zone. Since the attic can be equipped with ventilation, drying is possible if humidification occurs (e.g. temperature falls below dew point in winter).

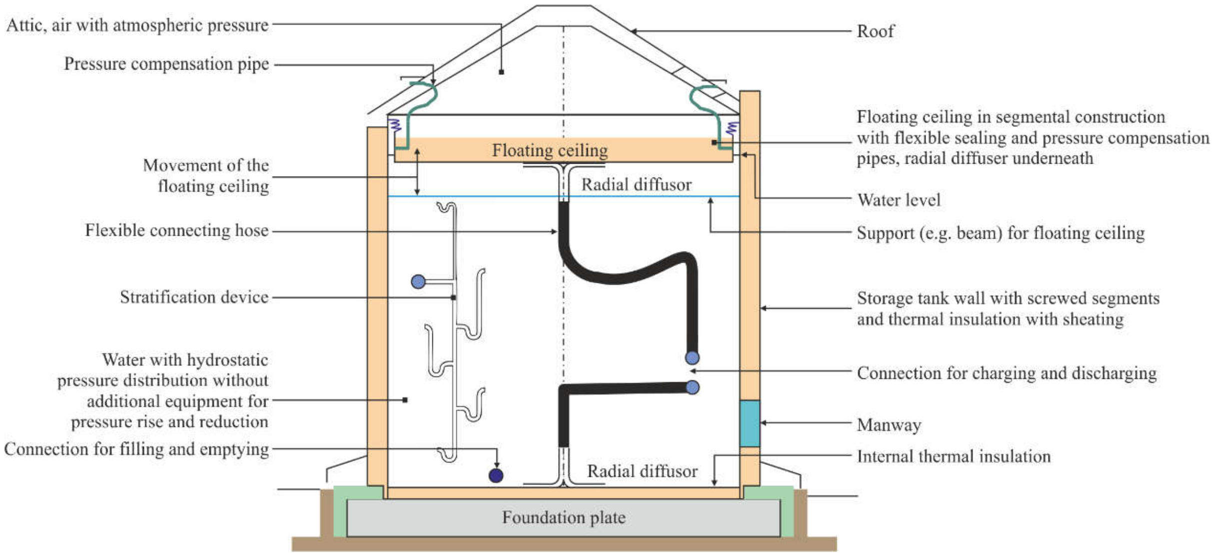

Fig. 2.10. Overground thermal energy storage with floating ceiling and directly mounted radial diffuser [5].

References

[15-17]

PROCESS DESCRIPTION	
Analyzed process	District heating systems
Integration goal	Increase efficiency and flexibility, increase the fraction off renewable energy
Thermal source(s)	Waste heat
Thermal sink(s)	District heating network
Heat transfer fluid	Water
Cycle frequency	Once per day
Temperature range (°C)	< 98 °C

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Sensible
Technology readiness level		TRL 4 - 6
Storage capacity	kWh	< 336,000 (6000 m^3)
Nominal power	kW	56,000
Response time of TES	minutes	2
Storage efficiency	%	99
Minimum cycle length of TES	min	30
Partial load suitability		suitable
SCC_{real}	€/kWh	6.4
SPC_{real}	€/kW	38.6
Storage material cost per CAPEX	%	<1%

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Power plant**	**Network operator**	**Government**
KPI 1:	Storage capacity	Storage capacity	CO_2 mitigation
KPI 2:	Nominal power	Nominal power	Increased use of RE
KPI 3:	Response time	Response time	Network stability
KPI 4:	Lifetime	Lifetime	
KPI 5:		CO_2 mitigation	
KPI 6:		Increased use of RE	
KPI 7:		Network stability	

Phase change material for load management in district heating

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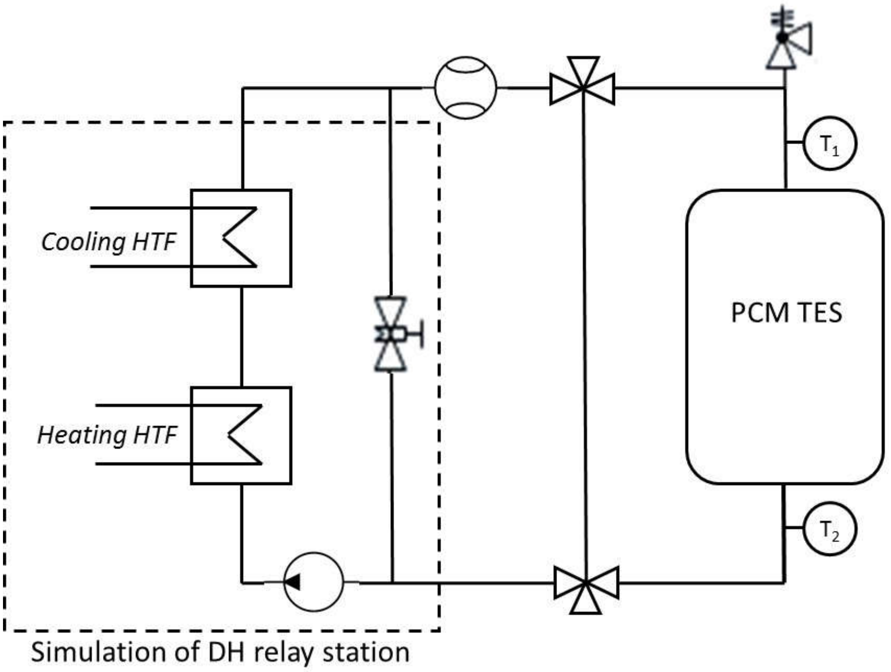

Fig. 2.1. TES System based on Phase Change Materials (PCM) devoted to district heating network.

Process Description

District heating systems distribute heat generated in a centralized location to multiple different users via pipe networks. The heat transfer fluid is water which is heated to temperatures depending on the application (between 35 and 210 °C for liquid water). A substation (or relay station) allows each user to retrieve heat with a heat exchanger. Then the water returns again to the heating plant. In order to optimize the running of these systems and to use heat from renewable technology, heat storage is a highly efficient option and can be integrated into fluctuating systems.

The heat demand can vary widely and heat storage can reduce the use of back-up heating systems to ensure the supply of heat demand. On the other hand, the integration of heat storage system allows the operator to optimize the operation of heating plant. The TES system stores surplus heat produced during off-peak periods to use it during peak periods when the demand exceeds heat production by the heating plant. This process has been designed to respond to the energy demands of various industrial processes and therefore district heating systems. The test bench is mainly composed of a storage unit which is a cylindrical tank filled with Phase Change Materials and a temperature controller used to simulate the operations. The heat transfer fluid is water which can be pressurized. The heating network is simulated via an 18 kW heating and cooling device which can heat water up to 180 °C.

Thermal Energy Storage System Description

The prototype has been designed to respond to the demands of various industrial processes and therefore district heating systems. The UPPA TES system is composed of a 0.1 m^3 tank filled with encapsulated phase change materials (PCM) (Figure 2). The tank is made of stainless steel surrounded by insulating material (0.05 m width mineral wool) and covered by aluminum sheets. This tank contains 122 spherical polyolefin capsules (diameter of 0.097 m) in which the PCM is confined. The tank is crossed by the heat transfer fluid carrying out heat exchange. These spherical capsules called nodules cannot support more than 100 °C and are exclusively reserved for the low temperature range. During storage, the nodules are heated by the hot heat transfer fluid ensuring the melting of the PCM. The heat is thus stored for later use. During the discharge mode, the heat transfer fluid cools the nodules and the heat is recovered during the PCM crystallization. Several PCMs can be used depending on application temperature level.

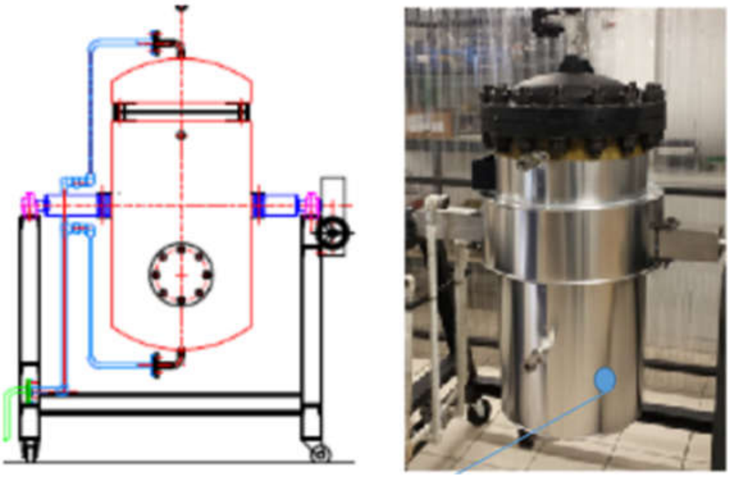

Fig. 2.2. Tank filled with encapsulated PCMs.

For example, for needs around 60-80°C, technical grade stearic acid can be used. Stearic acid storage capacity has been measured in calorimetry experiments and is equal to 200 $kJ.kg^{-1}$ for its latent part and 1.8 $kJ.kg.K^{-1}$ for its sensible part. The melting temperature is about 65°C. Compatibility between the PCM and the capsule envelop has been tested for a month at the temperature of 85°C. It highlights PCM energetic performance and polyolefin envelop mechanical behavior stability. Several charges and discharges have been done with different mass flow rates, inlet temperatures and tank positions (horizontal and vertical). Technical figures are included in the following table.

Finally, it is important to notice that this laboratory scale tested system has been replicated on a larger scale (50 kWh) in EDF research centre (Les Renardières, France).

This TES system has been designed and built within the STEEP project funded by the French National Research Agency (ANR-13-SEED-007).

References

[18]

PROCESS DESCRIPTION	
Analyzed process	District heating relay station (substation)
Integration goal	Load management for district heating
Thermal source(s)	District heating network (could come from renewable technology sources such as solar thermal plant)
Thermal sink(s)	District heating network
Heat transfer fluid	Water
Cycle frequency	Once a day
Temperature range (°C)	60 - 80°C

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Latent
Technology readiness level		4
Storage capacity	kWh	$ESC_{mat.lat}$=3.09 ESC_{comp}=1.85 ESC_{sys}= 4
Nominal power	kW	$P_{nom.sys}$ = 3.5 kW $P_{nom.sys.charge}$ = 5 kW
Response time of TES	minutes	5 minutes
Storage efficiency	%	N/A
Minimum cycle length of TES		60 minutes
Partial load suitability		Partially suitable because the charged system is subject to heat losses
CAPEX per capacity	€/kWh	N/A
CAPEX per nominal power	€/kW	N/A
Storage material cost per CAPEX	%	N/A

KEY PERFORMANCE INDICATORS			
Stakeholder:	**District heating operator**	**City council**	
KPI 1:	Storage capacity	Heat price	
KPI 2:	Power	Increased use of renewable energy	
KPI 3:	Lifetime		
KPI 4:	LCOE benefits		

2.3 Application evaluation

Thermal energy systems have seen widespread use in the district heating sector. These systems have been installed in many countries across Europe for two main purposes: a) buffer storage and b) seasonal storage. Generally, conventional designs for both storage types are at a high TRL.

Buffer storage

As a technology benchmark, the buffer storages are developed as both pressurized and non-pressurized hot water storages. In these cases the storage concepts are all sensible storage with water. Relevant technical parameters are summarized in the table on the following page.

As can be seen, the advantage of the pressurized systems is that they reach temperatures up to 180°C. Given the fact that pressurized vessels are more expensive, however, they are typically built with much smaller volumes than non-pressurized systems, as large as 50,000 m^3.

As a common application, TES systems can be used in combination with a cogeneration plant or other DH process unit to add flexibility in operation. In these cases, the thermal energy is stored at network temperatures and can be fed directly into the district heating system – here, no auxiliary heating source or heat pump is required. These buffer storages deliver a number of common benefits, including an improved performance and utilization of the CHP plant, optimized electricity market participation, fossil fuel savings (and CO_2 emissions reductions), reduced installed back-up capacity and an overall increase in stability of the DH network.

Research and development work focuses on improvements that address specific technical and economic issues (i.e. floating ceiling), but are not ultimately decisive on the affordability of the storage in many applications.

Seasonal storage

Seasonal storage of thermal energy for district heating has a number of technology options available that have seen varying levels of popularity around the world. This report has focused only on storages with water – specifically pit storage and tank storage. These technologies are similarly at a high TRL (7-9) and have been installed in Denmark and Germany. Relevant technical parameters are summarized in the following table.

Seasonal storages operate by charging at a high temperature and relying on insulation (i.e. a relatively high efficiency of 81% over the year) to discharge down to 10-15°C. In these cases, the storage is used in combination with a heat pump that operates on renewable electricity, renewable gas or heat to enable discharging the TES system to such low temperatures.

These storages are inexpensive but see large differences in stored energy and volume based on the chosen technology. Pit storages with water have an enormous storage volume, which is what makes them appropriate for seasonal storage in the first place. The seasonal storage volume of the Ackermannbogen single-tank storage is comparable to that of a mid-sized non-pressurized buffer storage. However, due to its large temperature difference, the volume-specific storage capacity (MWh/m^3) is quite high. This also explains the low costs of the seasonal tank storage (1.8 €/kWh), as the large temperature difference enables a large storage capacity within a smaller tank design.

Seasonal storage has the benefit of enabling a higher share of renewables when the storage is charged during the warmer months. In regions with high natural gas prices, this is accompanied by an overall lower cost of heat for the district heating network.

Table 2.1. Non-exhaustive selection of relevant system parameters for storage in district heating applications.

	Buffer storage		**Seasonal storage**	
	Pressurized	**Non-pressurized**	**Pit storage**	**Tank storage**
T_{min} (°C)	60 – 70	60 – 70	10 – 12	15
T_{max} (°C)	140 – 180	98	80 – 90	90
Volume (m^3)	1000 – 6000	1000 – 50,000	60,000 – 200,000	6000
ESC_{sys}	Up to 850 MWh	Up to 2 GWh	5 – 15 GWh	ca. 500 MWh
SCC_{real} (€/kWh)	20 – 25	6 – 20	as low as 0.4	1.8
Cycle frequency	1/day to 1/week		1-2/year	1-2/year
Efficiency	99%		< 81%	81%

Table 2.2. Key performance indicators for district heating.

Stakeholder:	**District heating company**	**Consumer or End-User**
KPI 1:	Max/min temperatures	Cost of delivered heat
KPI 2:	Storage capacity	CO_2 emissions reductions
KPI 3:	Charging/discharging power	
KPI 4:	CAPEX	
KPI 5:	Network stability	

3 Non-residential buildings

The following chapter examines the non-residential buildings application and its association to TES systems. Context is first given by a look at several benchmarks in non-residential buildings consisting of ice and snow storages. The chapter primarily consists of a presentation and evaluation of five case studies of TES development for non-residential buildings. It concludes with an evaluation of the non-residential buildings application based on the presented benchmarks and development cases. The contents of this chapter are shown in the table below.

Important note: the cases presented in this report should be understood as a non-exhaustive representation of each sector or technology. The goal of the Annex 30 network was to select interesting and informative cases that highlight key characteristics of thermal energy storage.

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3.1 Benchmarks in non-residential buildings

Ice storage in Paris, France

Fig. 3.1. Ice storage tanks (Source: www.enertherm.fr).

PROCESS DESCRIPTION		
Analyzed process	Ice storage for cold network at Paris La Défense	
Integration goal	Increase of cooling capacity of performance coefficient for cold production and better reliability of cold supply	
Thermal source(s)	Three refrigeration units with a unit capacity of 8 MW	
Thermal sink(s)	Cold network	
Heat transfer fluid	Water + glycol (charge), water (discharge)	
Cycle frequency	Once per day	
Temperature range (°C)	-7°C (charge), 4.5°C (discharge)	
THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Latent
Technology readiness level		TRL 9
Storage capacity	MWh	240
Nominal power discharging	MW	60
Storage efficiency	%	95
CAPEX per capacity	€/kWh	N/A

The business district of Paris La Défense is fed with cold from a centralized production and through a distribution network of cold water. Coupled with this production a storage system allows to modulate production and consumption, to increase the performance coefficient of refrigeration groups and to improve the reliability of the network.

Cold storage with snow at the new Chitose Airport in Hokkaido, Japan

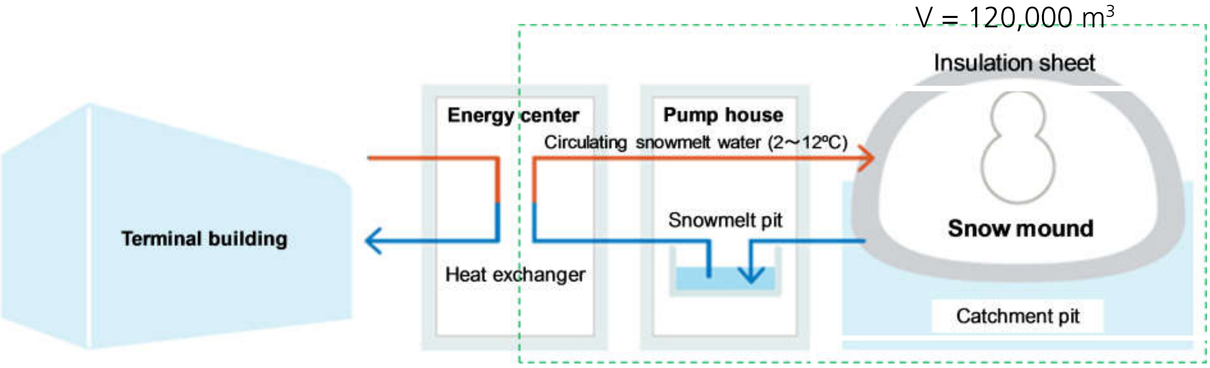

Fig 3.2. Schematic process diagram[2)]

Process description

In this process, snow accumulated at the airport during winter is used for building air conditioning as a cold source. This is a retrofit case, as one adsorption chiller (P_{nom}: 351 kW) is replaced by the snow energy supply facility. The goals of this thermal storage are two-fold:

1) To reduce fuel consumption and CO_2 emission for the air conditioning facilities of the airport terminal during summer by using snow as a cold heat source.

2) To reduce biochemical oxygen demand (BOD) that is present in the snow following de-icing of aircrafts. The snow storage acts as a buffer so the chemical evaporates during the storage period instead of melting on land or flowing into waterways.

PROCESS DESCRIPTION		
Analyzed process	Accumulated snow is stored at the airport during winter and used it for building air conditioning as cold heat source.	
Integration goal	i) reduce fuel consumption & CO_2 emissions ii) reduce BOD from de-icing fluids	
Thermal source(s)	Snow	
Thermal sink(s)	Air conditioning facilities during the summer season	
Heat transfer fluid	Snow meltwater	
Cycle frequency	Seasonal (1/year)	
Temperature range (°C)	2 – 12ºC	
THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Latent
Technology readiness level		TRL 8-9
Storage capacity	GWh	5 – 10 (120,000 m^3)
Nominal power discharging	MW	3.5 – 7.0
Storage efficiency	%	Each year is different
CAPEX per capacity	€/kWh	N/A

References
[19, 20]

Seasonal snow storage in Sundsvall, Sweden

Fig. 3.3. The seasonal snow storage system in Sundsvall (Sweden). The pump house is the white constructed block (left), and the snow pile insulated with wood chips can be seen (right) [21].

PROCESS DESCRIPTION	
Analyzed process	Seasonal cold storage using snow (for a hospital cooling system)
Integration goal	Cold storage (for a cooling system at a hospital)
Thermal source(s)	Snow (waste cold). 70 000 m^3 by 2011 [22], [23]
Thermal sink(s)	Hospital cooling loads
Heat transfer fluid	Water (i.e., from melting snow) [21]
Cycle frequency	Once/year [21]
Temperature range (°C)	2 – 8 °C (supply to return temperature range) [21]

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Latent
Technology readiness level		8-9
Storage capacity	MWh	480
Nominal power discharging	MW	3
Storage efficiency	%	N/A
CAPEX per capacity	€/kWh	3.3

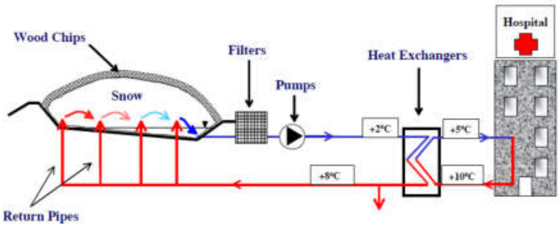

Fig. 3.4. The Sundsvall seasonal snow storage-based cooling system layout [21].

References

[21-23]

3.2 TES systems in development

PCM cold storage integration in an office building

(Working lab in Johanneberg science park)

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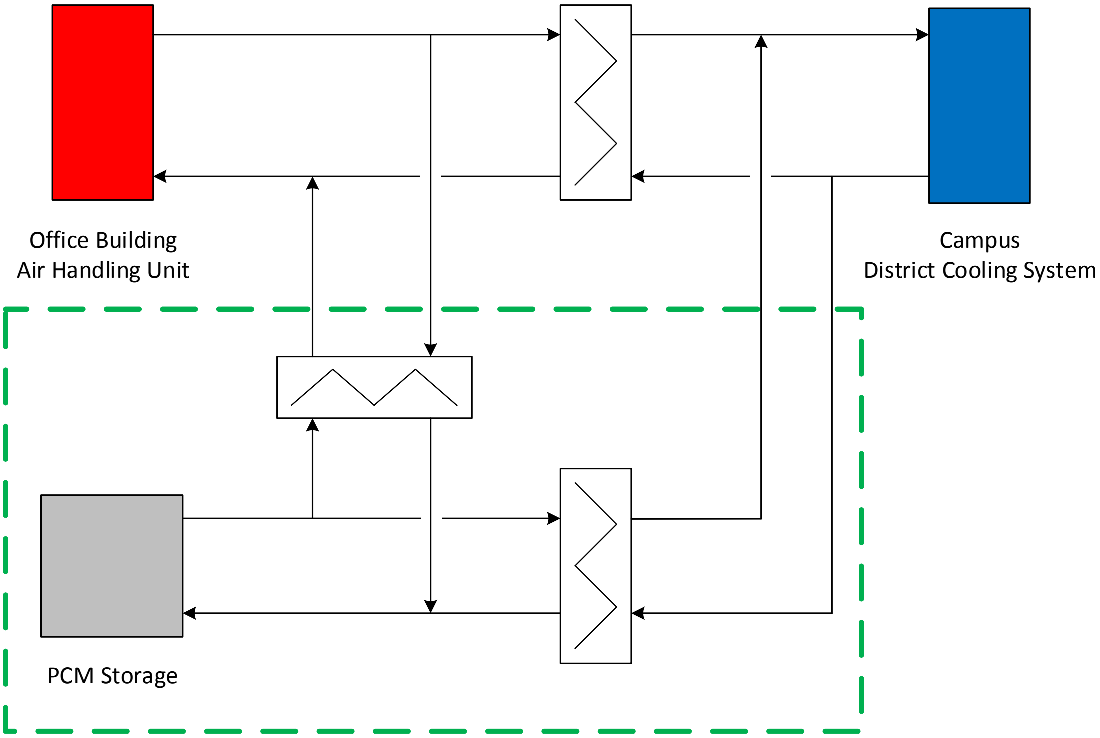

Fig. 3.5. Latent heat storage system (green boundary) integrated in the office building air handling unit process.

Process Description

Johanneberg Science Park 2 – A Working Lab; Generic process: An air handling unit (AHU) of an office building is supplied by the campus cooling system. Cold power and energy demand vary with the season and daily building occupancy. In order to shift peak cooling demand, a latent heat energy storage is charged by the campus cooling system during night and supplies the office building with additional cold energy during day time. The storage is designed to operate within the temperature limits of a pre-existing system. Operating the storage in this way enables a more economical utilization of the existing district cooling system. Due to the low operating temperature differences of the process, the utilization of the latent heat of phase change materials (PCM) allows for higher storage densities compared to sensible storage materials.

Thermal Energy Storage System Description

The storage is designed based on existing commercial ice storage technologies, but uses a PCM as a storage material. The storage consists of a tank filled with a commercial salt hydrate as PCM. A tube bundle heat exchanger made from several thousand polymer tubes is placed in the tank. Water as heat transfer fluid is circulated within the tubes to melt and solidify the surrounding PCM.

The full scale installation allows for a realistic monitoring of the storage integrated system. Research and development on this case study aims for developing design guidelines for similar storage integration cases in the future based on technical and economical benchmarking.

The full scale installation is to be accompanied by an equivalent lab scale setup at Chalmers University of Technology to study in detail the melting/solidification behavior and heat transfer as well as possible operating conditions of the storage during charging and discharging. Both the lab scale setup will be ready for operation during the autumn of 2018 and the full scale storage in 2019.

Fig. 3.6. A Working Lab office building of the Johanneberg Science Park.

References

[24, 25]

PROCESS DESCRIPTION	
Analyzed process	Air handling unit supplied with cold energy by a central cooling system.
Integration goal	Peak shaving of cold energy with a PCM storage
Thermal source(s)	Campus district cooling system
Thermal sink(s)	Air handling unit
Heat transfer fluid	Water
Cycle frequency	Once per day
Temperature range (°C)	ca. 7-18

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Latent
Technology readiness level		TRL 7 - 8 (demonstration installed in full scale)
Storage capacity	kWh	375
Nominal power	kW	75
Response time of TES	minutes	Immediate
Storage efficiency	%	N/A
Minimum cycle length of TES		ca. 13 (5 hours discharge, 8 hours charge)
Partial load suitability		Suitable
CAPEX per capacity	€/kWh	N/A
CAPEX per nominal power	€/kW	N/A
Storage material cost per CAPEX	%	N/A

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Building Owner**	**Energy Utility**	
KPI 1:	Net Economic Benefit of TES for Building Owner	Net Economic Benefit of TES for Utility	
KPI 2:	Net Environmental Benefit of TES for Building Owner	Net Environmental Benefit of TES for Utility	
KPI 3:	Increase in Process Flexibility	Increase in Process Flexibility	
KPI 4:	Reliability		
KPI 5:	Safety		

PCM storage with chilled water system at the University College of Bergen

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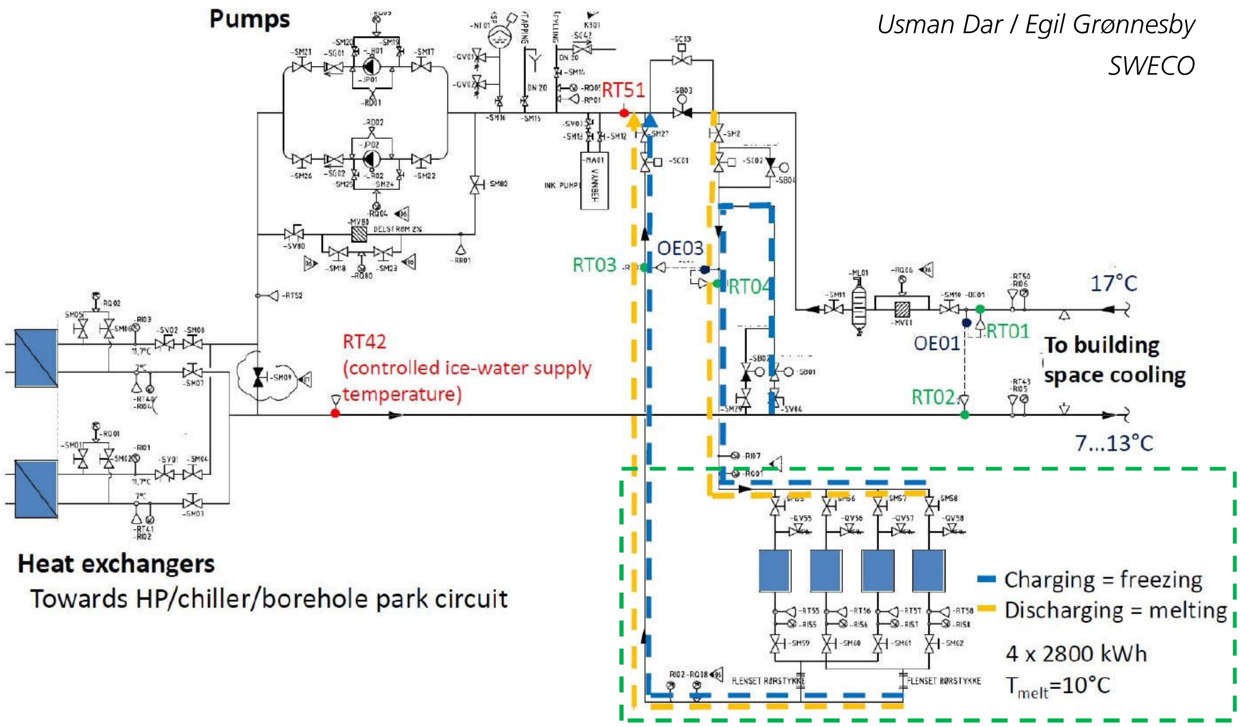

Fig. 3.7. Detailed system scheme of the chilled water distribution system at the University College Bergen. The PCM thermal energy storage system is shown by the green dotted line [27].

Process Description

The process of interest is the chilled water system installed at the University College of Bergen. The system was installed in 2014 while building the 50,000 m^2 University College, whose heating demand is ca. 2600 MWh/year and cooling demand is ca. 1060 MWh/year [27]. The peak cooling demand in daytime can reach up to 3000 kW due to solar radiation, high density of students and utilities.

The goal of the cold energy storage integration is to reduce the capacity of the heat pump/chiller unit for space cooling. The building has a low need for space cooling during the night and high cooling demand during daytime. The thermal energy storage (TES) system uses this discrepancy to store cold energy during the night and restitute it during daytime, while relying on a heat pump/chiller system much smaller than the peak load (1.4 MW for a maximum need of 3 MW). The integration of the TES component in the chilled water system is shown in Fig. 1. The main benefits of the TES integration are the higher energy efficiency for space cooling in peak demand, as well as the lower operational costs due to the reduced heat pump/chiller capacity.

Thermal Energy Storage System Description

The TES system relies on four tanks of 57 m^3 (see Fig. 3.8) filled with encapsulated PCM and uses water as heat transfer fluid. By the time of its installation, the TES system was the largest of its kind in the world. The PCM is a salt hydrate delivered by PCM Products Ltd [28] with melting temperature 10 °C and macro-encapsulated with the system FlatICE [28]. The FlatICE plastic containers have dimensions 500 mm x 250 mm x 45 mm. In total, about 51 000 FlatICE elements are stacked inside the four tanks to occupy most of the available volume. By their design, clearance is left between the small containers to ensure both the circulation of water through the stack and buffer space for thermal volume expansion. The tanks are thermally insulated inside, through the spacers keeping the FlatICE containers in position.

The operational strategy consists in cycles of 24 hours. Charging, thus cooling, the four PCM tanks occurs during night time when the cooling demand is low since the University College is not in business hours and the solar irradiance is low. During day time and especially during the 5-6 warmer months of the year, the PCM tanks are discharged to complement the cooling demand at peak times. The overall chilled water system is designed to support cooling demand peaks of up to 3 MW while using a heat pump chiller unit of 1.4 MW only. Therefore, the TES component is designed to deliver up to 1.6 MW.

The TES system must respond with available chilled water within seconds (discharge) for peak demands. When the circulation of water in the PCM tanks is low or shut, the water in the tanks may reach the lowest achievable temperature, leading to very short response time for sudden peak demands. The charge of the TES can respond within minutes and the TES can be fully charged within 12-15 hours. Shutdown times can be realized in winter time for maintenance, when sufficient cooling can be achieved only with the heat pump chiller.

Fig. 3.8. PCM tanks for cold thermal energy storage at the University College of Bergen, Norway [27].

References

[26-28]

PROCESS DESCRIPTION	
Analyzed process	Chilled water system for space cooling with cold energy storage
Integration goal	Achieve daily cold energy storage to match peak cooling demand with a very reduced size of the heat pump cooling system
Thermal source(s)	Cooling water / space cooling
Thermal sink(s)	Heat pump / chiller
Heat transfer fluid	Water
Cycle frequency	Once per day
Temperature range (°C)	4 – 18 °C

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Latent
Technology readiness level		TRL 6 - 7
Storage capacity	kWh	ESC_{sys} = 11240 kWh
Nominal power	kW	$P_{nom,sys}$ = 1600 kW (maximum demand) $P_{nom,sys,charge}$ = 1400 kW
Response time of TES	minutes	$ReTi_{sys}$ < 1 min when system fully charged and initially inactive
Storage efficiency	%	N/A
Minimum cycle length of TES		$MinCy_{sys}$ = 24 h
Partial load suitability		Partially suitable
CAPEX per capacity	€/kWh	N/A
CAPEX per nominal power	€/kW	N/A
Storage material cost per CAPEX	%	N/A

KEY PERFORMANCE INDICATORS			
Stakeholder:	**University School of Bergen**	**Electricity producer and distributor**	**Policy maker**
KPI 1:	Storage capacity	Improved grid stability	CO2 mitigation
KPI 2:	Power		Improved grid stability
KPI 3:	Response time		
KPI 4:	Lifetime		
KPI 5:	CO2 emission reduction		

PCM-air heat exchanger for peak and demand shifting in buildings

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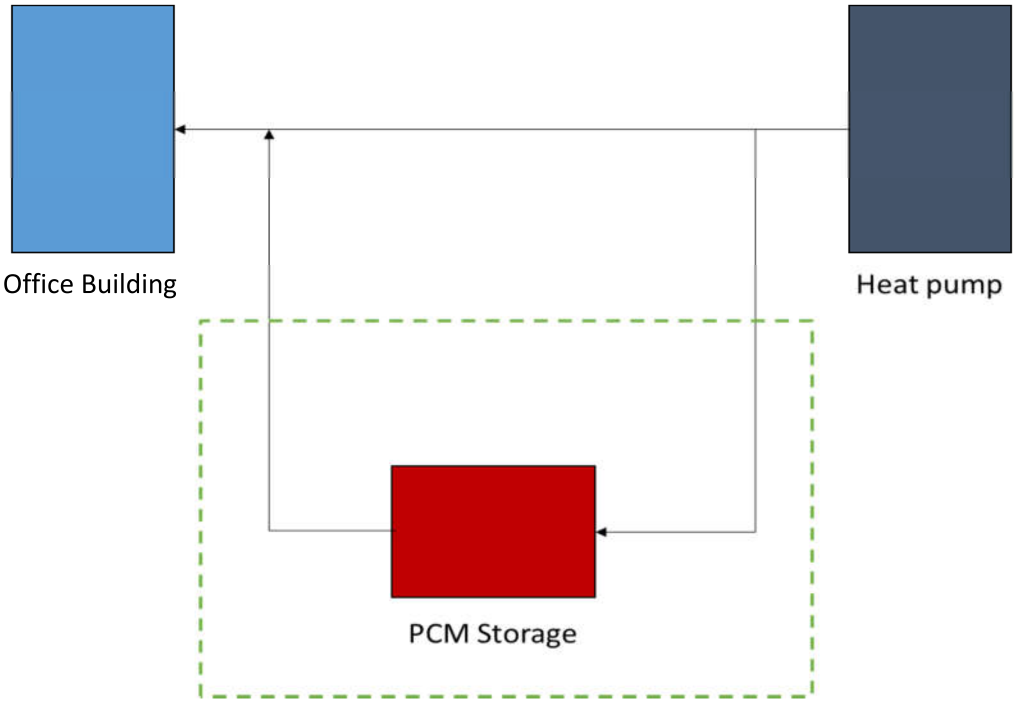

Fig. 3.9. Space heating of office building with PCM storage.

Process Description

The system was developed at ENTPE, France in order to address the peak electricity consumption observed in France during the late afternoon winter period, closely related to electrical space heating. The PCM storage unit enhances the thermal inertia of an existing mechanical ventilation system with the goal to perform electrical load shifting; this is therefore a retrofit case. For example it can be coupled to a heat pump used for office or residential space heating. Hence, the design process included considerations such as small size and light weight, as well as fast discharging period. The heating demand shift occurs by charging the storage unit during the night and releasing heat during the peak period, thus shifting part of the consumption. This also allows benefiting from reduced electricity night tariffs.

Thermal Energy Storage System Description

The dimensions of the PCM-Air heat exchanger are 1.05 m long, 0.75 m wide and 0.25 m high with a capacity of 31.8 kg of PCM. The heat exchanger is built from a set of 16 aluminum containers containing PCM (macro encapsulation) placed side by side. Mikrotek 37D paraffin was used as the heat storage medium, mostly due to its melting-solidification temperature of 37 °C. Fins are positioned between the containers to improve the heat exchange between the air and plates; they also ensure equal spacing between the containers (i.e. equal air layer thickness) contributing in such a way to a uniform distribution of the airflow within the heat exchanger. The containers were manufactured using extrusion process, having two openings for the introduction of PCM and controlling the pressure caused by the PCM volume change between phase transitions. Additional openings are added to introduce temperature sensors at variable depths inside the PCM (inlet, middle, outlet position), allowing the observation of the temperature evolution and of the state of charge of the unit. Polystyrene panels are used to enclose the PCM containers in order to thermally insulate it from the surrounding environment. Finally, wooden boards are used to assemble and ensure the stability of the structure. The storage system was connected to an office like room to evaluate and validate its performance under realistic charging/discharging needs and conditions.

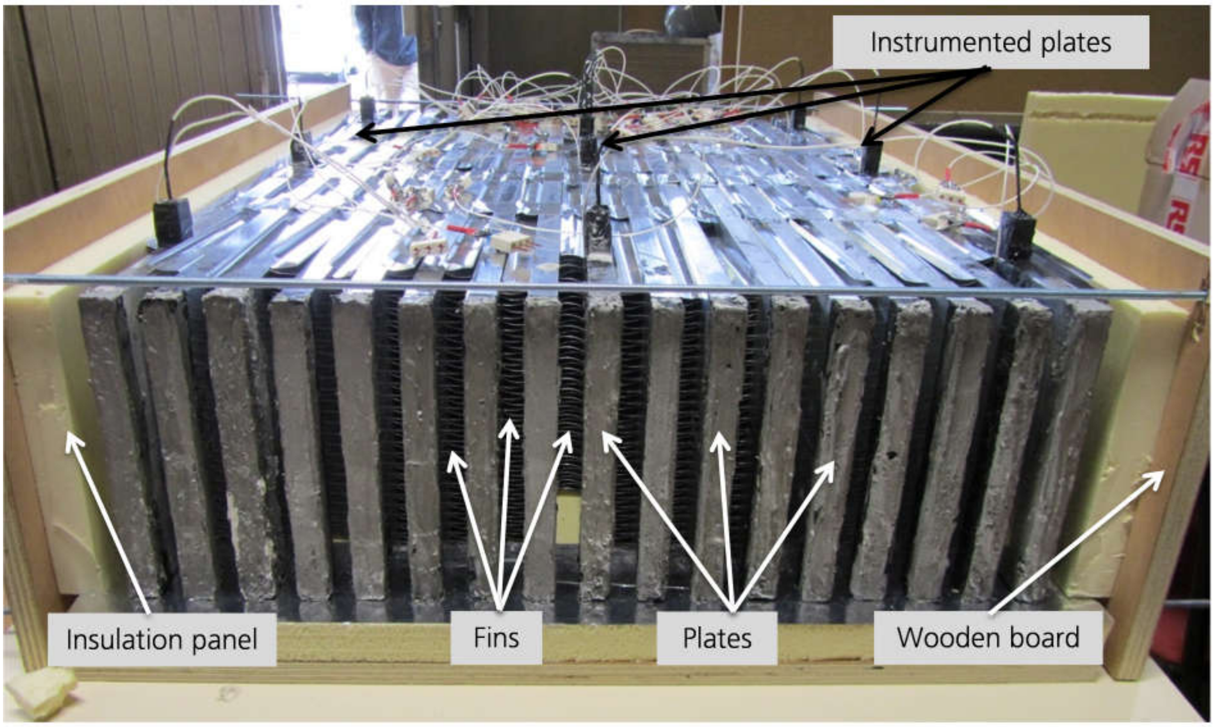

Fig. 3.10. The PCM-Air heat storage unit during the construction phase.

References

[29-31]

PROCESS DESCRIPTION	
Analyzed process	Heat pump providing space heating for office-residential buildings.
Integration goal	Electrical heating peak shifting with a PCM storage.
Thermal source(s)	Heat pump
Thermal sink(s)	Building
Heat transfer fluid	Air
Cycle frequency	Once per day
Temperature range (°C)	20-40.

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Latent
Technology readiness level		5 to 6 (system connected to office-like test room)
Storage capacity	kWh	4
Nominal power	kW	2
Response time of TES	minutes	Immediate
Storage efficiency	%	N/A
Minimum cycle length of TES		23 (11 hours discharge, 12 hours charge)
Partial load suitability		Suitable (changing from charging to discharging can be done immediately)
CAPEX per capacity	€/kWh	N/A
CAPEX per nominal power	€/kW	N/A
Storage material cost per CAPEX	%	N/A

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Building owner**	**Energy utility**	**Building occupant**
KPI 1:	Net Economic Benefit	Process Flexibility	Heating cost
KPI 2:	Process Flexibility	Network stability	
KPI 3:	Reliability		
KPI 4:	Downsize of heating equipment		

Plate-based latent heat thermal energy storage system

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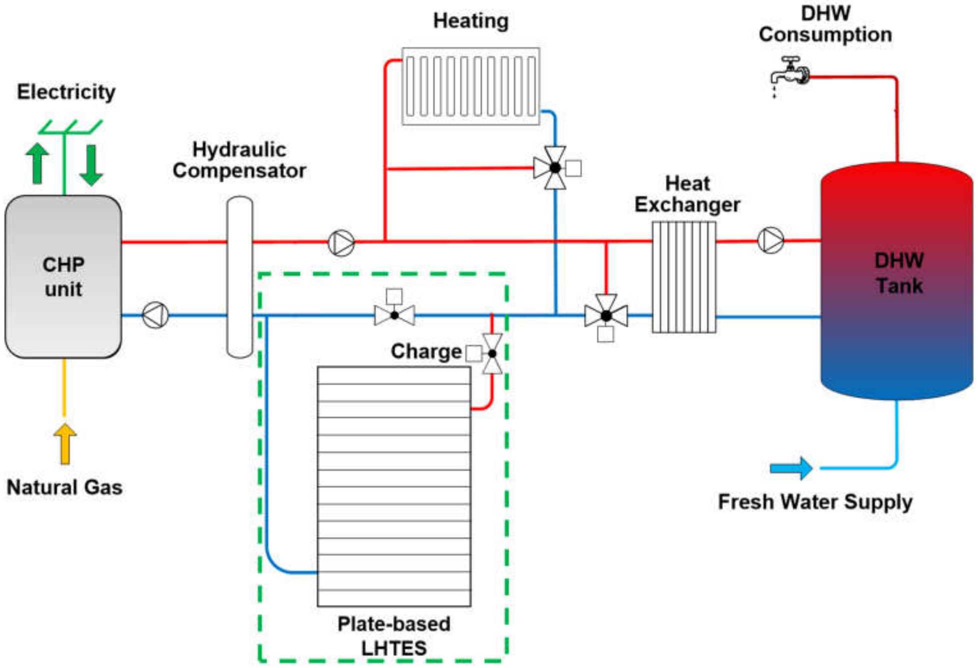

Fig. 3.11. Integration of a plate-based LHTES system in the cogeneration plant for a hospital.

Process Description

The process consists of a cogeneration (CHP) plant for the combined production of the electricity and thermal (heating and domestic hot water) needs of a hospital. The CHP unit is an internal combustion engine with a peak electric power of 100 kW and a peak thermal power of 240 kW. Exhaust heat from cogeneration units is recovered at two levels: exhaust gases and refrigeration water. The heat recovery system is incorporated in commercial CHP units. The CHP unit operates following a certain electricity load profile, with the aim of producing peak savings.

For this purpose, the LHTES system is placed at the return of the load side (Fig. 3.11). Thus, it stores the surplus heat, enabling the CHP unit to run at full load while all the produced heat is either consumed or stored. Once the LHTES system is fully charged, the flow bypasses the CHP unit. The specific arrangement of the LHTES system within the plant gives priority to the demand over the storage. On discharging, the LHTES system can be operated autonomously or together with the CHP unit, depending on the relation existing between the electricity and heat loads. The specific arrangement of the LHTES system within the plant gives priority to the storage over the CHP unit, which acts as a complement for the former.

The objective of the LHTES system integration in the analyzed process is: (i) to increase the operation hours of cogeneration units, (ii) to increase the efficiency (reducing the on-off cycles and setting the operation temperatures close to optimal) and (iii) to produce peak load savings.

Thermal Energy Storage System Description

The base of the plate-based LHTES system is the plate presented on the right side of Fig. 3.12a. The PCM is enclosed within hermetic hollow plates. The plates are arranged upwards on a disposition like that shown on the figure, and the HTF flows in parallel to the largest sides of the plates (y-z plane in Fig. 3.12b), exchanging the heat with that surface of the plate. A detailed description of the system is provided in [33, 34].

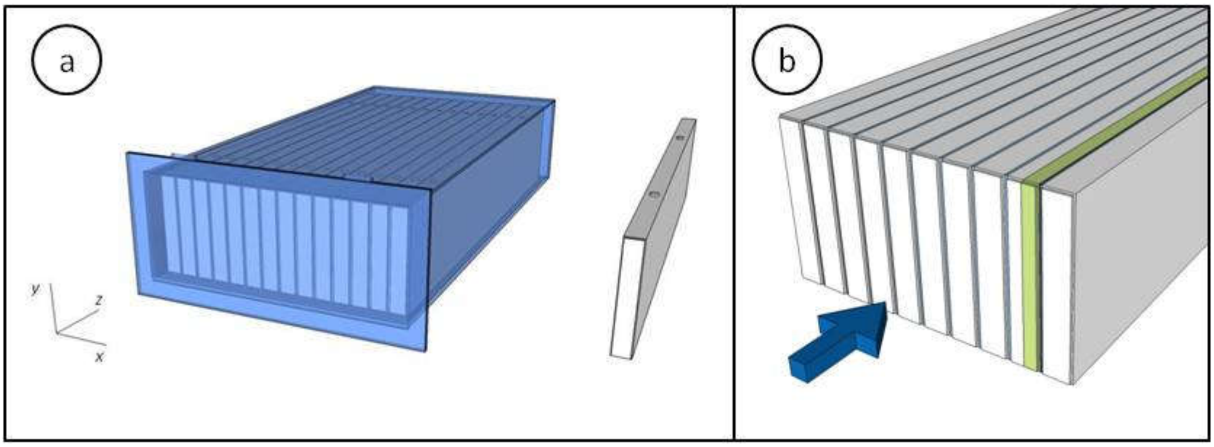

Fig. 3.12. Schematic representation of a single stack of 14 plates.

The in-parallel arrangement of the plates, with narrow channels between the plates, forms the channels where the HTF flows through. The plates can be gathered in stacks that form the LHTES system. These stacks can be placed in-series and/or in-parallel. Therefore, there is no need to use larger plates when large storage volume is required, neither to provide a large number of plates in-series: several stacks can be placed in-parallel, piled up or any combination of both. As an example, in Fig. 3.13, a LHTES system of 56 plates is presented, where the number of plates in-parallel is 14 and 4 stacks are connected in series (2 placed widthwise and 2 height-wise). In this way, specific designs can be provided for a defined application, adapted to the space availability.

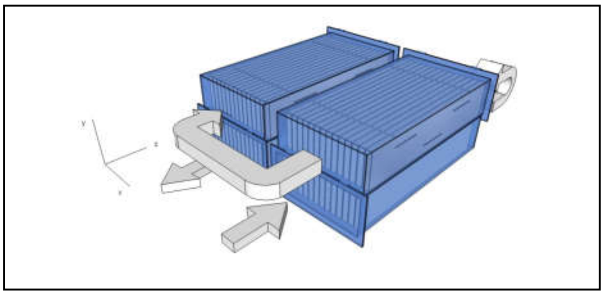

Fig. 3.13. Example of plate-based LHTES system with 56 plates divided into 4 stacks.

For the herein proposed process, 30 stacks are needed, each of them containing 32 plates of 6 cm thick (960 plates in total). The sizing of the system was performed based on a procedure previously published in [35]. Stainless steel is the material selected to construct the enclosure of each stack, while the plates consist of prefabricated aluminum profiles commonly used in the building sector. The proposed PCM is RT60 from Rubitherm GmbH. The outer thermal insulation consists of 10 cm-thick XPS. A scheme of the resulting plate-based LHTES system is presented on Figure 4.

References

[32-35]

PROCESS DESCRIPTION	
Analyzed process	Cogeneration unit that provides heating and domestic hot water to a hospital
Integration goal	To increase operational hours and efficiency of cogeneration unit To provide peak savings to the hospital
Thermal source(s)	Exhaust heat from cogeneration unit
Thermal sink(s)	Heating and domestic hot water distribution system
Heat transfer fluid	Water
Cycle frequency	Once per day (minimum)
Temperature range (°C)	50 - 80

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Latent
Technology readiness level		4 - 5
Storage capacity	kWh	947
Nominal power	kW	62
Response time of TES	minutes	1-2 *
Storage efficiency	%	95 * (daily)
Minimum cycle length of TES		18 h (2.7 charging + 15.3 discharging)
Partial load suitability		Partially suitable
CAPEX per capacity	€/kWh	103
CAPEX per nominal power	€/kW	1567
Storage material cost per CAPEX	%	19.2

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Process operator**	**Consumer**	**Policy maker**
KPI 1:	Storage capacity	Peak saving	Peak saving
KPI 2:	Power	Improved grid stability	Improved grid stability
KPI 3:	T-level required	Cheaper Heat Price	
KPI 4:	Lifetime		
KPI 5:	Efficiency		

Latent heat storage for low-temperature heat including solar cooling and domestic hot water

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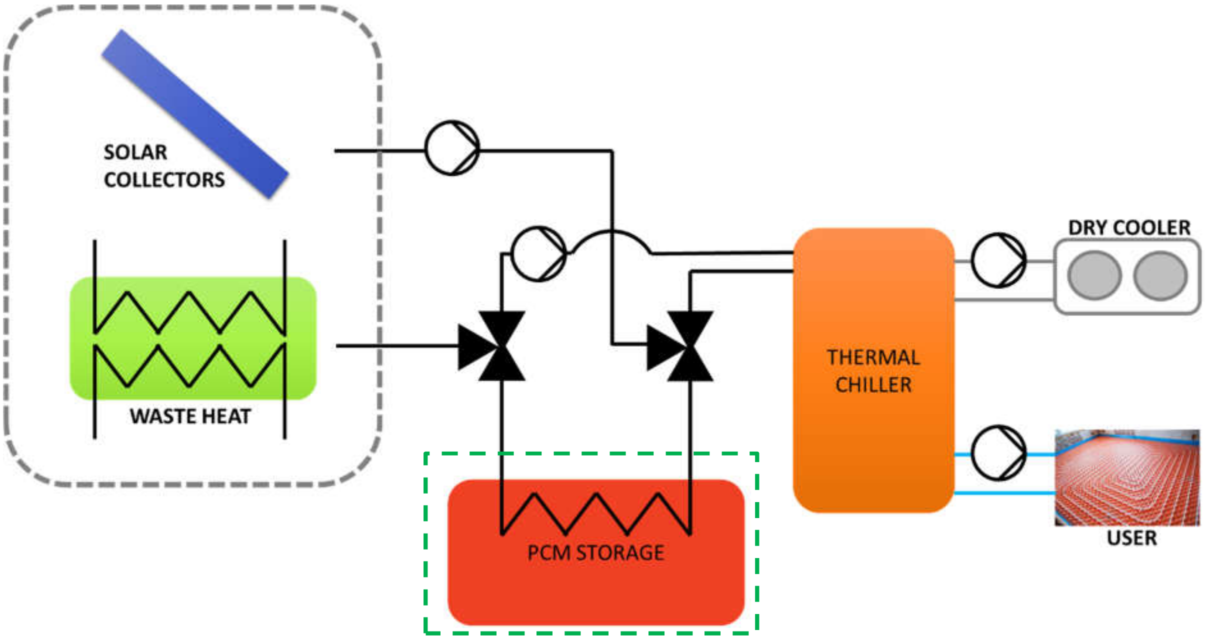

Fig. 3.14. Simplified scheme of the low-temperature heat process into which the storage could be integrated.

Process Description

The PCM storage serves as hot storage tank for feeding a thermal (e.g. adsorption or absorption) chiller/heat pump. The heat source for charging the storage is low-temperature heat (T<100°C), that can come either from waste heat recovery (e.g. industrial) or solar collectors. In this way, it is possible to extend the operation of the chiller even when there is no waste heat or solar radiation available, at the same time guaranteeing an optimal temperature level and therefore high performance of the thermal chiller. However, the storage is still at lab-scale and therefore there is not a specific application already proposed.

Thermal Energy Storage System Description

The storage is made up of a fin-and-tube heat exchanger entirely made of AISI 416 stainless steel, employing 48 fins and 4 parallel hydraulic circuits, connected by means of an external manifold. The space between the fins has been chosen as a compromise between heat transfer capacity of the system and the need for an easy filling with the PCM. To minimise thermal gradients both in longitudinal and transversal direction, 4 parallel circuits for the distribution of the HTF have been realised, with ½" stainless steel pipes. The circuits are connected through a 1 ½" stainless steel manifold. Moreover, volume for thermal expansion during melting has been considered during the design of the system. Thermal insulation of the system has been accomplished by 3 cm elastomeric foam, while an aluminium foil has been put over the foam, in order to reduce the radiative thermal losses. The employed PCM is PlusICE A82, a commercial paraffinic material with nominal melting temperature of 82°C. 37 kg of PCM were filled into the storage. A picture of the system is shown below.

Fig. 3.15. Latent heat storage installed in the laboratory.

References

[36, 37]

PROCESS DESCRIPTION	
Analyzed process	Storage of low-temperature heat for feeding of a thermal chiller
Integration goal	Extend operating time of a thermal chiller and peak shaving
Thermal source(s)	Waste heat, solar collectors
Thermal sink(s)	Thermal chiller
Heat transfer fluid	Water
Cycle frequency	Once per day
Temperature range (°C)	70-85°C

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Latent
Technology readiness level		4
Storage capacity	kWh	2 kWh @ 85°C heat source, 65°C user, 28°C ambient
Nominal power	kW	1.2 kW @ 85°C heat source, 65°C user, 28°C ambient
Response time of TES	minutes	1-5 min
Storage efficiency	%	30% @ 85°C heat source, 65°C user, 28°C ambient
Minimum cycle length of TES		N/A
Partial load suitability		Yes
CAPEX per capacity	€/kWh	N/A
CAPEX per nominal power	€/kW	N/A
Storage material cost per CAPEX	%	N/A

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Industrial customer**	**Consumer**	**Process operator**
KPI 1:	Storage capacity	Storage capacity	Storage efficiency
KPI 2:	Discharge power	Storage efficiency	Continuity of service
KPI 3:	Storage energy density	Specific price	
KPI 4:	Specific price		

3.3 Application evaluation

While use of thermal energy storage in the non-residential building sector has not yet seen widespread use, there are key examples of established technologies. The benchmarks highlighted in this report all use the latent heat of fusion of water to store thermal energy either daily or seasonally.

In the daily case, the benchmark is a moderately-large ice storage system of 240 MWh used to increase the cooling capacity of the cold network and improve reliability of the cold supply. Cycling daily, it has an efficiency of 95%. The use of water-glycol as a heat transfer fluid also allows a discharging temperature as low as -7°C.

When looking at the seasonal storages, these two benchmarks have large capacities of 0.5 – 10 GWh, depending on the accumulated snow through the cold season. The minimum temperature attained is 2°C in both cases, with similar discharging powers of 3 MW. Both of these benchmarks have replaced an already-existing process unit, in these cases a chiller, and can thus be seen as a retrofit case. The seasonal storages have the benefit of reducing fuel consumption and CO_2 emissions as well as improving operational characteristics of certain process components.

Research and development in this sector sees an emphasis on low-temperature PCM from 4 °C to 80 °C. The material used is most commonly a salt hydrate or a paraffin. These systems use either macro-encapsulated PCM or flat-plate heat exchangers. Largely, there are two categories of R&D: at TRL 6-8, pilot systems have been installed in real environments. At TRL 4-5, new concepts are under development for heating of non-residential buildings.

Table 3.1. Non-exhaustive selection of relevant system parameters for TES in non-residential building applications.

	Cold storage	Heat storage
T_{min} (°C)	-7 – 7	20
T_{max} (°C)	7 – 18	80
ESC_{sys}	0.3 – 11 MWh (R&D) 0.49 – 10 GWh (Benchmarks)	
SCC_{real} (€/kWh)	0.8 – 3.3	ca. 103 (PCM in R&D)
Cycle frequency	1/day to 1/year (seasonal)	
Response time	Immediate to 1-2 minutes	

In these cases, TES is used for peak shaving of cooling or heating load that allows for energy use reductions, downsizing of equipment and an operational benefit for certain process units (cogeneration, thermal chiller etc.). The storage delivers the following benefits:

- Time shift of heat/cold from periods with lower energy needs at sink to periods with higher energy needs
- Thus reducing peak loads, peak prices for energy and size of installed equipment which can be designed for levels below peak power
- Better performance of installed system components

Key performance indicators of TES systems in non-residential buildings are shown in the table below.

Table 3.2. Key performance indicators in non-residential buildings.

Stakeholder:	**Building owner**	**Energy utility**
KPI 1:	Net economic benefit (peak shaving, equipment downsizing)	Net economic benefit
KPI 2:	Net environmental benefit	Net environmental benefit
KPI 3:	Operational benefit for certain process units / flexibility	Higher flexibility in process operation
KPI 4:	Reliability	Improved grid stability

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4 Industrial processes

The following chapter examines the industrial processes application and its association to TES systems. Context is first given by a look at several benchmarks consisting of longstanding technologies for thermal management in the industrial process sector, namely regenerator storages and steam accumulators. The chapter continues with a presentation and evaluation of nine case studies of TES development for industrial processes. It concludes with an evaluation of the application based on the presented benchmarks and development cases. The contents of this chapter are shown in the table below.

Important note: the cases presented in this report should be understood as a non-exhaustive representation of each sector or technology. The goal of the Annex 30 network was to select interesting and informative cases that highlight key characteristics of thermal energy storage.

Name of Case	Type	Location	Page
Glass furnace regenerators	Benchmark	France	68
PS10 CSP plant with steam accumulator storage	Benchmark	Spain	71
Waste heat recovery with sensible storage in water	Development	Netherlands	72
Bitumen and water storage for industrial processes	Development	Switzerland	75
Dual-media high temperature thermal storage for industrial waste heat recovery	Development	Germany	79
Cogeneration power plant with integrated latent heat storage	Development	Germany	82
Thermochemical storage for low-temperature industrial processes	Development	Italy	85
Latent heat thermal energy storage pilot plant	Development	Spain	88
Thermal energy storage in a packed bed for industrial solar applications	Development	Turkey	91
Waste heat recovery using latent heat transportation system	Development	Japan	94
Waste heat recovery with PCM with the sailing heat concept	Development	Netherlands	97

4.1 Benchmarks in industrial processes

a. Regenerator storage in steelmaking and glass manufacturing

Process description

Thermal energy storage is an established technology in several types of industrial process as regenerator storages, large sensible storages (effectively heat exchangers between a hot and cold fluid) that can be alternately charged and discharged with a gaseous heat transfer fluid. Regenerator storages were first deployed in industrial sectors in the 1860s and have been in use ever since.

In steelmaking, a blast furnace is used to smelt a mixture of coke and iron by combusting bottom-fed air and gas to produce liquid metals. A significant portion of this energy is rejected as high-temperature waste heat that can subsequently be re-used to preheat combustion air prior to entering the furnace for more efficient furnace operation [39]. Use of a Cowper stove reduces the overall energy consumption of the steelmaking process by recovering waste heat and preheating air entering the main furnace (Fig. 4.1). Operation of a TES system in this manner leads to a reduction in fossil fuels burned for steelmaking, total decrease in energy consumed by the process and improved stove performance.

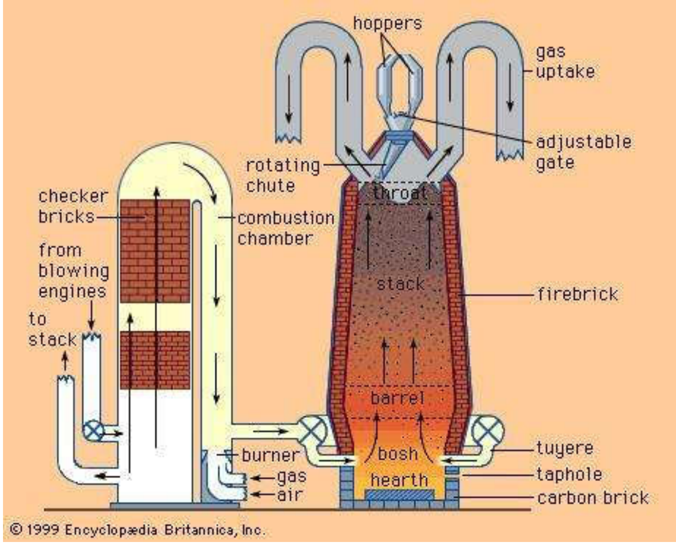

Fig. 4.1. Cowper stove (left) and blast furnace (right) [38].

As a benchmark, regenerator storages are highly relevant due to their longstanding deployment status in many industrial sectors e.g. steelmaking, glass, coke and cement manufacturing. They can be considered a standard process component in some manufacturing processes and are highly common in industry [41].

TES system description

Regenerator storages are characterized most prominently by their forced convection direct heat transfer method. The regenerator consists of a main vessel with hot or cold air funneled directly through the storage material to charge or discharge the storage, respectively. The most common variant, called Cowper stoves (Fig. 4.2), has been deployed in steelmaking and glass processes around the world.

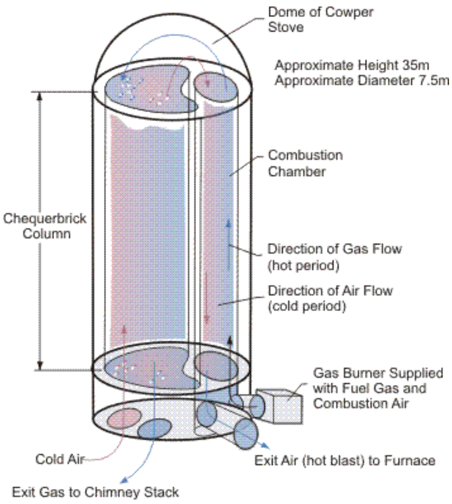

Fig. 4.2. Design of a Cowper stove [40].

Operationally, a Cowper stove alternates between:

- a hot period, during which it is charged with waste heat from the blast furnace and
- a cold period, during which it preheats the combustion air (a.k.a. hot blast).

With short cycling times of 30 – 180 minutes, it is common to have two or more Cowper stoves assigned to each blast furnace, as they may alternate hot and cold periods so that preheating of the combustion air entering the blast furnace is never interrupted.

Regenerator storages consist of either an internal or external combustion chamber. Using combustion gas as a heat transfer fluid, the regenerator is able to attain temperatures reaching 1000°C, a high temperature level that requires a certain type of material with a favorable material stability and optimized gaseous flow engineering.

Cowper stoves are built with either internal or external combustion chambers. While external are the standard construction, internal chambers provide significantly reduced losses due to heat dissipation to the environment. The most common storage material is packed bricks, usually available in a checker or hexagonal brick design to maximize heat transfer and withstand a heavy load at the top of the regenerator.

Fig. 4.4. Three Cowper stoves in operation at a steelmaking plant in Duisburg [42].

Table 4.1. Example data for a blast furnace regenerator [43].

Storage capacity	140 MWh
Nominal power	280 MW
Temperature range	1250 – 1400°C
Mass flow range	55 – 160 kg/s
Cycle time	60 min. (30 hot, 30 cold)

Fig. 4.5. Cowper stoves at Hyundai Steel Corporation (L) and Zhangjiagang Pros Iron Making (R) [42].

Glass furnace regenerators

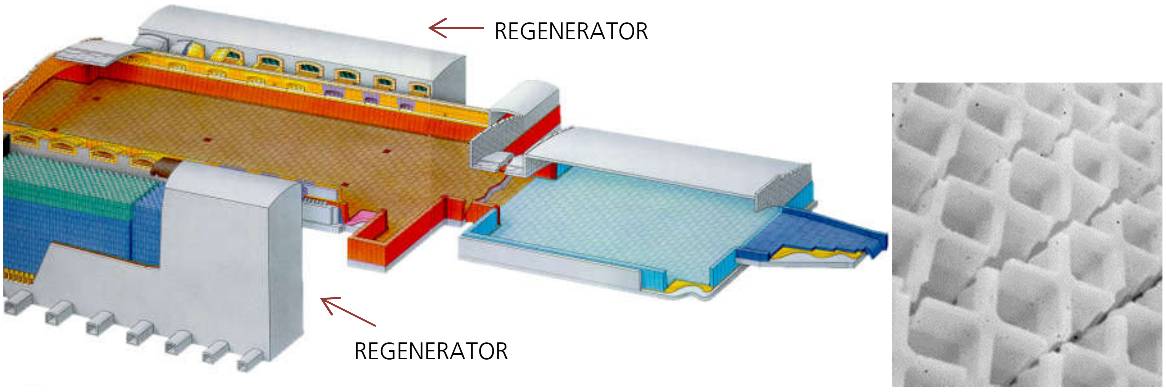

Fig. 4.6. Glass furnace with a regenerator on each side and heat storage material (Saint Gobain).

PROCESS DESCRIPTION		
Analyzed process	Glass furnace regenerators	
Integration goal	Heat recuperation	
Thermal source(s)	Flue gas from burners	
Thermal sink(s)	Fresh air for combustion	
Heat transfer fluid	Direct heat transfer between flue gas and air	
Cycle frequency	Every 20 min one side charges while the other discharges	
Temperature range (°C)	1400°C/300°C	
THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Sensible solid
Technology readiness level		TRL 9
Storage capacity	MWh	≈ 10
Nominal power discharging	MW	≈ 30
Response time of TES	minutes	1-2
Storage efficiency	%	65 to 75

Glass furnace regenerators work as indirect heat exchangers and heat storage systems at the same time. They are about ten meters high and composed of ceramic bricks of various shapes forming channels (Fig. 4.6, right). On one side, the burners are heating the glass bath, shown in brown in Fig. 4.6, and the flue gas is exiting through the regenerator on the opposite side transferring heat to the ceramic bricks. At the same time, the gas burners are supplied with hot combustion air by the circulation of cold air entering inside the other regenerator. Every 20 minutes the regenerator roles reverse. This way the regenerator's heat storage material present a large temperature gradient (1350°C - top, 300°C - bottom) and, due to the short (dis)charge periods, a small temperature difference between hot and cold periods at one level (50-70°C).

The main objective of these regenerators is to recuperate heat from the exhaust flue gas and to transfer heat for preheating combustion air up to a very high temperature (1400°C) where conventional heat exchangers are not available.

b. Steam accumulators as buffer storage

Steam is a frequent thermal energy carrier in many different high-temperature industries. It is often used in electricity generation, manufacturing or simply to move heat from one location to another. However, due to its low volumetric energy density, steam cannot be stored directly. Steam accumulators (SA) are a technology that solve this problem by storing the thermal energy delivered by steam as sensible heat in saturated liquid water. Originally patented in 1873, different types of SAs have been commonly used in industry and power generation ever since, with a well-known example of the Berlin-Charlottenburg steam storage power plant built in 1929. Using 16 storage tanks with an overall capacity of 67 MWh, it was operational for over 60 years covering peaking and balancing needs.

In industrial processes, steam accumulators are commonly used as buffer storage and fulfill three main principles: (i) balance fluctuations of steam load to maximize plant efficiency, (ii) balance supply of waste steam and thermal energy requirement and (iii) act as an instant steam reserve until stand-by boilers come online [44]. Given the prevalence of SAs in industry and power generation, there is no defined process chosen for this section however three key uses will be described.

Cogeneration (Combined heat and power)

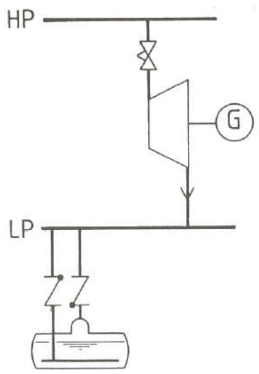

Fig. 4.7. Steam accumulator in CHP [44].

Steam accumulators are used in cogeneration to balance load variations by covering maximum peaks in power and demand. The accumulator charges using excess steam during periods of low load and discharges once steam demand rises. This enables the sizing of the electrical generator to be matched to the power demand and for it to run continuously for longer periods at full output and maximum efficiency [44]. Due to the SA's ability to respond rapidly and with high discharge rates, unexpected demand fluctuations can easily be compensated and pressure in the steam distribution system can be maintained.

Industrial processes

In steelmaking, the process is cyclical and steam is produced during half the cycle. As such, SAs are used to store steam during the blasting process to provide energy while switching between blasting and cooling [44]. Industrial processes also use accumulators to provide intermittent balancing energy. In Fig. 4.8, an SA is shown between consumption networks at different pressures. Here it responds to hourly fluctuations between the two networks.

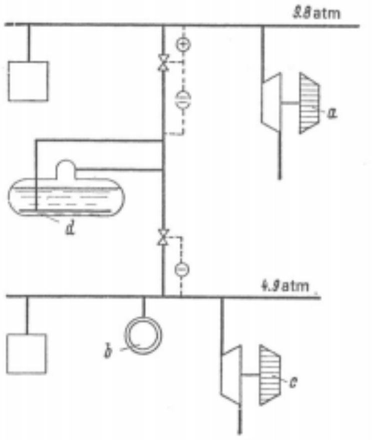

Fig. 4.8. Sliding pressure steam accumulator in steelmaking [44].

Concentrating solar power plants

Steam accumulators are also used in CSP plants with direct steam generation (DSG), which is the production of steam for power generation without the use of any intermediate heat transfer fluid. In these cases, SAs are the only commercial solution for thermal energy storage in DSG [45]. In this application, the steam is stored at high pressure in saturated liquid water as active direct storage, i.e. the steam is generated in the solar receiver and stored directly in the accumulator, as shown in Fig. 4.9. The first steam accumulator in CSP was installed in the world's first commercial CSP tower PS10. Operational in Spain since 2007, the system has four tanks and a total of 20 MWh of buffer storage capacity for 50 minutes of discharge at 50% turbine capacity [45]. The 20 MW installation PS20 became operational in 2009 and also uses SAs as buffer storage to mark the second commercial activity in this sector. The second generation of SAs in CSP uses a secondary receiver to produce superheated steam that reaches higher temperatures for more efficient turbine operation. This concept has been realized in the Khi Solar One project in South Africa, a 50 MW_e tower installation that uses 19 SAs to provide 2 hours of discharge [45].

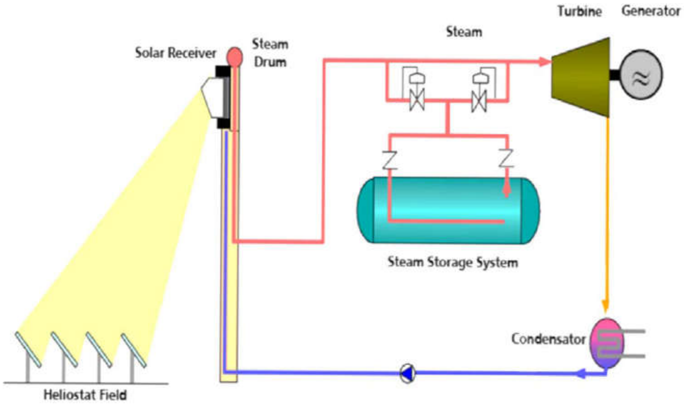

Fig. 4.9. Steam accumulator thermal energy storage system integrated in a DSG solar tower plant [46].

TES system description

The most common method employed by steam accumulators is the sliding or variable pressure system (a.k.a. Ruths storage systems) and it is the principle that has seen use in all previously-mentioned applications. As described, the SA does not literally store steam, but a saturated liquid water that is heavily pressurized. For charging, steam transfer heat to the water storage by condensing in the "liquid phase" section of the SA shown in Fig. 4.10. For discharging, the valve is opened and a pressure drop causes the flash evaporation of the surface water that is stored at saturation temperature. Through this method, the accumulator can deliver dry-saturated steam up to 100 bar [46] and, depending on tank size, usually reaches a discharging time of 30 minutes. The SA has short reaction times and high discharge rates that allow it to compensate for sudden transients in many types of application.

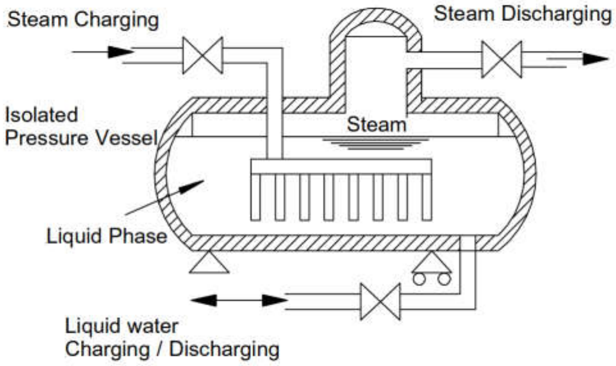

Fig. 4.10. Sliding pressure steam accumulator [46].

PS10 CSP plant with steam accumulator storage


Fig. 4.11. Steam accumulators installed at PS10 in Spain (© Abengoa Solar).

As previously mentioned, the PS10 project has been operational since 2007 and sees the deployment of four steam accumulators for buffer storage in a solar-tower power plant with direct steam generation. This project is the first commercial solar tower and integration of steam accumulator technology in concentrating solar power, making it the flag-bearer for direct steam generation technology. Depending on discharging power for turbine operation, the SAs store up to 50 minutes of thermal energy in saturated steam at 40 bar and provide a mass flow of 100,000 kg/h of steam [47].

PROCESS DESCRIPTION		
Analyzed process	PS10 power plant with four steam accumulator tanks for thermal energy storage.	
Integration goal	Buffer storage	
Thermal source(s)	Solar radiation	
Thermal sink(s)	Turbine (electricity generation)	
Heat transfer fluid	Steam (Direct Steam Generation)	
Cycle frequency	Depends on necessity	
Temperature (°C)	245 (40 bar sliding pressure)	
THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Sensible
Technology readiness level		8 to 9
Storage capacity	MWh	20
Nominal power discharging	MW	10
Response time of TES	minutes	<1

4.2 TES systems in development

Waste heat recovery with sensible storage in water

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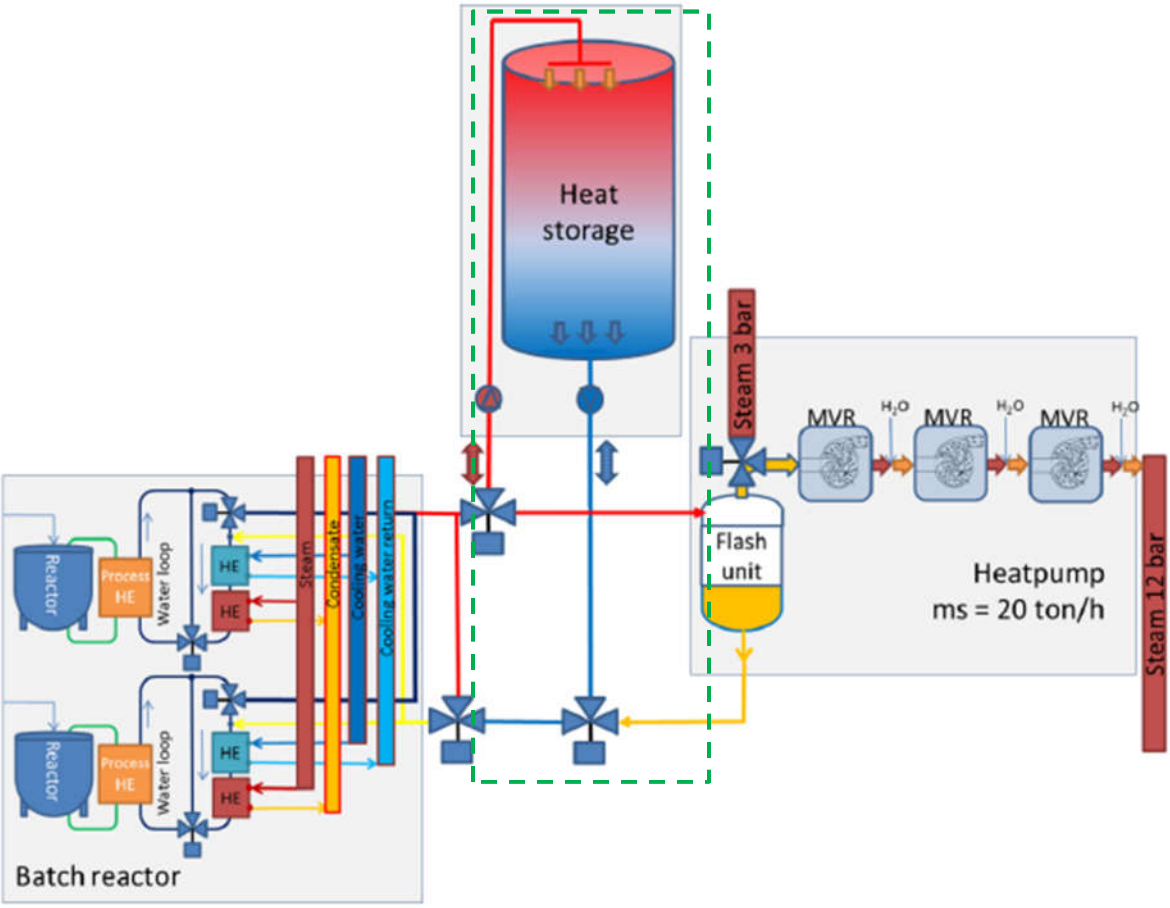

Fig. 4.12. Process diagram for waste heat recovery with integrated thermal storage unit.

Process Description

Purpose: The purpose of the system is to upgrade process waste heat from a batch polymerization reaction (exothermal process) to 12 bar process steam. This is realized by means of a flash unit in combination with a mechanical vapor recompression system (MVR). In order to facilitate continuous running of the MVR, heat can be taken either from the waste heat storage or from the 3 bar steam network. The heat storage is added to overcome the fluctuations in the availability of the waste heat and thereby maximize the use of the waste heat (minimize the use of 3 bar steam).

Goal of integration: Storage is necessary to overcome fluctuations in waste heat from the batch process, to facilitate continuous running of the MVR at minimal use of the 3 bar steam.

Type of case: retrofit (conceptual study for existing plant)

Thermal Energy Storage System Description

Storage design

The storage system is a pressurized water tank, placed between the batch reactors and the MVR. The tank is charged and discharged directly, without the use of a heat exchanger (displacement tank). The thermal storage system is assumed to be a perfectly stratified water tank without mixing of hot and cold water inside the tank.

Operational characteristics

The proposed MVR operates in the pressure range from atmospheric pressure at the suction side to 12barg steam at the outlet. This steam is fed to the existing steam lines on-site. In order to reach the desired temperature and pressure increase, a 3 stage compression process is introduced (with de-superheating by water injection between the stages). The design output of the heat pump is set at 20 tons of steam per hour.

The waste heat supply from the batch reactors strongly varies over time, and sometimes equals zero. This leads to large variation in the heat pump operational conditions. In addition, whenever the waste heat supply is higher than the maximum intake of the MVR, the existing cooling system of the batch reactors will remove the surplus heat, which is thereby lost. These disadvantages are largely overcome by adding a water storage of 1000 m^3. In addition, another steam supply at 3 bar from the existing steam lines is connected to the inlet of the MVR. This allows the MVR to remain operational in case the waste heat supply would drop below the threshold inlet conditions of the MVR.

Operational strategy

In the economic analysis of the thermal storage system, the cost savings are obtained by the reduction of the amount of 3 bar backup steam for the compressor. The calculated savings are based on steam price of 12.50 €/ton for 3 bar steam. The calculated steam cost saving for the 1000 m^3 storage system is around € 350,000. The use of waste heat instead of 3 bar steam reduces the COP of the heat pump system, which results in additional consumption of electricity. This additional cost (calculated for a range of prices from 20 to 50 €/MWh) needs to be subtracted from the earnings to calculate the simple payback times. The capital cost for the storage system is based on literature values for large industrial size systems, that are installed as thermal storage tanks in district heating systems. For a 1000 m^3 storage tank the investment costs are assumed to be €600,000. For the 1000 m^3 tank, a typical simple payback time is calculated to be in the order of 3-4 years.

References

[48]

PROCESS DESCRIPTION	
Analyzed process	Batch polymerization process.
Integration goal	Overcome fluctuations in available waste heat, acting as source for a heat pump system (based on mechanical vapor recompression).
Thermal source(s)	Water loop connected to the batch reactors
Thermal sink(s)	Source heat for an industrial heat pump
Heat transfer fluid	Water
Cycle frequency	1-3 cycles per day
Temperature range (°C)	80-140°C (maximum range)

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Sensible
Technology readiness level		8 - 9
Storage capacity	MWh	29.2 (105 GJ) (based on typical $\Delta T=25°C$)
Nominal power	MW	10
Response time of TES	minutes	fast
Storage efficiency	%	Not known
Minimum cycle length of TES		6 hours
Partial load suitability		suitable
CAPEX per capacity	€/kWh	20.5
CAPEX per nominal power	€/kW	60
Storage material cost per CAPEX	%	N/A

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Process Operator**	**Process Owner**	**Industrial Customer**
KPI 1:	Thermal power	Energy efficiency improvement of product	CO$_2$ emissions reductions
KPI 2:	TRL	CO$_2$ emissions reductions	Cost reduction of the product
KPI 3:	Improved process control and reliability	Cost reduction of the product	
KPI 4:	Process safety	Cost of delivered heat	

Bitumen and water storage for industrial processes

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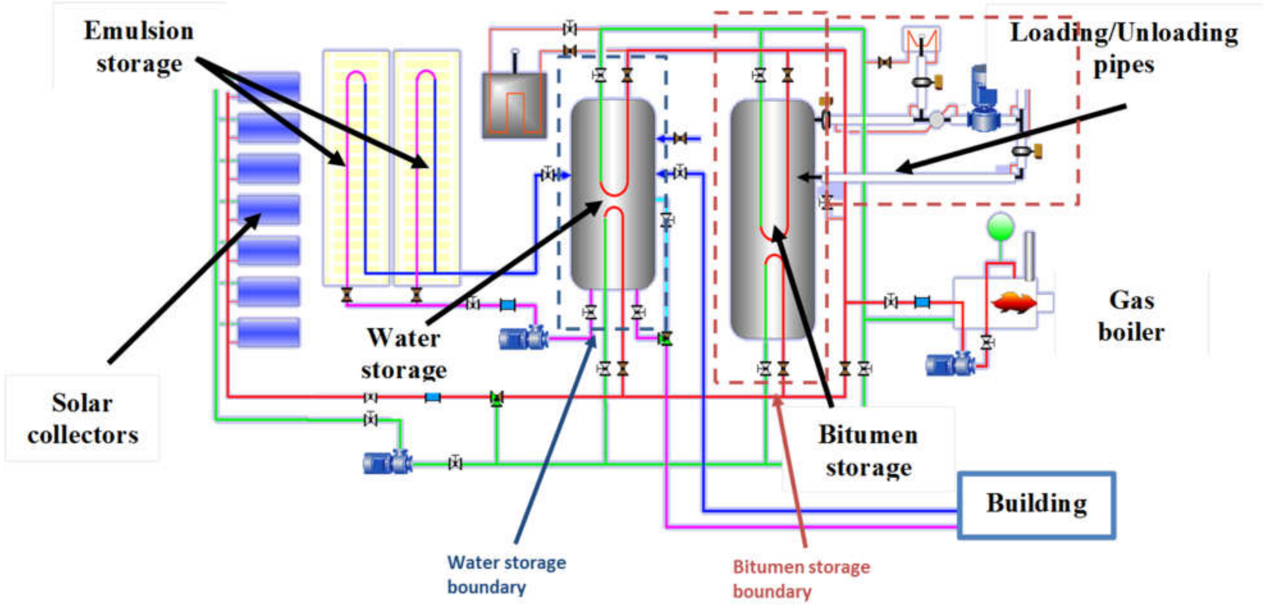

Fig. 4.13. Hydraulic scheme of heating system including storages

Process Description

COLAS SA, the industrial partner of this project uses bitumen and emulsion (mixture of water and bitumen) for road construction purposes. These products are stored on the site in Yverdon-les-Bains (Switzerland) in three different storages (two for emulsions and one for bitumen). They are delivered hot from the production plant and need to be maintained in temperature for viscosity reasons. Keeping them in a liquid phase eases the transfer of these products.

TES systems are used as buffer storages between the production plant of bitumen and the nearby road construction sites. Therefore, during the construction season (April to October) bituminous products are loaded and unloaded constantly to and from the storages depending on the daily needs. The storing temperature needed varies according to the product stored:

- between 50°C and 80°C for the emulsion tanks
- between 160°C and 180°C for the bitumen tank

A fourth storage water tank is employed for storing low temperature energy for emulsion and to provide an onsite building with hot water for both sanitary purposes and space heating. This building is located next to the bitumen-emulsion storage facility. The main goal of this storage was to increase the solar share in the process heat consumption. While the emulsions storages are supplied through the water storage, they are considered as a heat sink for the latter, the boundaries are set around the water storage for simplicity reasons.

Thermal Energy Storage System Description

Bitumen storage - The particularity of the bitumen storage is that it only has heat sources and no heat sinks, while the purpose is to store material and the only need is to compensate heat losses of TES. Therefore, an efficiency indicator is difficult to define. The most important parameter in this case is thermal resistance of the system to reduce losses.

If a heat demand is not required by the water storage, the solar collectors will charge the TES. When solar energy is not available a 350 kW gas boiler provides the energy needed by the storage. In case of extra solar energy (both bitumen and water storage have reached the desired temperature and solar energy is available), this storage also allows higher temperatures than the set point temperature. Therefore, it avoids stagnation temperatures for the collectors and this energy can be used later to reduce gas consumption for its own needs or for the water storage.

The loading/unloading circuit also requires energy supply from the same sources in order to avoid bitumen solidification on the piping. This circuit was included in the boundaries of the TES as it is necessary to the system operation. Measurements have shown that heat losses in this loop of three meters are in the same range with the ones of the 70 m^3 storage itself.

Water storage - The water storage requires operating temperature between 60 and 90°C depending on the building or emulsion needs. The TES is charged in priority via middle temperature solar thermal collectors or, when solar energy is not available, via the gas boiler. The building and emulsions can be supplied with energy from this storage separately or at the same time if needed. The water storage was included in the heating system in order to take most advantage of the solar collectors on the one hand by considerably reducing their operating temperature and on the other hand by allowing their operation in the winter time when bitumen utilization is stopped.

Fig. 4.14. Storage tanks in the COLAS bitumen facility.

References

[49, 50]

The table below has been completed only for the bitumen storage and its respective process.

PROCESS DESCRIPTION	
Analyzed process	Liquid phase bitumen storage
Integration goal	Storing thermal energy and material (bitumen)
Thermal source(s)	Natural gas, solar thermal
Thermal sink(s)	Storage bituminous material + SH and DHW
Heat transfer fluid	Thermal oil (source), Water-glycol (sink)
Cycle frequency	Once per day but may vary
Temperature range (°C)	160°C-200°C

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION (BITUMEN STORAGE ONLY)		
Type of storage system		Sensible
Technology readiness level		TRL 8-9
Storage capacity	MWh	2.5
Nominal power	MW	5.6kW (heat loss) / ~100kW charging
Response time of TES	minutes	Difficult to estimate with the existing sensors
Storage efficiency	%	0% (see section before)
Minimum cycle length of TES		~24h
Partial load suitability		Suitable
CAPEX per capacity	€/kWh	25
CAPEX per nominal power	€/kW	625 (charging power)
Storage material cost per CAPEX	%	7%

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Process operator**	**Policy maker**	**Consumer**
KPI 1:	Storage Efficiency	Storage Efficiency	Average power during discharging
KPI 2:	Max power during charging phase	Increased use of renewable energy	
KPI 3:	Lifespan	CO2 mitigation	
KPI 4:	CAPEX		
KPI 5:	OPEX		

The table below has been completed only for the water storage and its respective process.

PROCESS DESCRIPTION	
Analyzed process	Emulsion temperature maintain + space heat and DHW preparation for an on-site building
Integration goal	Reducing fossil fuel consumption by integrated solar thermal energy
Thermal source(s)	Natural gas, solar thermal
Thermal sink(s)	Storage bituminous material + SH and DHW
Heat transfer fluid	Thermal oil (source), Water-glycol (sink)
Cycle frequency	Once per day but may vary
Temperature range (°C)	60°C-90°C

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION (WATER STORAGE ONLY)		
Type of storage system		Sensible
Technology readiness level		TRL 8-9
Storage capacity	MWh	0.8
Nominal power	MW	0.12
Response time of TES	minutes	Difficult to estimate with the existing sensors
Storage efficiency	%	85% (annual basis)
Minimum cycle length of TES		~8h
Partial load suitability		Suitable
CAPEX per capacity	€/kWh	53
CAPEX per nominal power	€/kW	354
Storage material cost per CAPEX	%	4%

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Process operator**	**Policy maker**	**Consumer**
KPI 1	Storage Efficiency	Storage Efficiency	
KPI 2	Lifespan	Increased use of renewable energy	
KPI 3	CAPEX	CO2 mitigation	
KPI 4	OPEX		
KPI 5			

Dual-media high temperature thermal storage for industrial waste heat recovery

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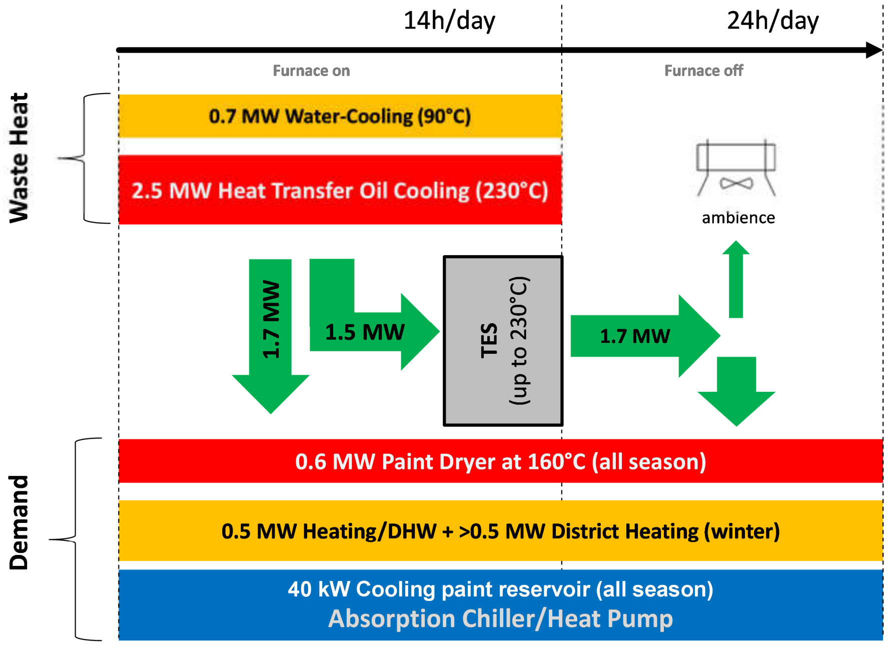

Fig. 4.15. Thermocline dual media thermal energy storage for waste heat recovery in a foundry (planned installation).

Process Description

In energy-intensive industries, the use of waste heat reduces the consumption of primary energy and greenhouse gas emissions. Especially, the utilization of discontinuous waste heat (> 100 ° C) by means of thermal energy storage has been discussed and theoretically investigated. At the moment, only a few industrial applications can be found. The main reason for that are the high investment costs of commercially available storage technologies for temperatures above 100° C. Another reason is the comparably low energy price for gas and electricity for energy-intensive industries. Low numbers of cycles (loading and unloading) of the thermal energy storage cause difficulties in achieving an economic operation. A suitable thermal energy storage in terms of performance, capacity, temperature, cycle stability and cost-effective availability has to be developed. At the ZAE Bayern, the development of such a thermal energy storage for temperatures up to 300°C includes material tests and storage experiments with a thermocline dual-media storage (solid filler material in direct contact with heat transfer oil). This non-pressurized design offers considerable advantages compared to alternative storage concepts (e.g. thermal oil only). Using a cost effective solid material (e.g. rocks) as a packed bed, the costs for the storage material can be reduced by up to 60%. Additionally, material storage capacity can be increased by up to 40%. The investigated energy storage system should be used to store the waste heat of a furnace of a foundry. During the daily downtime of the furnace a continuous using of waste heat for process/space heating can then be realized.

Thermal Energy Storage System Description

At the ZAE Bayern a test site for a thermocline dual-media storage under real conditions has been constructed. Thermal oil is used as a heat transfer fluid. The test storage has a diameter of 80 centimeters and a volume of 670 liters. It is filled with a packed bed of rocks with a bulk density of 60%. Inside the test storage 54 Pt-100 temperature sensors are installed to measure temperature distribution in the vertical and horizontal directions. The inlet and outlet temperature at the top and the bottom connection adapter is also measured by Pt-100 temperature sensors. The mass flow of the thermal oil through the test storage and its pressure drop are measured as well. The test storage can be charged and discharged with a mass flow of more than 1 kg/s. Tests have been realized with a maximum temperature of around 215° C and thermal power up to 250 kW.

The test site was built to analyze the thermodynamic und physical behavior of a thermocline dual-media storage. Efficiency of the storage is being investigated, in particular. Here efficiency is defined as storage capacity in relation to the temperature level. This means at which temperature level can the stored heat be delivered during discharge process. An additional focus is on pressure drop to estimate auxiliary energy demand for the pumps as well as on operational safety. The loss of packed bed material must be especially prevented. As the thermal storage will be used in industrial applications durability is important. Long-term studies of the chemical and thermo-mechanical behavior of the solid material in direct contact with the thermal oil have therefore been conducted. After finishing the testing phase a pilot plant will be installed at the foundry. The thermal storage is planned to consist of three standardized module. Each module has a volume of 50 m³ with a diameter of 2.7 meter. The commissioning is planned in the beginning of 2019.

Fig. 4.16. Thermal energy storage test site at ZAE Bayern, Garching.

PROCESS DESCRIPTION (Planned system at foundry)	
Analyzed process	Foundry with waste heat recovery from a cupola furnace and various sources of heat
Integration goal	Increasing waste heat recovery of the furnace
Thermal source(s)	Cupola furnace
Thermal sink(s)	i) Paint dryer, ii) Building heating, iii) District heating, iv) Absorption chiller
Heat transfer fluid	Thermal oil
Cycle frequency	Once per day, excluding weekends
Temperature range (°C)	100° C – 215° C

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION (Planned system at foundry)		
Type of storage system		Sensible
Technology readiness level		6 - 7
Storage capacity	MWh	3.6 per module
Nominal power	MW	1.7
Response time of TES	Minutes	N/A
Storage efficiency	%	N/A
Minimum cycle length of TES		N/A
Partial load suitability		Suitable
CAPEX per capacity	€/kWh	N/A
CAPEX per nominal power	€/kW	N/A
Storage material cost per CAPEX	%	N/A

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Foundry owner**	**Process operator**	**Policy maker**
KPI 1:	Cost saving caused by energy saving	Difference between charging/discharging temperature	CO2 mitigation per ton of steel produced
KPI 2:	Investment cost	Storage capacity	Ability of waste heat recovery
KPI 3:	ROI	Efficiency/Heat loss	
KPI 4:	Ability of waste heat recovery	Pressure drop	
KPI 5:	Emission reduction (CO2 mitigation)	(Dis)charge time	

Cogeneration power plant with integrated latent heat storage

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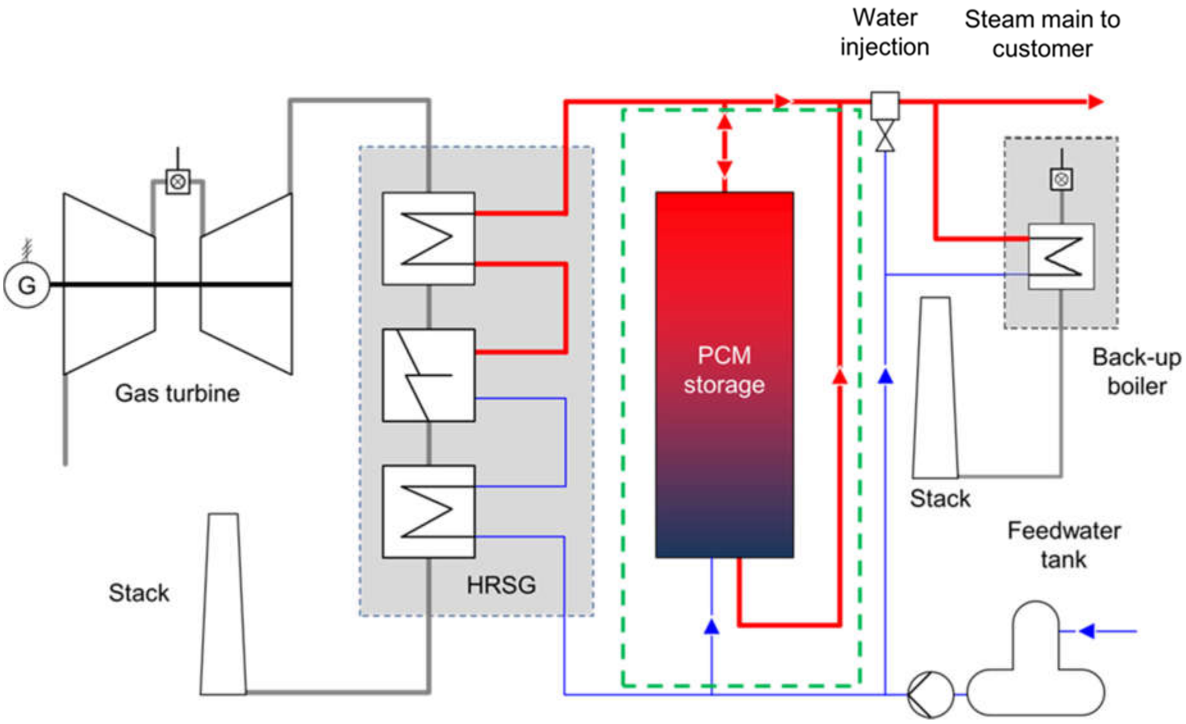

Fig. 4.17. Steam production in a cogeneration power plant with integrated latent heat storage. system.

Process Description

In the cogeneration plant in Saarland, Germany, process steam is produced by burning mine damp in a gas turbine and producing steam in a heat recovery steam generator. One of the customers requires a very constant delivery of high quality steam, for which a backup boiler is kept at warm load in order to assume steam production within two minutes if the gas turbine trips. The goal of the storage integration is to reduce fossil fuel use by reducing the load of the backup boiler to cold load, from which it requires fifteen minutes to assume steam production. For these fifteen minutes, the latent heat storage unit will produce steam for the steam customer.

Thermal Energy Storage System Description

The thermal energy storage unit is a finned tube latent heat concept. It is equipped with 852 finned tubes. The extruded aluminum fins result in a 70 mm tube spacing. The steel tubing is welded into upper and lower headers optimized for a fast switching of modes from standby to discharging. The storage unit has approximate outside dimensions, without thermal insulation, of 2.5x3x8m, and will be integrated outside the turbine house of the plant, in parallel to the heat recovery steam generator and the backup boilers.

Sodium nitrate is the storage material, and the mass of the storage unit, including storage material and insulation, will be approximately 60 tons. The storage unit will discharge with an evaporation of feedwater to steam in the tubes. During charging, the steam will not be condensed, so that it can also be sent to the steam customer.

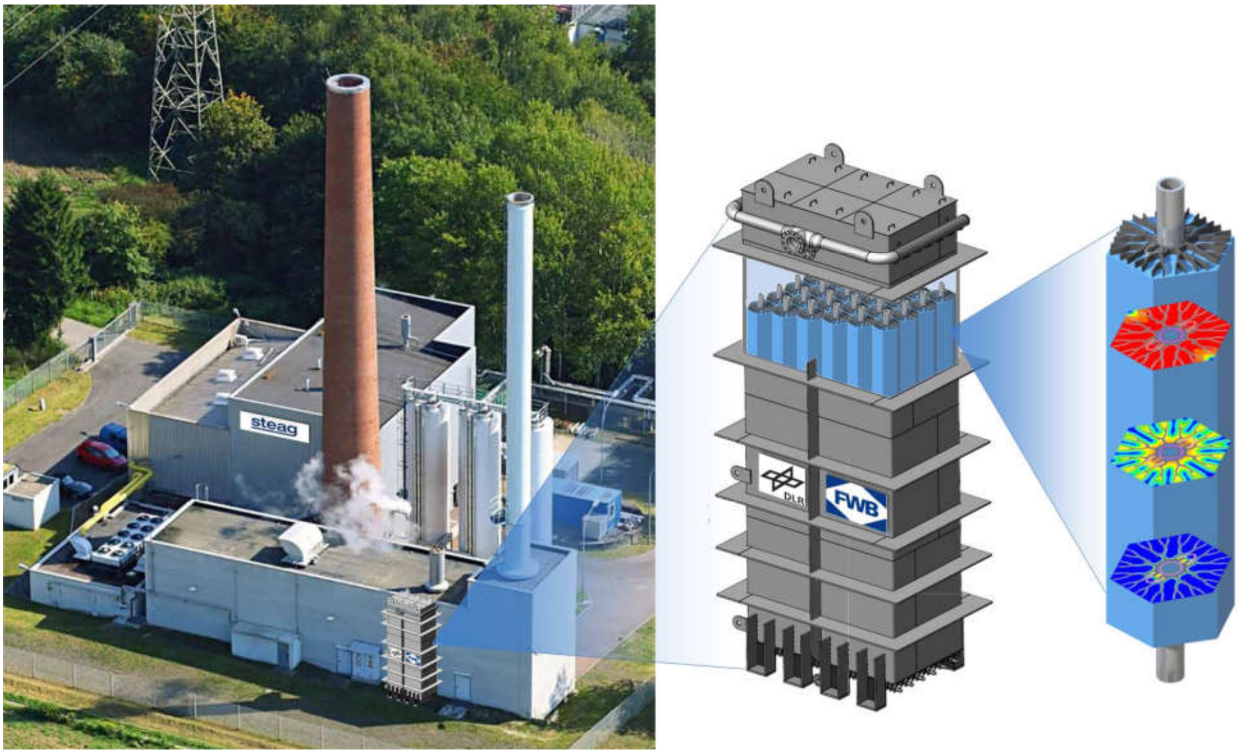

Fig. 4.18. Schematic showing integration of latent heat storage unit in the cogeneration plant. © FW Brökelmann

This work is being conducted in the project TESIN (Contract Nr. 03ESP011), which is partially funded by the German Federal Ministry for Economic Affairs and Energy.

References

[51-53]

PROCESS DESCRIPTION	
Analyzed process	Cogeneration plant in Germany consisting of a mine-damp gas turbine, HRSG, two back-up boilers, and feedwater pump.
Integration goal	Reduce fossil fuel use by reducing use of backup boilers. Increase plant flexibility.
Thermal source(s)	HRSG outlet steam
Thermal sink(s)	Steam customer
Heat transfer fluid	Water/Steam
Cycle frequency	Unclear & sporadic, possible once per month
Temperature range (°C)	103-350

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Latent
Technology readiness level		3 - 5
Storage capacity	MWh	5.22 (strictly according to Annex 30 definition)
Nominal power	MW	6
Response time of TES	minutes	2
Storage efficiency	%	Q.sys.charge will depend on variable standby time and thereby required re-charge energy. Therefore no value possible at this time.
Minimum cycle length of TES		15.25 h
Partial load suitability		Partially suitable
CAPEX per capacity	€/kWh	85 (based on definition of storage capacity; some costs still estimated)
CAPEX per nominal power	€/kW	74 (some costs still estimated)
Storage material cost per CAPEX	%	5% (some costs still estimated)

KEY PERFORMANCE INDICATORS

Stakeholder:	**Process operator**	**Industrial customer**	**Policy maker**
KPI 1:	Discharge time	Reliability	Reduced fossil fuel use
KPI 2:	Response time	Steam quality	Lifetime
KPI 3:	Reliability		CO_2 reductions
KPI 4:	Lifetime		
KPI 5:	Increased system flexibility		

Thermochemical storage for low-temperature industrial processes

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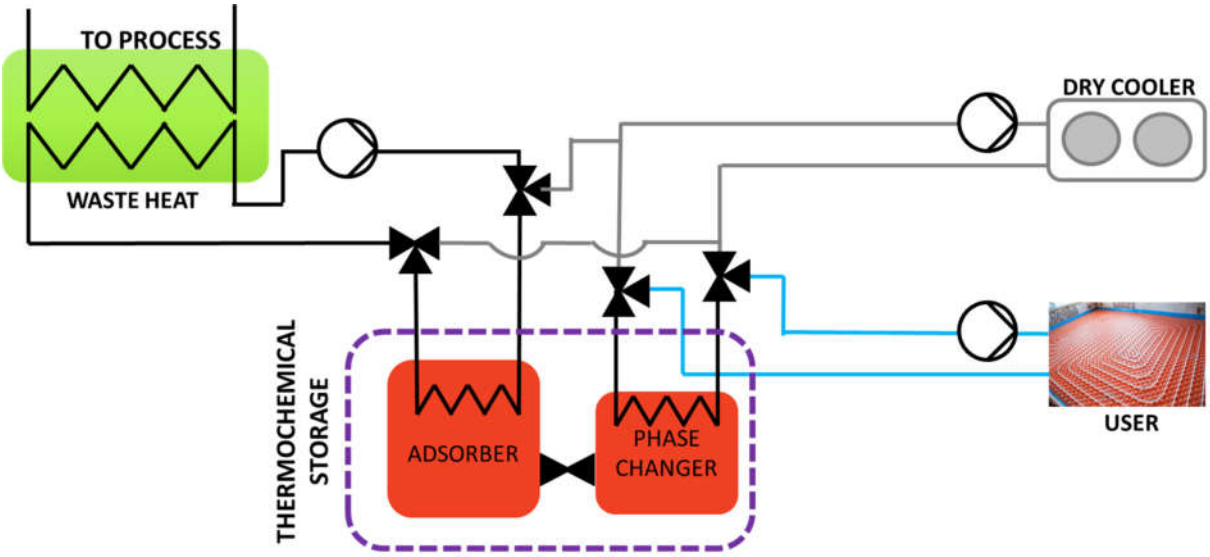

Fig. 4.19. Example of process diagram for the thermochemical storage

Process Description

The thermochemical storage developed is intended for cold storage starting from waste heat recovery in industrial processes at low temperature (T<100°C). Equipment cooling or space cooling are two examples of the possible applications of the storage. However, the storage is still at lab-scale and therefore a specific application has not yet been determined. For the purposes of this report, a process with cold water storage for space cooling has been proposed. The goal of the integration in this process would be to increase industrial process efficiency by storing cold with waste heat.

Thermal Energy Storage System Description

The prototype, shown in Fig. 1, consists of two vacuum chambers, representing the adsorber and the phase changer (working alternatively as condenser and evaporator). The dimensions and main characteristics of the chambers both for the adsorber and the phase changer are reported on the following page. Both chambers are realised in AISI316, to avoid corrosion problems; the chamber of the adsorber has a removable cover, in order to change the heat exchangers to be tested, whereas the chamber of the phase changer is entirely welded. Inside the phase changer, four commercial fin-and-tube heat exchangers with copper fins and stainless steel tube have been placed. They are connected in parallel through a brass manifold.

Fig. 4.20. Thermochemical storage installed in a lab at CNR-ITAE.

The vacuum chamber of the adsorber has overall dimensions of 250 x 353 x 774 mm and is constructed out of AISI316 stainless steel. The internal chamber is 240 x 543 x 769 mm and has 4 connections on the cover: 2 pipes for connecting hydraulic circuits, 1 connection for the thermocouple, 1 connection for a pressure sensor and 1 vacuum flange for the vacuum circuit. Additionally, it has 2 connections for linking with the phase changer or 2 phase changers in case of future expansions. Also constructed of AISI316 stainless steel, the vacuum chamber for the phase changer has external dimensions of 304 x 177 x 298 mm with a wall thickness of 2 mm. There are four copper/stainless steel fine and tube heat exchangers as well as six total connections. Four on the front of the chamber: 2 pipes for connecting hydraulic circuits, 1 connection for thermocouple, 1 vacuum flange for pressure sensor, 1 vacuum flange for the vacuum circuit. The last two connections are found on the chamber lateral and are both for connection with the absorber, or two absorbers in case of future expansion.

Both chambers are realized in AISI316, to avoid corrosion problems; the chamber of the adsorber has a removable cover, in order to change the heat exchangers to be tested, whereas the chamber of the phase changer is entirely welded. Inside the phase changer, 4 commercial fin-and-tube heat exchangers with copper fins and stainless steel tube have been placed. They are connected in parallel through a brass manifold.

References

[54]

PROCESS DESCRIPTION	
Analyzed process	Cold water storage for space cooling
Integration goal	Increase the efficiency of industrial processes by storing cold from waste heat
Thermal source(s)	Waste heat
Thermal sink(s)	Radiant ceiling/floor, fan coils
Heat transfer fluid	Water
Cycle frequency	Different frequencies are possible.
Temperature range (°C)	Charge: 70-90°C, discharge: 5-15°c

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Thermochemical
Technology readiness level		4
Storage capacity	kWh	220 Wh/kg @ 90°C desorption, 34°C condensation/adsorption, 10°C evaporation
Nominal power	kW	500 W @ 90°C desorption, 34°C condensation/adsorption, 10°C evaporation
Response time of TES	minutes	< 1 min
Storage efficiency	%	38% @ 90°C desorption, 34°C condensation/adsorption, 10°C evaporation
Minimum cycle length of TES		N/A
Partial load suitability		Suitable
CAPEX per capacity	€/kWh	N/A
CAPEX per nominal power	€/kW	N/A
Storage material cost per CAPEX	%	N/A

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Industrial customer**	**Electric grid owner**	**Policy maker**
KPI 1:	Storage capacity	Discharge power	Storage efficiency
KPI 2:	Discharge power	Storage efficiency	GHG reduction
KPI 3:	Storage energy density	Electricity saving	Electricity saving
KPI 4:	Max power charging		Lifetime
KPI 5:	Heat loss/day		

Latent heat thermal energy storage pilot plant at the University of Lleida

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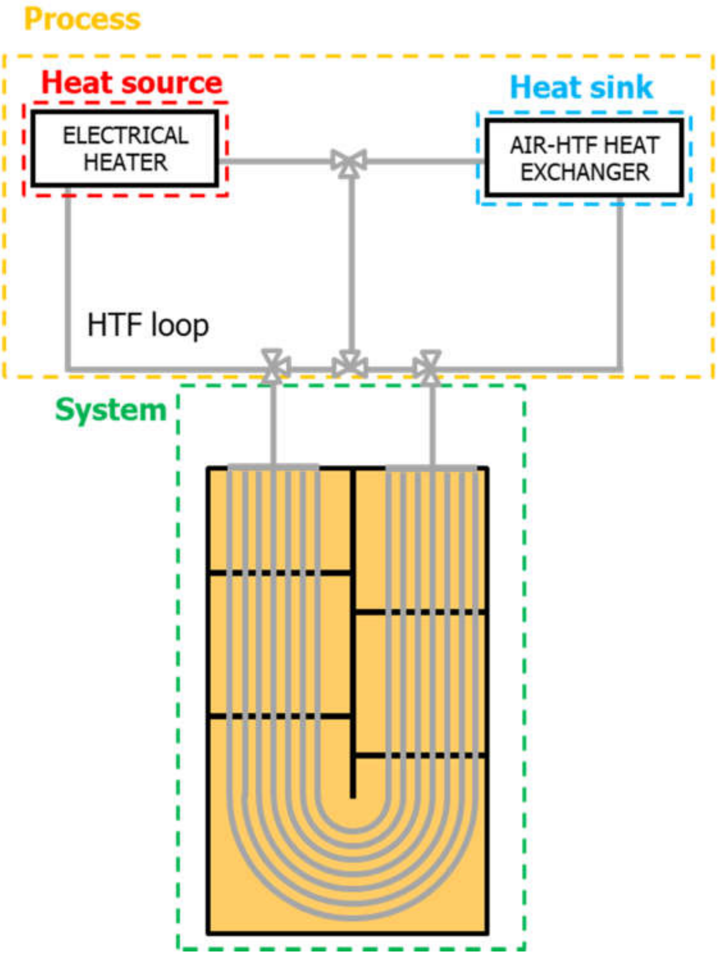

Fig. 4.21 Simulation at pilot plant scale of a waste heat recovery process (electrical heater) to be further used in an industrial process with similar temperature needs (HTF-air heat exchanger).

Process Description

This is a pilot plant that aims at testing or simulating different cases. The process could be the recovery of the waste heat from an industry or heat or cold production for industry or buildings (solar heating or solar cooling). Nearly any cases could be simulated, both a greenfield or a retrofit case. Due to the nature of the pilot plant some components are oversized due to the commercial availability of them at different scales.

Thermal Energy Storage System Description

The storage system consists of a storage tank, based on the shell-and-tube heat exchanger concept. This design consists on a rectangular prism shaped vessel, where the PCM is located, with a tubes bundle inside containing 49 tubes distributed in square pitch. The tubes are bended in U-shape, the distance between tubes center is 30 mm and all the tubes are connected in the same side to two different manifolds which distribute the HTF. All the elements in the tanks are made of stainless steel 304 L in order to withstand temperatures up to 300 °C, to avoid galvanic corrosion, and to avoid compatibility problems between the storage material and the tank itself.


Fig. 4.23. Storage system installed in the pilot plant.

With the aim of reducing the heat losses, both storage tanks are insulated. 450 mm of Foamglass® are installed under the storage tanks to minimize the heat losses to the ground and 240 mm of rock wool are installed on the lateral walls and on the cover of the storage tanks to minimize the heat losses to the ambient. Concerning to the distribution of the TES material in the storage tank, it has to bear in mind that the bigger amount is located within the tubes bundle along the main part of the tank and the rest of material is located in the central part and in the corners.

Table 4.2. Characteristics of the storage system.

Parameters	Units	Value
Material	[-]	Stainless steel 304L
Tank width	[mm]	527.5
Tank height	[mm]	273
Tank depth	[mm]	1273
HTF pipes average length	[mm]	2485
Heat transfer surface	[m^2]	6.55
Tank vessel volume (V_{tank})	[m^3]	0.183
HTF pipes volume	[m^3]	0.028
Inner parts and fins volume	[m^3]	0.002
Useless height	[mm]	12.5
Useless volume (V_{uless})	[m^3]	0.008
Real volume of PCM (V_{PCM})	[m^3]	0.145

The pilot plant has been used to test commercial high density polyethylene (HDPE) PEAD ALCUDIA 6020L, supplied by REPSOL whose results are reported in Gil et al. [55]. Furthermore, various other materials have been tested using the pilot plant, including commercial paraffins (RT58), byproducts (Bischofite), sugar alcohols (d-mannitol), organic compounds (hydroquinone) and inorganic compounds ($NaNO_3$ and molten salts).

References

[55-60]

PROCESS DESCRIPTION	
Analyzed process	No further information can be introduced due to the research nature of this set-up.
Integration goal	Reduce the final energy consumption of the final user
Thermal source(s)	Waste heat (Experimentally simulated with an electrical heater) In previous experiments, a solar field was simulated.
Thermal sink(s)	Undefined thermal process (Experimentally simulated with an HTF-air heat exchanger)
Heat transfer fluid	Silicone fluid (Syltherm 800)
Cycle frequency	No further information can be introduced due to the research nature of this set-up
Temperature range (°C)	105 - 155 °C. (Pilot plant can reach 380 °C)

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system	-	Latent
Technology readiness level	-	4
Storage capacity (system)	kWh	7.66
Nominal power	kW	3.5
Response time of TES	minutes	<1
Storage efficiency	%	95
Minimum cycle length of TES	h	4.38
Partial load suitability	-	Suitable
Auxiliary energy ratio	-	0
CAPEX per capacity	€/kWh	N/A
CAPEX per nominal power	€/kW	N/A
Storage material cost per CAPEX	%	N/A

KEY PERFORMANCE INDICATORS			
Stakeholder	Researcher	N/A	N/A
KPI 1	Partial load suitability		
KPI 2			
KPI 3			
KPI 4			
KPI 5			

Thermal energy storage in a packed bed for industrial solar applications

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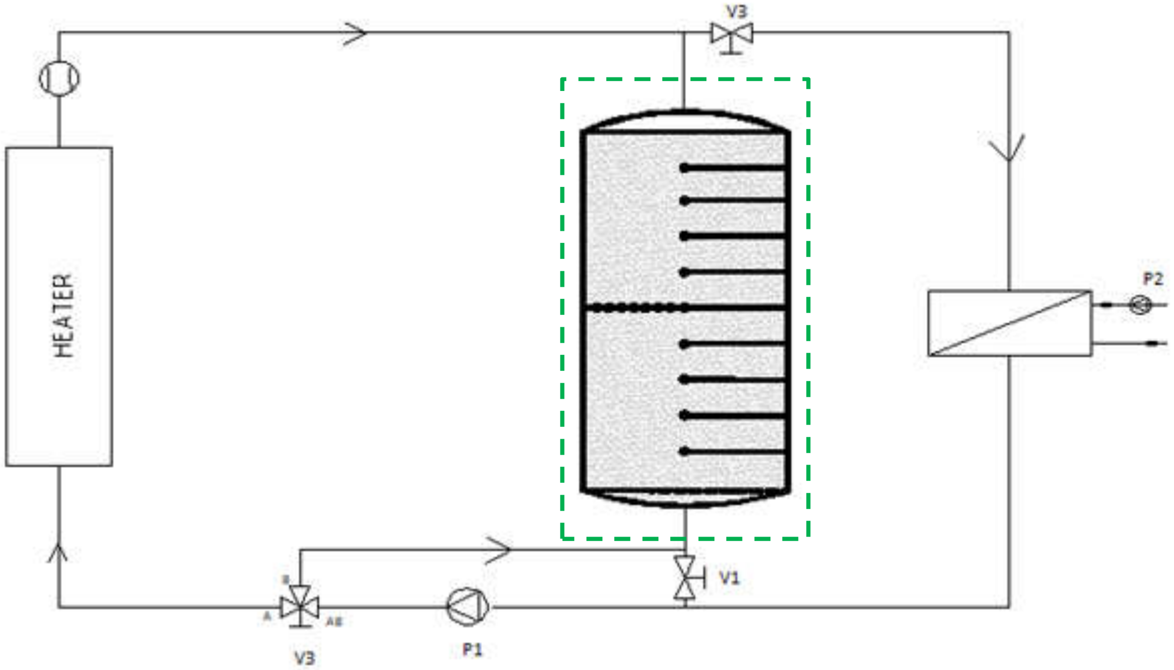

Fig. 4.24. Sensible heat thermal energy storage in packed bed.

Process Description

A straightforward way to prevent environmental degradation and reduce energy costs in industry is the effective use of renewable energy sources. Processes in the food sector, especially in the 100 - 200 °C temperature range, have great potential for solar energy usage. But the efficiency of solar energy varies according to different times of the day and season. For this reason, solar energy should be stored with an appropriate TES method.

The aim of this study is to develop sensible heat TES in a packed bed at 130 – 180 °C that will be suitable for industrial solar applications. In the packed bed, construction wastes from urban regeneration are used as sensible heat storage. This provides the cheapest storage material and makes waste material useful.

Integrating TES and using cheap storage materials is essential for economical solutions for industrial applications. This can lead to significant savings from imported energy resources in Turkey. These savings will decrease CO_2 emissions, contribute to the economic growth of Turkey and increase energy security and competitiveness of industry.

Thermal Energy Storage System Description

Fig. 4.25. Packed bed thermal energy storage system in the lab.

In this study, packed bed system is developed as a SHTES media and the TES system parameters can be found in Table 4.3. The packed bed column is a cylindrical storage tank of 0.30 m diameter and 0.90 m height. Aspect ratio htank/Dtank is 3. According to Bruch et al. (2014), the ratio the characteristic dimension of the tank to the rock should be greater than 30, i.e. Dtank/Dr > 30, to have negligible wall effects. Synthetic thermal oil will be used as heat transfer fluid in temperature range of 130 -180 C. The density (ρf), kinematic viscosity(νf) and the specific heat capacity (Cpf) of the synthetic thermal oil vary with temperature.

Table 4.3. TES system parameters

Parameter	**Value**
Height of storage tank; h_{tank}	0.90 m
Diameter of storage tank; D_{tank}	0.30 m
Bed void fraction	0.45
Inlet temperatue	130C-180C
Diameter of STESM, D_s	≤0.01 m
Density of STESM, ρ_s	2100 kg/m^3
Specific heat of STESM, Cps	1400 J Kg^{-1}K^{-1}
Density of heat transfer fluid, ρ_f	Eqn. 1
Specific heat of heat transfer fluid, Cp_f	Eq.3
Fluid velocity; V_0	0-12 mm/s

References

[61]

PROCESS DESCRIPTION	
Analyzed process	Various processes in the food industry
Integration goal	Integration of STES systems in industrial solar applications aims to reduce the dependency on fossil fuels and to increase the efficiency and competitiveness of the industry
Thermal source(s)	Solar heat
Thermal sink(s)	Processes using steam in the food industry
Heat transfer fluid	Therminol 66 synthetic heat transfer fluid
Cycle frequency	Once per day
Temperature range (°C)	130 – 180 °C

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Sensible
Technology readiness level		TRL 3 - 5
Storage capacity	kWh	7
Nominal power	kW	16.8 (charging)
Response time of TES	minutes	8
Storage efficiency	%	Storage tank is still under construction
Minimum cycle length of TES		50 min
Partial load suitability		<u>Suitable:</u> the system fulfils the four statements.
CAPEX per capacity	€/kWh	1205
CAPEX per nominal power	€/kW	502
Storage material cost per CAPEX	%	0.036%

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Industrial customers**	**Electric Utility**	**Government**
KPI 1:	Storage capacity	Efficiency	Efficiency
KPI 2:	Lifetime	Power	CO2 Footprints
KPI 3:	Discharge time		Waste reduction
KPI 4:	Response time		
KPI 5:	Power		
KPI 6:	Efficiency		

Waste heat recovery using latent heat transportation system

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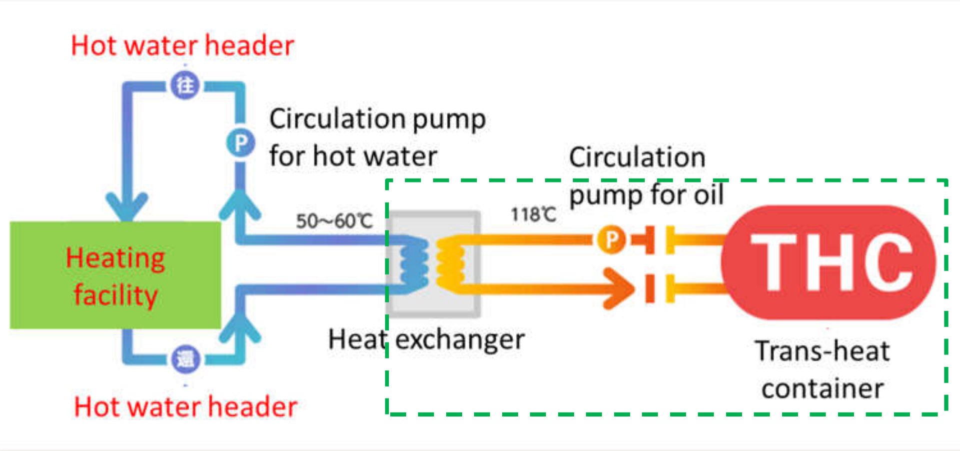


Fig. 4.26. Cooling with an mobile heat storage unit (Trans-heat) with indicated system boundary.

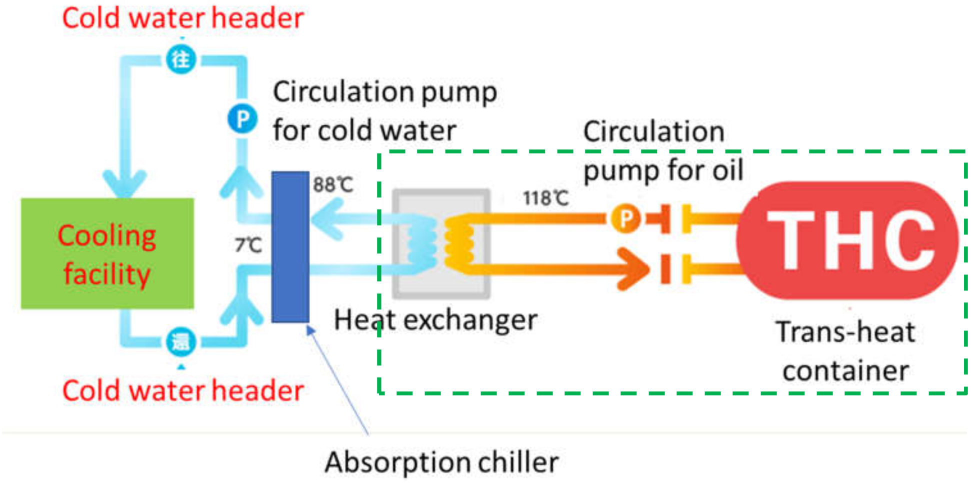


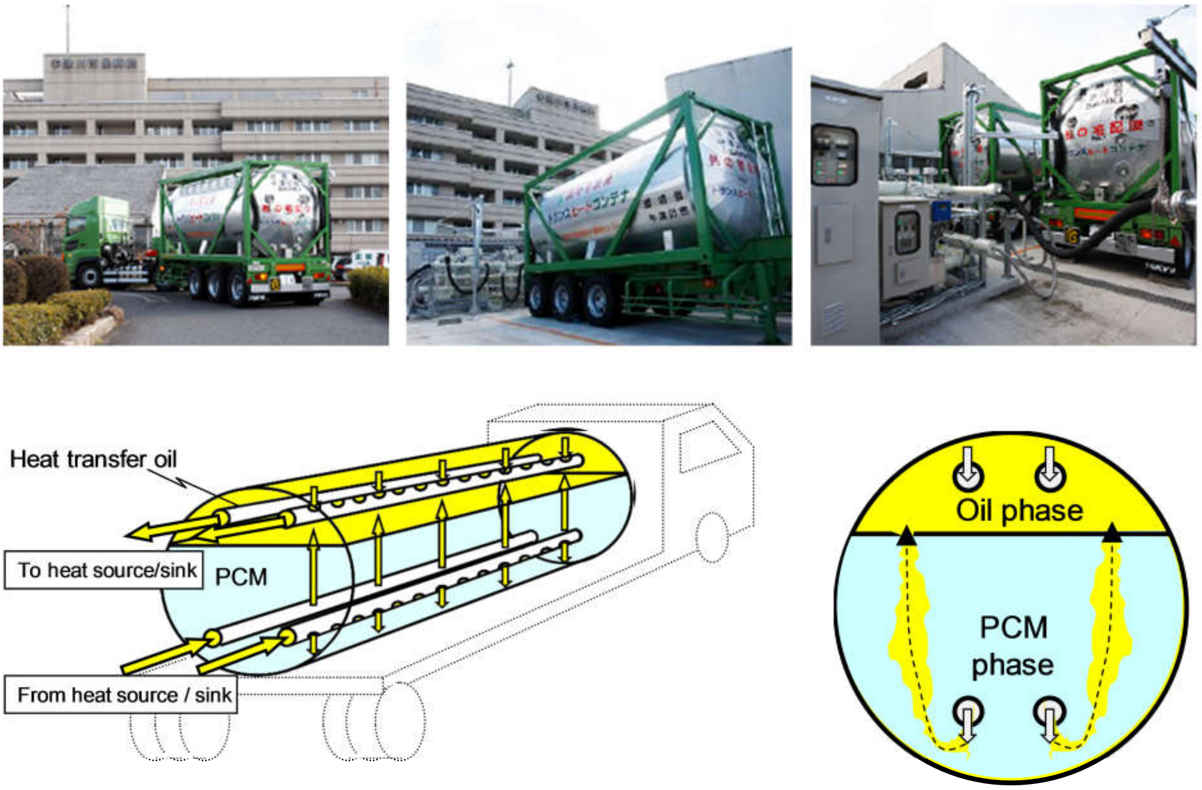
Fig. 4.27. Heating with an mobile heat storage unit (Trans-heat) with indicated system boundary.

Process Description

The process analyzed in this case is a heat transportation system using phase change material to recover industrial waste heat, transport it into cities and utilize it as heat sources for hot water supply and air conditioning. The PCM is packed in a heat transportation container and it can be transported by a container truck. Here industrial waste heat generated in local processes can be used to overcome a mismatch in time and space to recover and supply heat by using a heat transportation system. The goal of the storage integration is to utilize waste heat to save fossil fuels and reduce CO_2 emissions. This is a retrofit case where already-existing heating and cooling solutions in buildings will be supplemented with waste heat from an off-site location.

Thermal Energy Storage System Description

The mobile heat storage container (Trans-Heat container) contains approximately 14.6 tons of erythritol (T_m: 118ºC, L: 340 J g^{-1}) and a direct-contact heat exchanger that transfers heat between the PCM and a heat transfer fluid (HTF). The HTF is an insoluble thermal oil that is non-reactive with erythritol. The container and heat demand or supply systems are simply connected and disconnected with flexible tubes. Currently, around 28 km of heat transportation has been realized. The system can be controlled by a single operator and the stored heat is used as a heat source for hot water or for an adsorption chiller to supply cold water.



Overview of heat transportation container

Cross-section of the container

Fig. 4.28. Photos and schematic images of a latent heat transportation system.

References

[62, 63]

PROCESS DESCRIPTION	
Analyzed process	Building hot water and air conditioning facilities
Integration goal	To recover and transport low temperature unused heat sources from industrial plants and waste disposal/treatment facility.
Thermal source(s)	i) Waste heat from plant, ii) Excess steam from fire-plant for industrial waste, iii) Excess steam from fire-plant for non-industrial waste
Thermal sink(s)	Hot-water supply, space heating, absorption chiller
Heat transfer fluid	Thermal oil (source) and water (sink)
Cycle frequency	Once or twice per day
Temperature range (°C)	90 - 140°C (Temp. range of PCM and supplying heat)

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Latent
Technology readiness level		8 - 9
Storage capacity	MWh	1.4 per container
Nominal power	MW	0.2 – 0.3
Response time of TES	minutes	1 – 2 min (Stabilization of flow rate of oil and warming up of pipes)
Storage efficiency	%	90 - 95
Minimum cycle length of TES		About 10 h (Average)
Partial load suitability		Not suitable
CAPEX per capacity	€/kWh	> ca. 190 (only for container)
CAPEX per nominal power	€/kW	> ca. 900 (only for container)
Storage material cost per CAPEX	%	N/A

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Fire plant (heat source)**	**City (heat demand)**	**Policy maker**
KPI 1:	Storage density	Storage density	Fuel reduction
KPI 2:	Heat exchanger rate	Heat exchanger rate	CO2 reduction
KPI 3:	Material durability	Fuel reduction	
KPI 4:	Fuel reduction	CO2 reduction	
KPI 5:	CO2 reduction		

Waste heat recovery with PCM with the sailing heat concept

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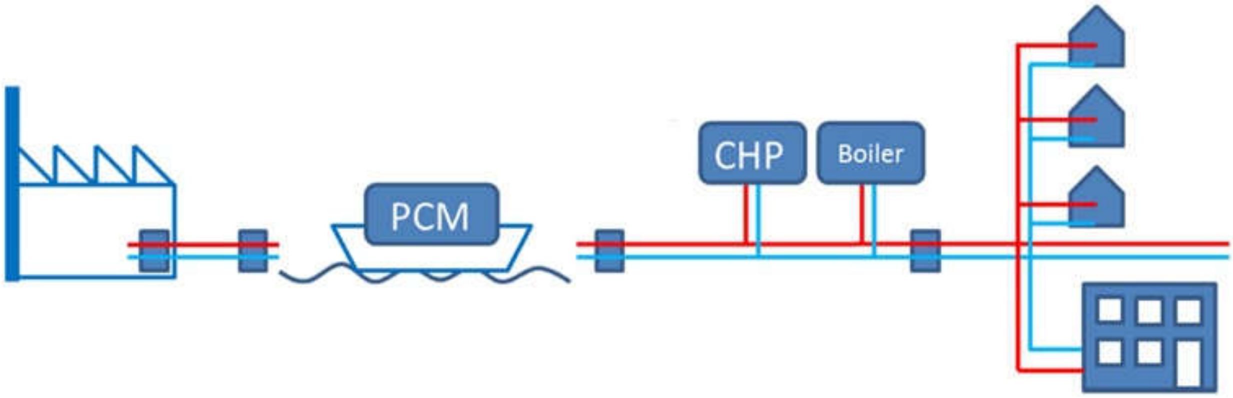


Fig. 4.29. Schematic representation of the sailing heat concept.

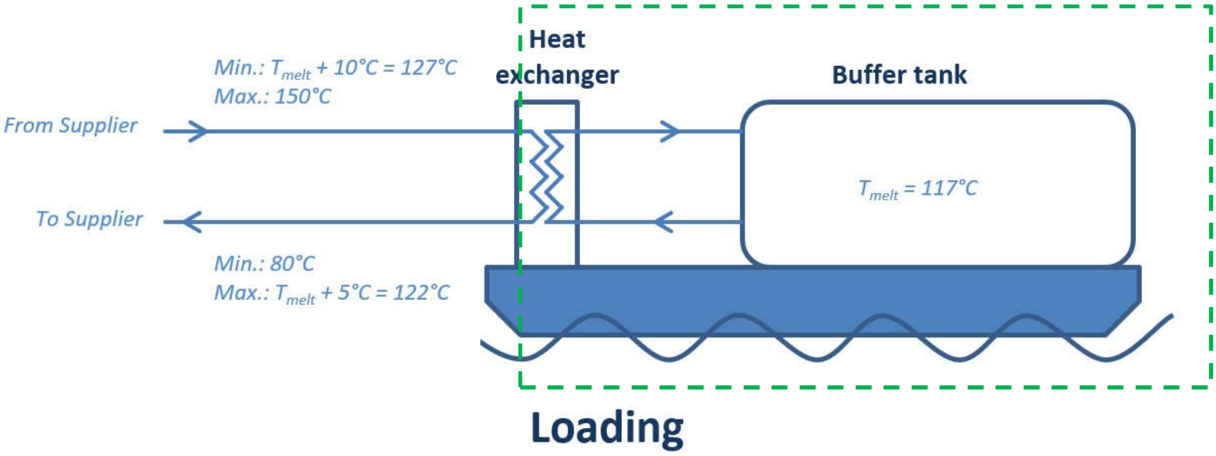


Fig. 4.30. Sailing heat barge with indicated thermal storage system boundary.

Process Description

In industry, a large amount of waste heat is available that cannot be recovered and reused on site. The alternative option of using this heat for district heating can be problematic due to the large distances between thermal source and sink, as well as high investment costs for district heating infrastructure. In the present case, waste heat from industry is available in the temperature range of 130 – 150°C at a location 20 km from a district heating network. The purpose of the present integration is to transport this waste heat to the district heating system by push barge. This concept is considered applicable for many industrial sites, since industrial operations are often located near waterways, allowing for heat transportation by boat. This case is considered to be a retrofit case, as the process infrastructure is already in place and operational before integration of the TES system has occurred in this conceptual study.

Thermal Energy Storage System Description

The heat storage system is a large PCM storage located on a push barge. The storage contains $MgCl_2.6H_2O$ (melting point ~117°C) in a shell-and-tube configuration. Each tank contains 90 tons of PCM, so 2520 tons of PCM per barge. The tubes in the shell and tube configuration are made of nylon and are carrying pressurized water as heat transfer fluid. The nylon tubes have 16 mm internal diameter and are arranged in a triangular pitch at a distance of 50 mm. The tubes are arranged in 16 vertical passes, giving a single tube length of 50 m and 500 tubes per tank in parallel. Total tube length per tank is 25000 m, with 1250 m^2 of heat exchange surface between tubes and PCM.

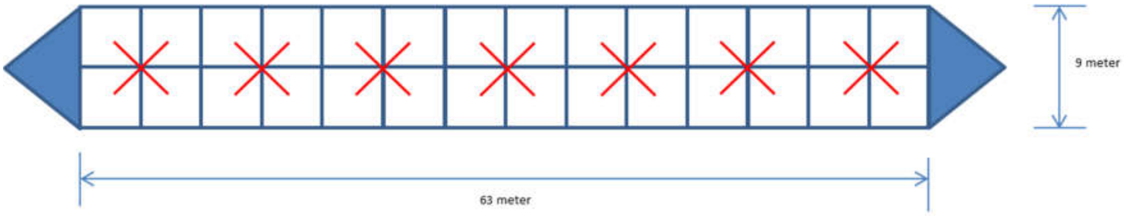


Fig. 4.31. Geometry of barge with storages (top view).

It is assumed that the heat is transported by two push barges, which are equipped with 28 PCM tanks, as shown in the figure above. A push boat is used to push the barges from heat source to heat supplier and back. The distance between charge and discharge location is 20 km and the barges are assumed to have a speed of 12 km/hour. A cycle of bringing a thermally charged barge to the heat consumer and returning the discharged barge to the heat supplier is considered as reference case. In this situation it is of importance that the timing of charging, discharging and transportation are such that the demands for the heat supply system can be met.

With the charging time and transportation time to be the rate limiting step, a total number of 300 charge-discharge cycles is achieved with the 2 barges. This provides 188,000 GJ/year of heat delivered to the district heating network, equivalent to the consumption of 5.9 million m^3 of natural gas. To transport the thermal storage barges, the ship needs a calculated amount of diesel of 6700 GJ/year and a comparable amount is calculated for the primary energy needs for electricity (650,000 kWh/yr) to run the pumps for the heat transfer fluids. The primary energy ratio of energy consumed over thermal energy delivered is 7%. The calculated carbon ratio, being the ratio of CO_2 emitted over CO_2 emissions avoided, is 9%. The CAPEX for two barges with PCM, tanks and heat exchangers, as well as onshore installations, is estimated at €6 million, of which the cost of the PCM storage on one barge is estimated at €2.4 million. The CAPEX is dominated by tank, heat exchangers and pipes, while the OPEX is dominated by labour costs (staff), followed by fuel and maintenance. The calculated economic payback time is 11 years.

References

[64]

PROCESS DESCRIPTION	
Analyzed process	Heat transportation system with industrial waste heat as a source for district heating
Integration goal	Provide technical and economical viable heat transportation of surplus heat from industry to cities.
Thermal source(s)	A range of waste heat sources with min. temperature of 130°C.
Thermal sink(s)	District heating system
Heat transfer fluid	Pressurized water
Cycle frequency	Once per day
Temperature range (°C)	T_{charge} ~127°C, $T_{discharge}$ ~77°C.

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Latent
Technology readiness level		3 - 5
Storage capacity	MWh	162 (583 GJ)
Nominal power discharging	MW	22.4
Nominal power charging	MW	7
Response time of TES	minutes	2
Storage efficiency	%	N/A
Minimum cycle length of TES		~2 days (~1 day charge & ~1 day discharge per barge)
Partial load suitability		Technically suitable but economically unsuitable
CAPEX per capacity	€/kWh	15
CAPEX per nominal power	€/kW	346 (based on charge power)
Storage material cost per CAPEX	%	17

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Waste Heat Supplier**	**Process Operator**	**District Heating Operator**
KPI 1:	Recycling of heat (energy efficiency)	Thermal power	Temperature level
KPI 2:	Energy saving	Temperature level	CO_2 emissions reductions
KPI 3:		Storage capacity	Cost of delivered heat
KPI 4:		Cost of delivered heat	

4.3 Application evaluation

Thermal energy storage systems have been standard process components in industrial processes since the 19th century. Regenerator storages are benchmarks in the key sectors of steelmaking and glass manufacturing. Furthermore, steam accumulators have seen widespread use in industrial processes for buffering of steam. These benchmarks are briefly summarized in the table below.

Table 4.4. Non-exhaustive selection of relevant system parameters for benchmarks in industrial processes.

	Regenerator (steelmaking)	**Regenerator (glass production)**	**Steam Accumulator**
Temperatures (°C)	1250 – 1400	300 – 1400	150 – 230
ESCsys (MWh)	140	10	up to 30
Pnom (MW)	140	30	variable
SCCreal (€/kWh)	15 – 40	N/A	70 – 300
Cycle frequency	2/hour – 1/3 hours	3/hour	several/day

Modern and novel uses of thermal energy storage in industrial processes represent the most diverse application field in this report. Excluding the benchmarks, there is no standard integration of TES technologies into industrial processes and there are various storage types that have been deployed. Nevertheless, especially at high temperatures, there are several examples of innovative storage systems that have already reached technology readiness levels close to commercial applicability. This report highlights sensible storage in solids (bulk materials or bricks) for gaseous heat transfer fluids at high temperatures, sensible storage in liquids (water, oil, salt, bitumen) and hybrid sensible storages that combine solid and liquid phases. Additionally, latent heat storages and thermochemical storages have found use in industrial processes. Based on this diversity of technology, an evaluation can only highlight some specific examples that emphasize the utility of TES systems in industrial processes.

Beginning with sensible heat storages, there are many outside of the realm of regenerator benchmarks that have reached a high technology readiness level at lower temperature levels. Most noteworthy is the pressurized hot water storage that has been implemented in a batch polymerization process. This storage has an ESC_{sys} and CAPEX (€/kWh) that is in the range of the pressurized water storages from DHC, suggesting a high potential for technology transfer between these applications. Furthermore, the unconventional use of a bitumen storage and water storage together in a single application highlights the breadth of opportunities available for storing heat for industrial processes. Through such applications, new perspectives can be considered that re-evaluate product/educt streams or storages as thermal masses that can help increase flexibility.

The sensible storages highlighted here are cycled daily, often with multiple cycles per day. The multiple streams of waste heat used for charging the TES system in the foundry case study[+] underline the various purposes that a single storage can fulfil in an industrial process. The modular nature of the storage also allows adaptation to various levels of required capacity in a process. Also at the low-TRL level, a packed bed with sensible heat storage has been used at a small scale in industrial solar applications for temperatures from 130 – 180°C.

Latent heat storage and thermochemical storage in industrial processes remain at a low level of development. Nonetheless, there are examples of high-temperature latent heat storage for steam generation and thermochemical storage for cold generation reaching TRL levels of 5. In the latent heat storage case, the TES system is being integrated into a CHP-process for backup of steam generation and will serve as a forerunner for high-temperature latent heat storage for industrial process steam applications.

Two cases of mobile heat storage for waste heat from industrial processes are also highlighted in this report. These cases represent a novel approach to energy efficiency in instances where waste heat is generated and a thermal sink is located either in a district heating system or in non-residential buildings.

In summary, TES for industrial processes is a highly diverse sector in terms of potential applications. The TES systems can reduce the use of backup systems, preheat components and compensate for fluctuations in available heat sources.

However, the use of the TES system relies entirely on the specific process requirements and therefore only standard applications such as generation of industrial process steam or low-temperature drying processes could be prone for standardized thermal energy storage solutions. As such, there are very few standard TES storages for industrial processes, unlike in district heating and to some extent non-residential buildings and power plants. The thermal sources are often some form of waste heat that is either used on-site for reintegration or generation of power/cold, or transported to a thermal sink, even in another sector entirely.

Thermal energy storages in industrial processes deliver a broad range of benefits including waste heat recovery at various temperature ranges, reduction in the use of fossil fuels and increase in process flexibility. Currently, TES systems will in most cases be retrofit solutions to already-existing industrial processes being optimized in terms of output and quality of the product. The integration of a thermal energy storage as an additional process unit must not change the process itself and should at the same time be beneficial in terms of process flexibility and/or energy efficiency. Integrations of innovative thermal energy storage systems will therefore mostly be first-of-its-kind applications with high technical and economic risk. Until TES becomes a standard industrial process component for greenfield installations, financial support from funding agencies will be needed to overcome this hurdle, bring down storage costs and collect important operational experience in the industrial environment.

[+] pg. 79

Identified key performance indicators of TES systems in industrial processes are shown below. It should also be noted that given the wide variety of thermal energy storage in industrial processes, it is not feasible to create generalized tables as can be found in tables 2.1 and 3.1. Furthermore, this report features nine of these cases and given this total, they have not been depicted in a singular table as in Table 5.3 in the coming chapter and are represented in the text only.

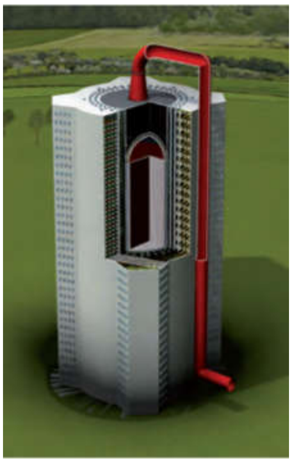
Table 4.5. Key performance indicators in industrial processes.

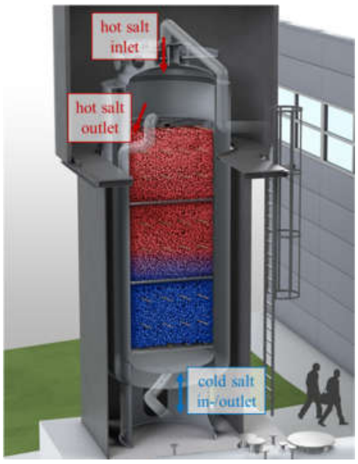
Stakeholder:	**Process owner**	**Energy utility**	**Industrial customer**
KPI 1:	Economic benefit (waste heat usage)	Industrial process flexibility (grid balancing)	Environmental benefit
KPI 2:	Environmental benefit	Net economic benefit	Product cost reduction
KPI 3:	Discharging power	Net environmental benefit	
KPI 4:	Process flexibility and reliability	Higher flexibility in process operation	
KPI 5:	Storage capacity		

5 Power plants

The following chapter examines the power plant application and its association to TES systems. Context is first given by an overview of TES integrated into power plants, an application with a strong focus on concentrating solar power. One benchmark case will be evaluated in particular. The chapter continues with a presentation and evaluation of five case studies of TES development for power plant applications. It concludes with an evaluation of the application based on the presented benchmarks and development cases. The contents of this chapter are shown in the table below.

Important note: the cases presented in this report should be understood as a non-exhaustive representation of each sector or technology. The goal of the Annex 30 network was to select interesting and informative cases that highlight key characteristics of thermal energy storage.





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DLR (R)

5.1 Benchmarks in power plants

Concentrating solar power plants with two-tank molten salt storage

Concentrating solar power (CSP) plants are novel solutions for generation of renewable electricity at utility-scale. By using mirrors to concentrate solar radiation on a small area, the power plants are capable of producing large amounts of electricity. The most mature techniques for concentration are solar tower/central receiver, in which mirrors (also known as heliostats) are dynamically positioned to redirect sunlight onto a receiver, and parabolic trough, where semicircular mirrors concentrate solar energy onto a long tube that heats a contained fluid [65]. In both cases, the heat transfer fluid is then sent to a power block where electricity is generated via a turbine. As of the end of 2016, 4.8 GW of CSP have been installed around the globe, over 80% of which is located in Spain or the US [66].

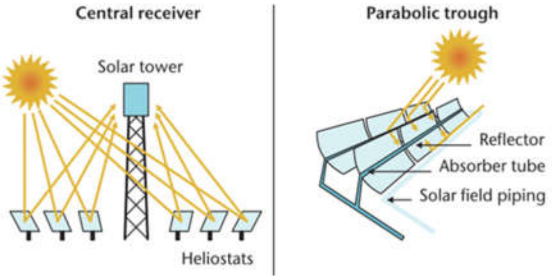

Fig.5.1. Mature technologies for CSP [65].

Process description

There are two methods for delivering concentrated solar radiation to the power block:

1. the receiver is used to directly generate steam which is sent straight to the power block, known as direct steam generation (DSG) as introduced previously, or
2. the receiver contains an intermediate heat transfer fluid (e.g. thermal oil, molten salt) that is used to produce steam that drives a turbine.

The main disadvantage of electricity generation from solar energy is the intermittency of the primary energy source that leads to a lower capacity factor of the power plant. A storage solution applicable for CSP technology is the introduction of a thermal energy storage system to store heat provided by the heat transfer fluid (HTF) in order to buffer through weather events and provide thermal energy for electricity generation when solar energy is otherwise absent (e.g. at night). The storage method presented in this benchmark is two-tank molten salt storage, as it is commercially available and currently the most common method of storing thermal energy in CSP plants [65]. Common benefits for integrating TES into CSP plants can be found in Table 5.1.

TES system description

In two-tank molten salt storage systems, hot salts are stored in one tank and cold salts in the other. There are two potential storage methods: direct storage and indirect storage. In direct storage, shown in Fig. 5.3, the storage medium of molten salt also acts as the heat transfer fluid, absorbing solar energy in the receiver and transporting it to the hot salt tank. After generating steam for the power block, the salts are circulated through the cold tank and sent back to the receiver. In indirect storage, the storage medium is decoupled from the heat transfer fluid and retrieves heat from the receiver via a heat exchanger. In general, direct and indirect storage for two-tank molten salts have comparable thermal storage capacities, but are differentiated by the required amount of storage material. In direct storage, higher temperatures can be achieved in the hot salt tank and since the storage capacity is a direct result of the temperature difference between hot and cold tanks, less storage material is needed than in indirect storage where lower hot tank temperatures are present [67]. Originally demonstrated in 1991, there are currently 69 two-tank molten salt thermal storage systems operational or in planning [68]. Of 24 direct storage systems, seven are operational, seven under construction and 12 under development with a combined hourly capacity of 270 hours. Comprising 44 indirect storage systems, 28 are operational, six under construction and 10 under development can be found with a combined 298 hours of storage capacity [69].

Fig. 5.2. Molten salt storage tank (© Solar Reserve).

Molten salt storage systems are a common form of sensible heat storage that causes a temperature change in a solid or liquid material to store or release thermal energy. The storage material often used is a eutectic salt mixture of 60 wt% $NaNO_3$ and 40 wt% KNO_3, known as "solar salt". Molten salt technology in a direct storage configuration is shown in Fig. 5.3 [70]. The direct storage configuration is charged by pumping the cold salt through the receiver tower where solar energy heats it to 565°C. It then enters the hot tank where it is stored until required for power generation, at which point the salt is sent to a heat exchanger where it generates steam for the turbine. After leaving the heat exchanger, the cold salt at 290°C circulates through the cold salt tank and back to the receiver tower to be heated again.

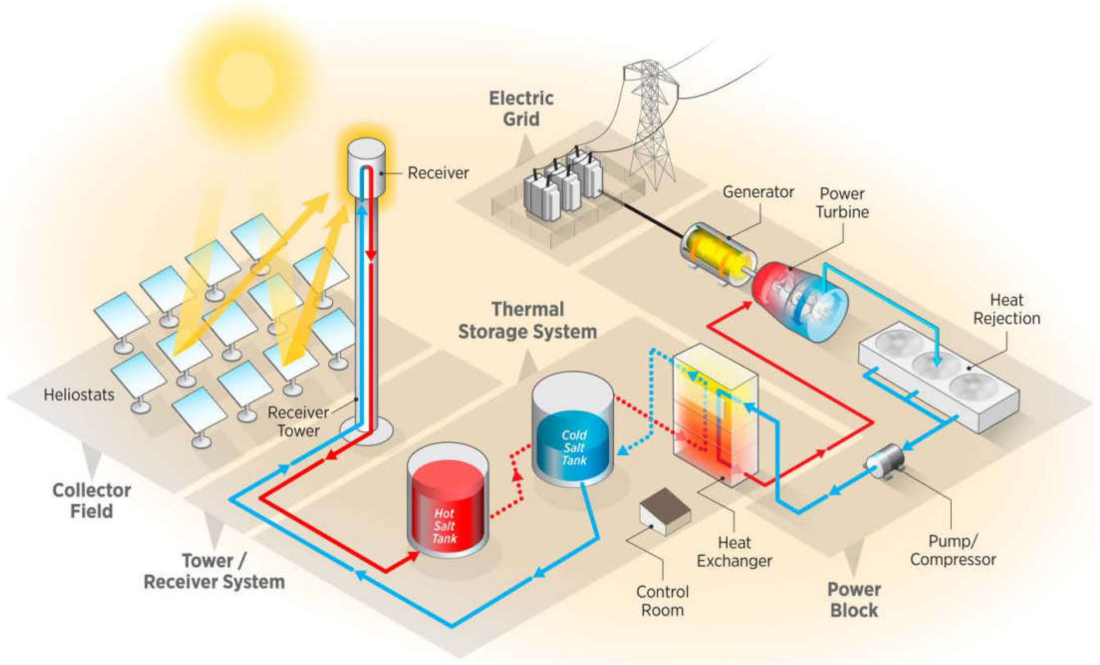

Fig. 5.3. State-of-the-art molten salt direct storage system in a central receiver power plant [70].

For a CSP central receiver plant with two-tank direct storage of solar salt, cost estimates for the entire power plant range from 10.3 – 14.2 US ¢/kWh depending on heliostat technology [70]. Regarding costing of the TES system, a direct storage system using solar salt (upper limit of 565°C) ranges from USD 20-33 per kWh, which is highly dependent on the storage material costs [70]. Considering that the storage material inventory makes up 51-57% of the total system cost, the upper limit can be reduced to USD 27 per kWh if a lower salt price per ton is used (Abengoa price of USD 1100/t) [70]. Another significant cost is assumed by the storage tanks, which cover 20-30% of the total storage system cost.

For indirect storages, the storage material inventory is responsible for 49% of the total storage cost – a value similar to that of direct storages. The storage tanks generally make up a smaller share, taking just 17% of the total storage cost while heat exchangers, unnecessary in direct storage, occupy 13% of the total cost [70].

Table 5.1. Process benefits delivered by integrated TES [1].

Outcome of TES integration	**Description**
Increased plant capacity factor	- Night-time generation - Buffering during weather events
Improvements in energy efficiency	- Less curtailment during periods of high generation - Lowering turbine start-up losses
Dispatchable power	- Economic incentives - Improved grid flexibility
Reduced LCOE	- Maximized generation at peak demand - Reduction in solar multiple (i.e. smaller solar field)
Ancillary benefits	- Start-up buffering & avoiding back-up capacity - Frequency regulator for power grid

Crescent Dunes CSP plant with two-tank direct molten salt storage

Commissioned in 2015, the 100 MW_{el} Crescent Dunes project in Nevada, USA is a prominent example of direct thermal energy storage in two-tank molten salts, as shown in Fig. 5.4. The TES system stores approximately 3300 MWh of thermal energy in solar salt that corresponds to a total storage duration of 10 hours. This is a commercial example of a state-of-the-art design for CSP that generated over 125 GWh of electricity for the Nevada grid in 2016.

Fig. 5.4. Crescent Dunes CSP plant (© SolarReserve).

PROCESS DESCRIPTION	
Analyzed process	Crescent Dunes CSP plant with direct thermal energy storage in two-tank molten salt
Integration goal	see Table 5.1
Thermal source(s)	Solar receiver
Thermal sink(s)	Steam generator in power block
Heat transfer fluid	Molten salts (direct thermal energy storage)
Cycle frequency	Once per day
Temperature range (°C)	288 – 565°C

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Sensible
Technology readiness level		8 to 9
Storage capacity	MWh	10 hours (approximately 3300 MWh)
Nominal power discharging	MW	330
Response time of TES	minutes	<1
Storage efficiency	%	99
CAPEX per capacity	€/kWh	ca. 20

5.2 TES systems in development

Molten salt thermocline in concentrating solar power

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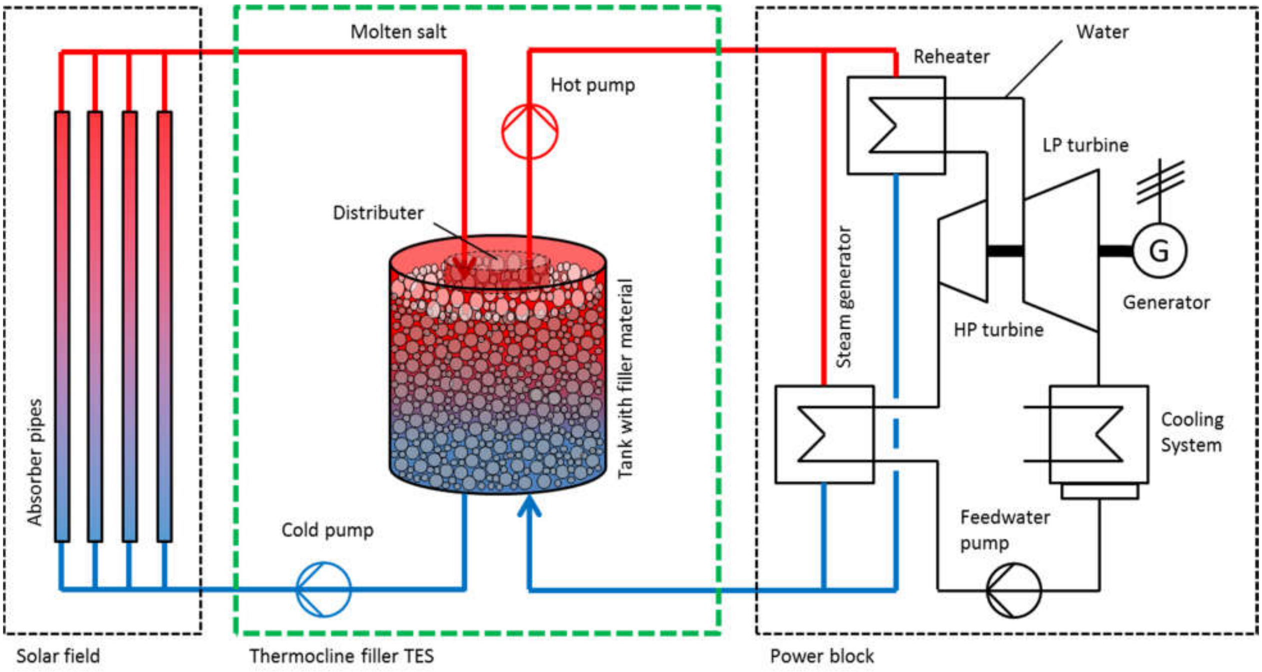

Fig. 5.5. Molten salt thermocline filler storage (in green) integrated into a concentrating solar power plant.

Process Description

As described in the benchmark on two-tank molten salt TES, CSP plants use storage to provide numerous technical and economic advantages to the process and the greater energy system. Nevertheless, two-tank molten salt storage does still have opportunities for optimization.

There are several cost reduction potentials in large-scale thermocline storages with filler material. One, a large portion (up to 75%) of expensive molten salt is replaced with inexpensive natural stones. In addition, only one single tank is necessary. Hence not only the costs per kWh can be cut by 30-40% (depending on the process integration) but also the gas volume exposed to thermal cycling can be reduced drastically which leads to lower gas expansion and contraction and thereby lower or no emissions to the environment.

In the thermocline filler storage concept, a temperature zone (the thermocline) moves through a packed bed within the tank when charged with hot salt from the top or discharged with cold salt from the bottom. At the end of a charge or discharge cycle this zone is partly extracted from the storage. Thus the solar field and the power block will experience a temperature increase or decrease respectively. After many cycles the thermocline zone expands which is why a partial extraction of the thermocline zone is a requirement to keep it narrow.

Thermal Energy Storage System Description

The storage system is a molten salt thermocline (single tank) with filler material. The tank measures 20m high and is in atmospheric pressure. It has a concrete foundation, high-temperature insulation and two molten salt pumps. The molten salt used is solar salt and basalt stones comprise the filler material. The storage components are non-toxic, non-flammable or explosive so pose no risks to the immediate environment and do not require additional measures regarding material toxicity.

Thermocline storages with filler material provide high energy densities and decoupling of power and capacity. Storage power scales with the size of the steam generator and the solar field, i.e. the solar multiple. The storage capacity however is scaled based on the size of the storage unit.

Molten salt is used as a heat transfer fluid and as such, the storage is suitable for application in direct thermal energy storage scenarios in CSP plants. Molten salt as a HTF yields a low pressure drop and effective heat transfer. A theoretical investigation has already been performed. Experimental tests are currently underway at the test facility TESIS in Cologne, Germany.

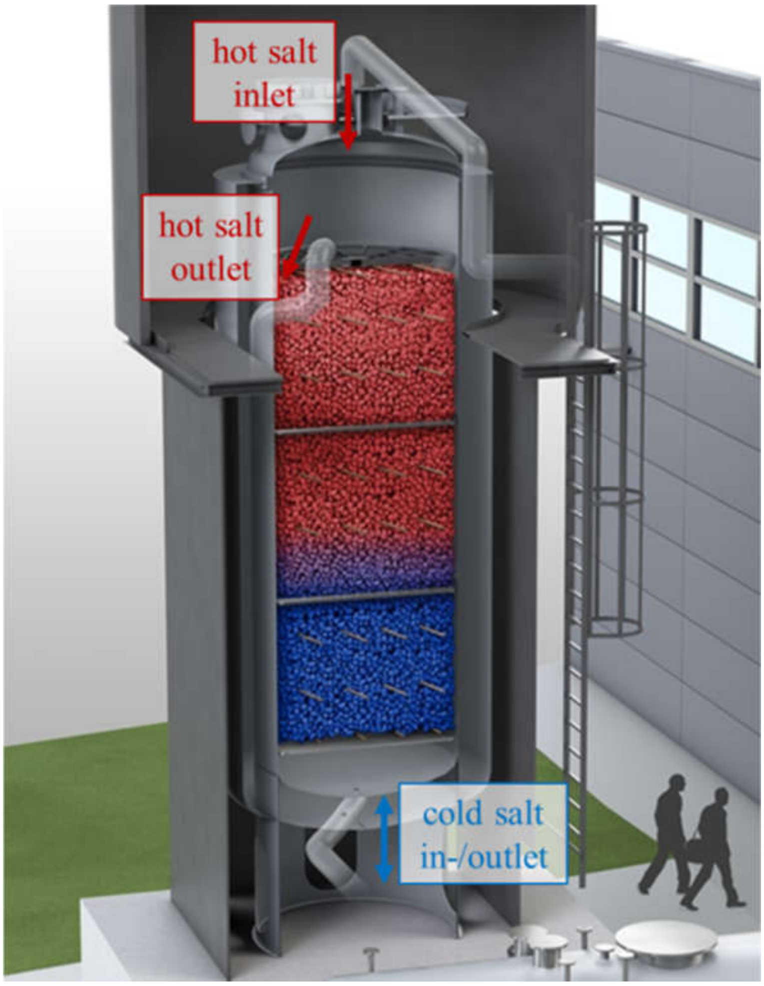

Fig. 5.6. Molten salt thermocline filler storage.

References

[71-73]

PROCESS DESCRIPTION	
Analyzed process	Parabolic trough CSP plant
Integration goal	Increase capacity factor of power plant by allowing dispatchable electricity and power plant efficiency improvements.
Thermal source(s)	Parabolic trough solar field
Thermal sink(s)	Steam generator in power block
Heat transfer fluid	Molten salt (solar salt)
Cycle frequency	Once per day
Temperature range (°C)	290-560°C

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Sensible
Technology readiness level		TRL 3 - 5
Storage capacity	MWh	2800
Nominal power	MW	235
Response time of TES	minutes	< 1
Storage efficiency	%	> 98
Minimum cycle length of TES	h	< 18
Partial load suitability		Suitable
CAPEX per capacity	€/kWh	18
CAPEX per nominal power	€/kW	92
Storage material cost per CAPEX	%	30

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Process operator**	**Grid operator**	**Government**
KPI 1:	Maximum delta-T during (dis)charge	Storage capacity	CO2 reductions
KPI 2:	Storage capacity	Power	Fossil fuel replacement
KPI 3:	Power	Dispatchability	
KPI 4:	LCOE reduction	Capacity factor	
KPI 5:	Dispatchability		

High-temperature thermochemical energy storage for CSP

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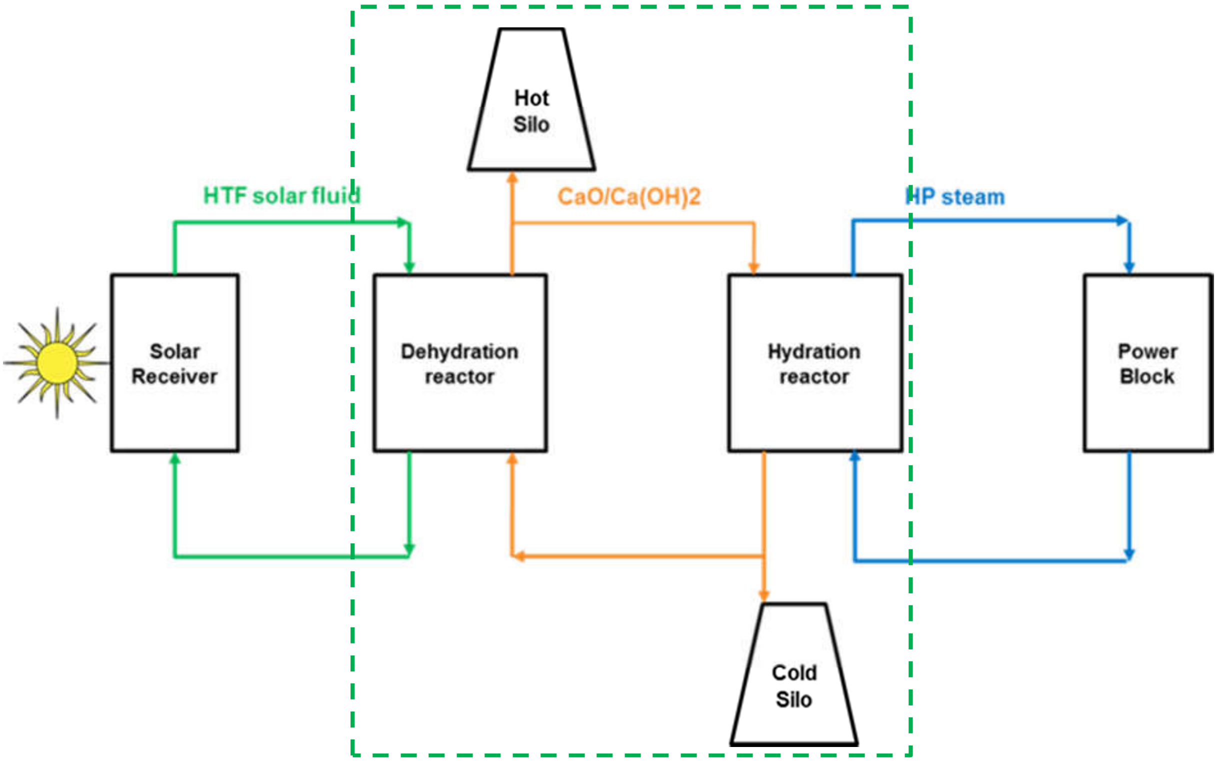

Fig. 5.7. Process diagram for CSP with thermochemical storage and an indirect dehydration loop.

Process Description

The process is a CSP plant with an 85 MWe steam turbine. The required steam properties are 110 bar and 550°C. The direct use of heat with a heat exchanger between solar fluid and water to produce HP steam is not represented here. The figure above present the principle of heat storage system that allow producing electricity without sun by storing the excess of heat during the day. Another interest is to be able to maintain, with the storage, the turbine at nominal power and maximum efficiency over a longer time period. This system can be used for short-term storage during the day without losses from the sensible heat of thermochemical material, as well as for longer-term storage depending on silo size.

Thermal Energy Storage System Description

The TES system includes a hot storage silo, a cold storage silo, a dehydration reactor, a hydration reactor and transport systems for the solid. On one side, the dehydration reactor design determines the storage nominal power, as hydration reactor determines the discharge power and they can be different. On the other side the silos volumes determine the energy storage capacity. Reactors are shell and tubes heat exchangers with fluid inside tubes and solid materials outside as a fluidized circulating bed. On specific solution could be to put the dehydration reactor directly inside the solar receiver and to have direct heat transfer to solid.

The COCHYSE facility from CEA is designed to study both dehydration and hydration in a single shell and tube type fluidized bed reactor. Silos and two transport systems (pneumatic and mechanical) are also included. Solid material and reaction used for this facility is lime:

Ca(OH)2 <--> CaO.

The values of the thermal energy storage system description hereafter are linked to this facility.

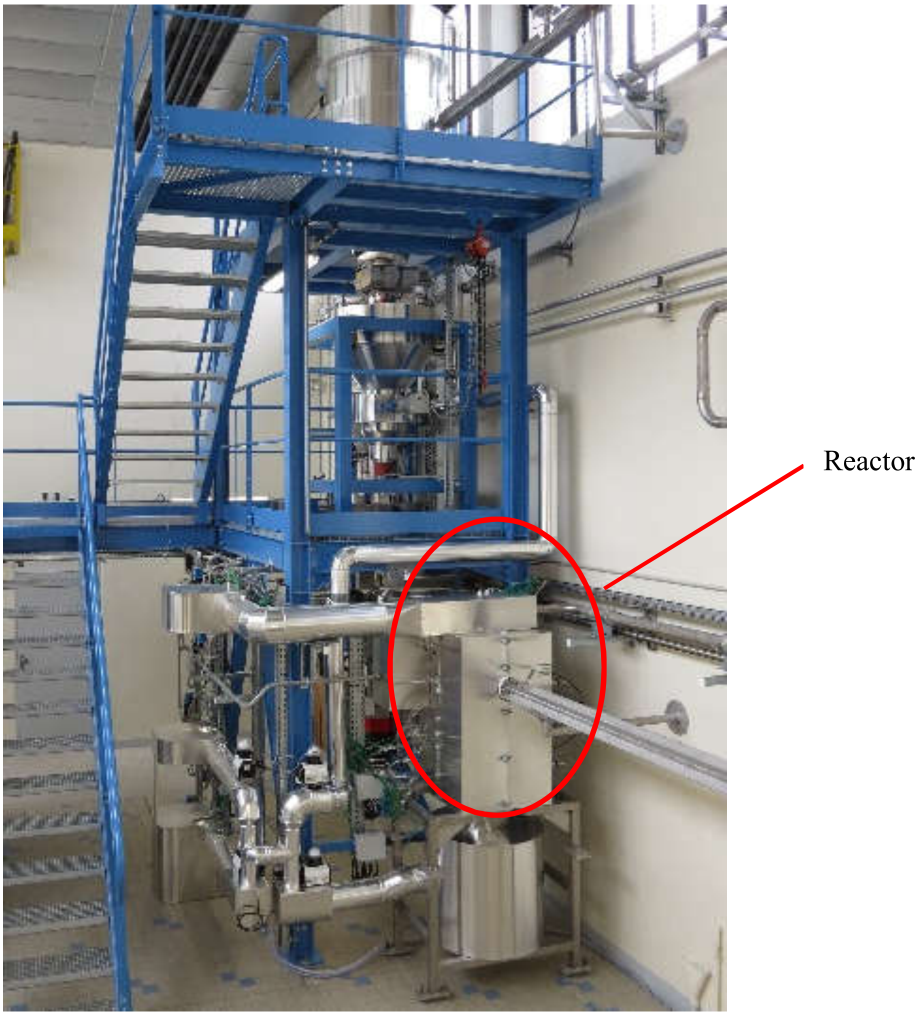

Fig. 5.8. Cochyse facility at CEA.

References

[74-76]

PROCESS DESCRIPTION	
Analyzed process	CSP plant
Integration goal	Increasing capacity factor of power plant, dispatchability of electricity, LCOE reductions
Thermal source(s)	Sun: direct (solar particle receiver) or indirect using a high temperature HTF (molten salt or other)
Thermal sink(s)	High-pressure steam generation
Heat transfer fluid	Solid thermochemical media
Cycle frequency	Once per day
Temperature range (°C)	> 600 °C

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Thermochemical
Technology readiness level		TRL 3 - 5
Storage capacity	kWh	15
Nominal power	kW	5
Response time of TES	minutes	5
Storage efficiency	%	60 % (size effect theoretically 97 %)
Minimum cycle length of TES		3 hours
Partial load suitability		suitable
CAPEX per capacity	€/kWh	N/A
CAPEX per nominal power	€/kW	N/A
Storage material cost per CAPEX	%	< 1

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Process operator**	**Industrial customer**	**Policy maker**
KPI 1:	Storage power	Storage density	Solid material life cycle
KPI 2:	Temperature level	Storage capacity	LCOE
KPI 3:	Process flexibility	Storage power	CO2 reductions
KPI 4:	Storage material cost	Solid material life cycle	
KPI 5:		Process flexibility	

Regenerator storage for process flexibility in combined cycle power plants

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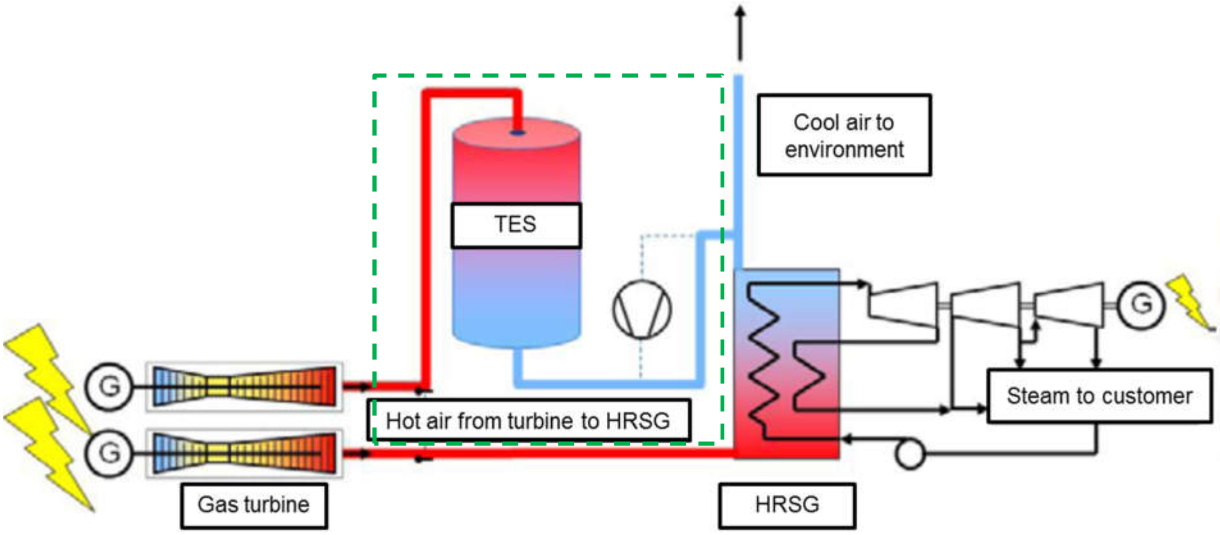

Fig. 5.9. Combined cycle power plant with integrated thermal energy storage system to provide flexibility.

Process Description

In combined-cycle gas turbine (CCGT) power plants, electricity and heat production are coupled. Combustion in the gas turbines generates electricity as a first step, then the exhaust gas is sent to a heat recovery steam generator (HRSG). The steam produced in the HRSG can either be sold directly to industrial clients or sent to a series of low- and high-pressure turbines to generate further electricity, raising the round-trip efficiency of the power plant.

Gas turbines often serve as peaker power plants and during times of low power demand, it is not in the interest of the power plant to continue generating electricity. Thus the production of steam is also curtailed. Integration of a thermal storage system can decouple the power and heat supply by charging the TES with excess heat during times of high power demand. Then, when power demand is low, thermal energy from the TES supports the steam boiler and heat is produced. This integration provides flexibility to compensate for fluctuations in variable renewable energy, supports grid stability and delivers balancing energy. A TES integrated into CCGT plant is a classic example of a retrofit application, in that it exploits a technical and economic potential in an already-existing process.

Thermal Energy Storage System Description

An concept design for an innovative regenerator-type storage for gas turbines has been prepared for this application. The storage design consists primarily of the components storage material, high-temperature insulation and storage container. Theoretical and experimental tests have been run on a test rig at DLR in Stuttgart, Germany that covered thermal, fluid flow and thermomechanical aspects of the storage. For regenerator storages the selection and geometric design of the storage material pose critical techno-economic design concerns that directly influence the component costs, storage power and thermal utilization. Selected for the storage material was thus specially-engineered ceramic bricks and bulk storage from natural stone.

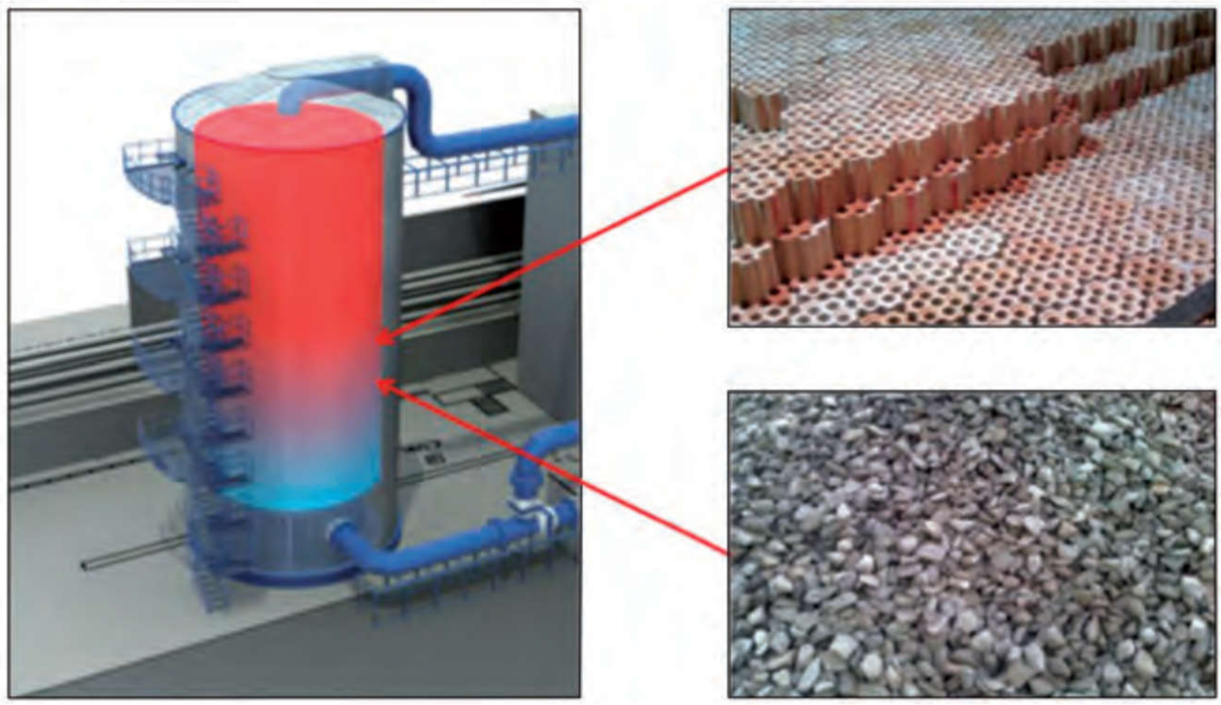

Fig. 5.10. Solid media thermal energy storage design for integration in a combined cycle power plant.

Conceptual design has been accompanied by investigation on material certification and further technical trials to reduce pressure losses in the bulk storage inventory, among other aspects. Following the theoretical design, a pilot storage for further verification and testing of the storage concept should be built. Preliminary technical parameters for this pilot plant are presented on the following page.

References

[77, 78]

PROCESS DESCRIPTION	
Analyzed process	Combined-cycle gas turbine power plant
Integration goal	Decoupling of power and heat supply that allows heat to be stored during times of high power demand
Thermal source(s)	Exhaust from gas turbine
Thermal sink(s)	Heat recovery steam generator
Heat transfer fluid	Flue gas
Cycle frequency	Once per day
Temperature range (°C)	400 – 600°C

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Sensible
Technology readiness level		TRL 2 - 4
Storage capacity	MWh	3,000
Nominal power	MW	250
Response time of TES	minutes	< 1
Storage efficiency	%	> 95 %
Minimum cycle length of TES		> 4 h
Partial load suitability		Suitable
CAPEX per capacity	€/kWh	N/A
CAPEX per nominal power	€/kW	N/A
Storage material cost per CAPEX	%	N/A

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Process Operator**	**Electric Utility**	**Policy maker**
KPI 1:	Storage capacity	Outlet temperature	Energy efficiency
KPI 2:	Mass flow	Discharge time	Flexibility of energy system
KPI 3:	Outlet temperature	Energy efficiency	
KPI 4:	Discharge time	Flexibility of process and energy system	
KPI 5:	Economic incentive (arbitrage)		

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Buffer storage for faster startup of combined cycle power plants

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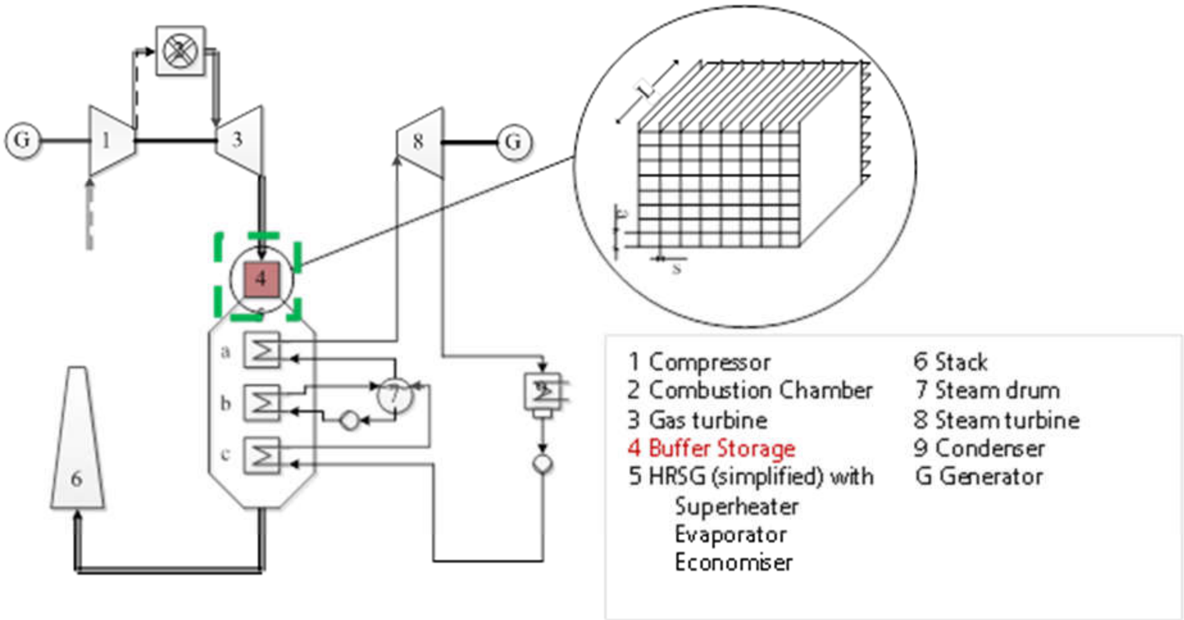

Fig. 5.11. Combined cycle plant with buffer storage to decouple gas turbine and heat recovery generator.

Process Description

To achieve a temporary decoupling of the gas turbine (GT) and heat recovery generator (HRSG) in a combined cycle power plant (CC) during startup and shutdown, a sensible thermal storage is placed in the flue gas path between the HRSG and GT (see Fig. 5.11).

The storage is charged during start-up from standstill and acts as a damper to the temperature increase of the flue gas from the GT. This allows operation of the gas turbine at the limits of its fast startup-capabilities without inducing significant thermal stress-induced fatigue damage in the HRSG. During shutdown, heat is extracted from the storage and the cooling of the flue gas is slowed down, again reducing thermal gradients and hence stresses in the HRSG. After shutdown, about ¾ of the stored thermal energy is left. This heat can be used to keep the HRSG warm and thus reduce thermal stresses of following startups. It furthermore minimizes the impact and damage of the purging procedure of the HRSG. In this procedure required prior to the next start-up, the HRSG is purged with three times its volume of air leading to a strong cooling of the system. In the investigated plant, the storage is capable of reducing the cycling fatigue damage in the most critical part of the HRSG by up to 90% and hence enables flexible operation of the GT as if it had no HRSG connected downstream.

As shown in [17] and [18], the faster start-up achieved though the storage integration leads to reduced startup costs and enables economic incentives through participation in e.g. the control power market. The integrated plant furthermore can provide the necessary flexibility and grid support to deal with intermittent renewable electricity generation.

Thermal Energy Storage System Description

A conceptual design for a sensible regenerator-type storage has been developed and analyzed for this application. A detailed modeling strategy has also been developed to assess the behavior of different storage geometries based on measurement data from a real plant GT startup, as shown in [16]. The storage consists of a matrix structure of steel plates mounted in the flue gas channel directly before the first heat exchanger bundle of the HRSG. The storage fills the 100 m² cross section of the flue gas channel at this point. The wide cross section reduces the flow speed inside the storage, minimizing pressure losses. For the investigated power plant, the storage has a length L of 0.75 m, a channel width of 10 mm and a steel plate thickness of 3 mm. The total heat exchanger surface area is 17 740 m² and a steel mass of 245 ton.

Fig. 5.12 shows the flue gas heat fluxes at the storage inlet, outlet and the resulting charging and discharging power (heat flux stored). After approximately 15 min. the storage power reaches a maximum of 100 MW. The storage is designed such that this point of maximum storage power coincides with the maximum thermal stress in the critical components, to achieve a maximum reduction of the thermal stress during startup.

Following the theoretical design, a pilot storage for further testing of the storage concept should be built to validate the operation and the pressure losses. Based on [16], the latter range between 1.5-2.5 mbar, resulting in a reduction of the overall plant efficiency of max. 0.1%.

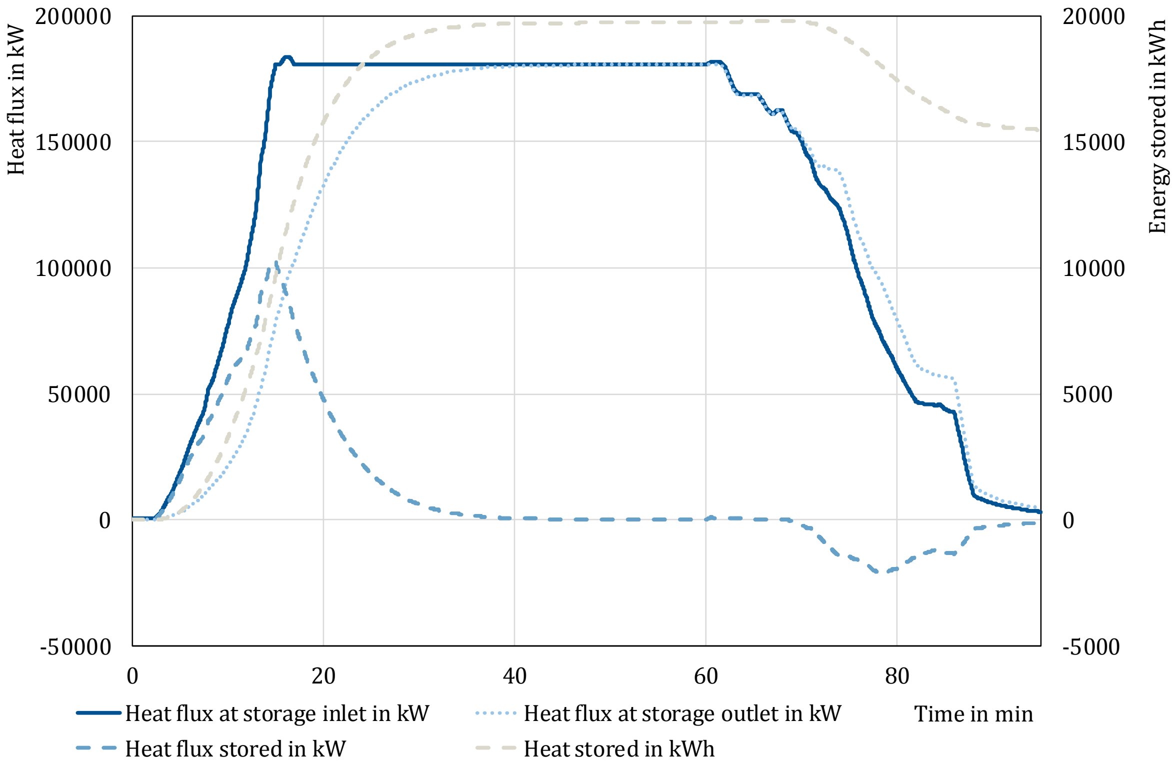

Fig. 5.12. Heat fluxes and storage charge state during charging and discharging of the storage.

References

[79-81]

PROCESS DESCRIPTION	
Analyzed process	Combined cycle power plant
Integration goal	Decoupling of gas turbine and HRSG to achieve faster gas turbine start-ups and higher flexibility of the power plant
Thermal source(s)	Flue gas from the gas turbine
Thermal sink(s)	HRSG (via flue gas from the gas turbine)
Heat transfer fluid	Flue gas
Cycle frequency	Depends on energy & control balance market – ca. once/day
Temperature range (°C)	400 – 600 (defined by process rather than storage)

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Sensible
Technology readiness level		TRL 2-3
Storage capacity	MWh	20
Nominal power	MW	100 (charging)
Response time of TES	minutes	15 (matches occurrence of max. stress peak)
Storage efficiency	%	> 95%
Minimum cycle length of TES		> 80 min.
Partial load suitability		suitable
CAPEX per capacity	€/kWh	N/A
CAPEX per nominal power	€/kW	N/A
Storage material cost per CAPEX	%	N/A (linked to steel price)

KEY PERFORMANCE INDICATORS

Stakeholder:	**Process Operator**	**Electric Utility**	**Policy maker**
KPI 1:	Economic incentive (control balance & day ahead energy markets, startup costs)	Increase in startup time	Flexibility of energy system
KPI 2:	Increase in startup time	Ramp rates of the electricity generation	
KPI 3:	Storage volume (retrofit)		
KPI 4:	Pressure & corresponding efficiency loss		
KPI 5:	Storage Outlet temperature		

Adiabatic compressed air energy storage power plant with regenerator heat storage

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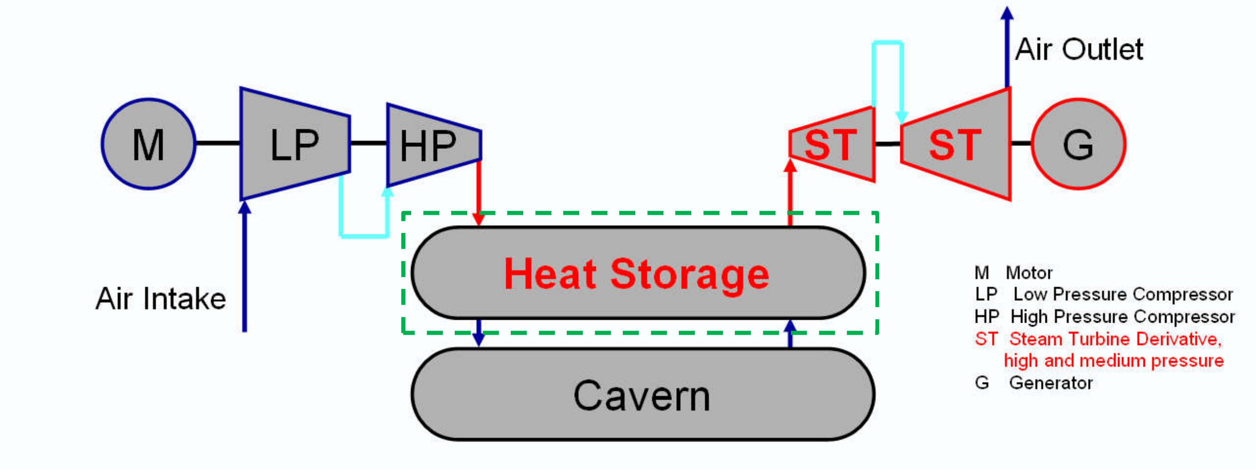

Fig. 5.13. Regenerator storage (in green) integrated into a compressed air energy storage power plant.

Process Description

In compressed air energy storages (CAES), electricity is used to compress ambient air which is then stored in an underground compressed air storage system consisting of a large cavern. During the initial compression process (shown in HP), heat is released as waste which contributes to a lower round-trip efficiency. Adiabatic compressed air energy storages (A-CAES) address this problem by reintegrating the compression heat into the discharging cycle. During loading of the A-CAES (compression of ambient air), the TES system absorbs the compression heat and stores it until the A-CAES is discharged, at which point it is reintegrated and used to preheat the cavern air before entering the turbine. This increases the round-trip efficiency of the A-CAES storage process from 50% without TES to 70% with TES.

By increasing the round-trip efficiency of the process, integration of the TES system contributes to reducing fossil fuel consumption of the power plant and subsequent emissions. Although only 2 CAES installations currently exist in the world, this can be considered a retrofit integration because the TES system is being integrated following design of the power plant and CAES.

Thermal Energy Storage System Description

One-stage A-CAES concepts have been developed within the European project "AA-CAES". As a result, such a process has high round-trip efficiencies (ca. 75 %) on the one hand. On the other hand, high temperatures of up to 600 °C and high pressures of 65 bar occur during charging phase, challenging the TES-component, which has to withstand the combination of thermal and mechanical stress. Besides that, no electrically driven compressor is available off-the-shelf operating at such high temperatures (600 °C) [82,83]. Therefore, within ADELE-ING project 2-stage concepts at utility-scale (100 MW_e) have been in development since 2013.

In the LP-stage, there are moderate pressures up to 15 bar and temperatures up to 400 °C. Highly-efficient and robust storage component (pressure vessel design) is required for this stage due to high energy conversion rate of this stage during discharging mode. Packed bed regenerator with low-cost solid media storage (natural stones like gravel, concrete, refractory bricks, for instance) and high energy densities due to high storage temperatures is favorable. Thus, solid media bulk and hollow brick storage are considered. The storage consists of 2 tanks of 15 m diameter and 40 m height. In charging, the pressurized air streams through a packed bed TES where the compression heat of the air is transferred in direct contact to the solid media storage material. Afterwards the air is cooled down for safety reasons by an additional cooler and enters the second stage. In discharging, the outlet temperature air from HP-expander enters the regenerator, which preheats the airstream to temperatures of 380 °C.

In the HP-stage, due to high pressures up to 80 bar, a heat exchanger is needed to transport the compression heat of the HP-compressor to the TES media. Here, salt storage, two-tank thermal oil storage or concrete storage are suitable options for the HP-stage because low-cost solid media storage with small exergy losses in heat exchanger is required. In charging, the pressurized air streams through the heat exchanger transfer heat to the flowing salt or oil on the other side of the heat exchanger. Afterwards the air is cooled down before entering the cavern. In discharging, air released from the cavern (40°C) enters the same heat exchanger, which uses the contrary flow from the hot oil/salt tank to the cold tank exchanging the stored thermal energy with the pressurized cavern air steam. During this process, cavern heat is preheated to temperatures of 300 °C before entering the HP-expander

The solid media bulk storage implemented in LP-stage in combination with two-tank oil storage within HP-stage obtain the highest efficiencies [84].

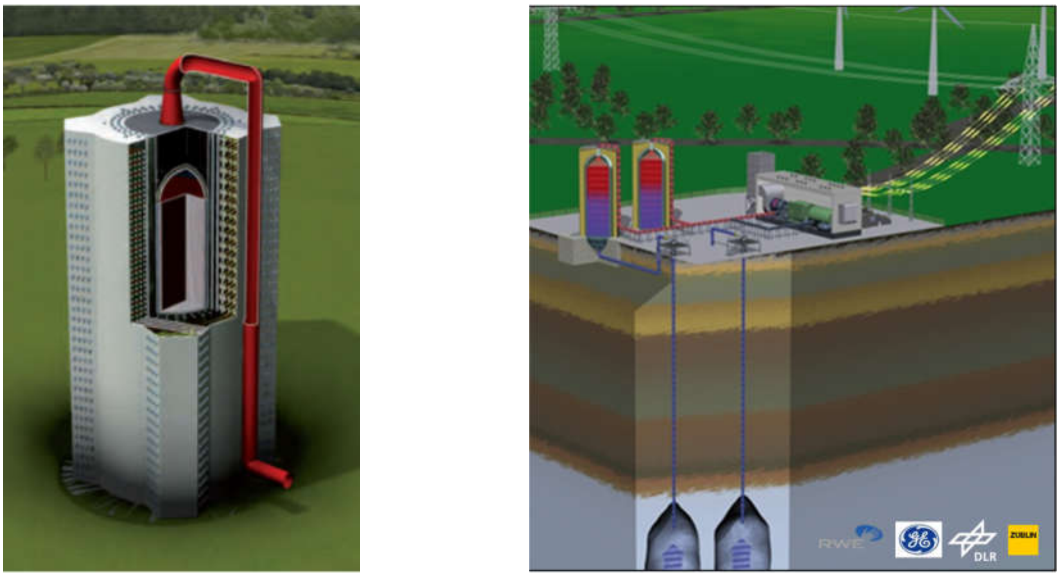

Fig. 5.14. Sensible heat storage integrated into a compressed air energy storage power plant.

References

[82-84]

PROCESS DESCRIPTION	
Analyzed process	Adiabatic compressed air energy storage power plant
Integration goal	Increasing round-trip efficiency through reintegration of compression heat with thermal energy storage
Thermal source(s)	Compressor (heat generated during loading ACAES cavern)
Thermal sink(s)	Power block (air is preheated by TES before entering expander)
Heat transfer fluid	Air
Cycle frequency	Once per day
Temperature range (°C)	Ambient temperature – 400 °C (2-stage) and 600 °C (1-stage)

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Sensible
Technology readiness level		TRL 2 - 4
Storage capacity	MWh	340
Nominal power	MW	34
Response time of TES	minutes	< 1 min
Storage efficiency	%	> 98 %
Minimum cycle length of TES		> 4 h
Partial load suitability		Suitable
CAPEX per capacity	€/kWh	80
CAPEX per nominal power	€/kW	800
Storage material cost per CAPEX	%	20

KEY PERFORMANCE INDICATORS			
Stakeholder:	**Process operator**	**Policy maker**	**TSO**
KPI 1:	(Dis)charge time	Fewer fossil fuels burned	(Dis)charge time
KPI 2:	Mass flow	CO2 emission reductions	Energy system efficiency
KPI 3:	Inlet and outlet temperatures	Process efficiency	
KPI 4:	Power density		
KPI 5:	Material costs		

5.3 Application evaluation

The most common benchmark in power plants is the storage of thermal energy in concentrating solar power (CSP), which has been a common industry practice for the past ten years. At the time of writing, there are 12 GWh of thermal energy storage installed in CSP applications worldwide.

As identified in this report, TES in 2-tank molten salt in a direct storage configuration is currently the most common method of thermal storage in CSP. Nevertheless, indirect storage in 2-tank molten salts and steam accumulators round out the commercialized technological options for this application field, as shown in Table 5.2.

Table 5.2. Non-exhaustive selection of relevant system parameters for benchmarks in power plants.

	2-tank molten salt Direct	**2-tank molten salt Indirect**	**Steam accumulator**
Temp. (°C)	290 – 565	290 – 390	250 – 300
ESC_{sys}	~ 6 GWh (Atacama)	~ 4 GWh (Solana)	3 – 5 MWh per tank <100 MWh (KhiSolar1)
SCC_{real} (€/kWh)	20 – 40	N/A	N/A
Cycle frequency	1/day	1/day	multiple times per day

Research and development work in this field is focused on several key potentials for improving the technologies including

- integration concepts of TES into power plant cycles for optimized operation,
- optimized functionality of storage within the process,
- cost reduction of storage technologies and
- long-term stability of storage at high temperatures.

Within Annex 30, several development cases were chosen that highlight the progress being made in TES for power plant applications. Consisting mainly of cases with regenerator-type storages and complemented by one with thermochemical storage, high capacities (>20 MWh) and temperatures (>290 °C) are the norm for either storing heat for later electricity generation or buffering for power plant flexibility.

As in industrial processes, a diverse array of application within specific power plant configurations can be found (e.g. TES for A-CAES power plants, process flexibility in combined cycle power plants) yet there are cases that have a broader, more standard potential with integration possibilities not restricted to their specific applications (e.g. thermocline with filler material, thermochemical storage for CSP). Regarding the latter, it is conceivable that significant technology transfer could occur across power plant configurations and even sectors once the technologies reach a commercial status.

Table 5.3. Selection of relevant parameters for TES systems in development in power plants.

	Molten Salt Thermocline	**CSP with TCS**	**Regen. combined cycle (DLR)**	**Regen. combined cycle (TUM)**	**Regen. A-CAES**
Storage type	sensible	thermochem.	sensible	sensible	sensible
Temp. (°C)	290 – 560	550 – 600	400 – 600	400 – 600	400 – 600
ESC_{sys} (MWh)	2800	15 kWh (lab) ~750 MWh (real)	3000	20	340
P_{nom} (MW)	235	5 kW (lab) ~250 MW (real)	250	100	34
Efficiency	> 98%	~97% (real)	> 95%	> 95%	> 98%
SCC_{real} (€/kWh)	18	N/A	N/A	N/A	80
Cycle frequency	1/day	1/day	1/day	1/day	1/day

Thermal energy storage in power plants delivers a number of benefits including: dispatchability of power generation, lower levelized cost of electricity, power plant and component efficiency, reduction of fossil fuel use and short-term compensation of demand fluctuation and generation interruptions.

Identified key performance indicators are shown in the table below.

Table 5.4. Key performance indicators for TES systems integrated in power plants.

Stakeholder:	**Power plant**	**Energy utility**
KPI 1:	Economic benefit (LCOE reduction)	Dispatchability
KPI 2:	CO_2 emissions reductions	CO_2 emissions reductions
KPI 3:	Storage capacity	
KPI 4:	Discharging power	
KPI 5:	Dispatchability	
KPI 6:	Optimization for power block components	

6 Vehicles

Thermal energy storage development in automobile applications is still a nascent sector. Many of the developmental efforts are still focused on concept validation and as such, this chapter does not contain any benchmarks for the vehicles application. Here, one case of TES development for automobiles is presented to comprise the entire chapter. Thermal management in automobiles through storage will nevertheless be an increasingly important topic in the coming years following publication of this report.

Name of Case	**Type**	**Location**	**Page**
Thermochemical energy storage in vehicles (VTES)	Development	Japan	124

Thermochemical energy storage in vehicles (VTES)

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Japan

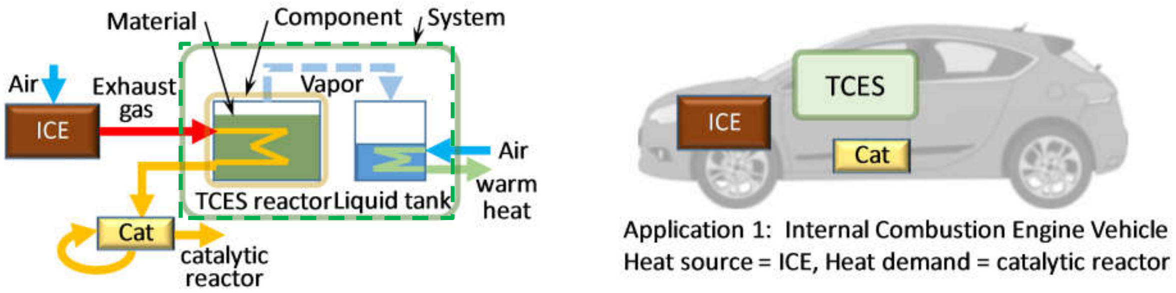

Fig. 6.1. Internal combustion engine exhaust gas system and catalytic reactor for gas purification with integrated thermochemical energy storage system of MgO/H_2O showed in green dotted line.

Process Description

Vehicle thermal energy storage (VTES) is becoming important for energy saving and carbon dioxide emission mitigation of vehicles by thermal energy utilization. Exhaust heat recovery from an internal combustion engine (ICE) by a thermochemical energy storage (TCS) is one of VTES way. A catalytic reactor for exhaust gas purification by CO/hydrocarbon oxidation and NOx reduction is required for each ICE vehicle. The catalytic reactor needs to be kept at a high temperature over 300 °C for conventional operation [85]. The heat is supplied from exhaust gas from the engine. However, during the daily start period the reactor lacks the heat and requires some external heat assistance. When gasoline is used, vehicle's fuel mileage gets worse for the inefficient fuel usage. Magnesium oxide/water (MgO/H_2O) TCES has been studied for the utilization of exhaust heat at a medium temperature of approximately 220–350 °C [86].

$$\mathrm{MgO\ (s) + H_2O(g) = Mg(OH)_2},\ \ \Delta H = -81.0\ \mathrm{kJ\ mol^{-1}}$$

The reaction system could be applicable on VTES and the following VTES process could be useful:

- Surplus exhaust gas heat is stored by $Mg(OH)_2$ dehydration during normal running on the day before.
- MgO hydration supplies heat for the catalyst reactor during initial heating at a daily start.
- Because initial fuel consumption of the reactor heating could be saved by the TCES, the fuel mileage and CO_2 emissions will be improved.

Thermal Energy Storage System Description

The planned application of TCS on automobile catalyst heating is shown in Figure 79. The internal combustion engine in automobiles emits exhaust gas containing hydrocarbons, carbon monoxide and nitrogen oxide (NO_x). NO_x should be reduced into nitrogen and oxygen by an on-board catalytic reactor over 300 °C. Because there is no commercial VTES system based on MgO/H_2O TCES, the calculation was based on following assumptions.

Thermal sink: Catalytic reactor for diesel ICE vehicle exhaust gas purification [87]. The catalytic reactor mass and volume is 10.0 kg and 12 L, respectively. Heat requirement of the reactor for 25 °C to 300 °C in 10 min, 2.14 MJ and 3.56 kW

- TCS material [86]: Magnesium hydroxide of 2.5 kg
- Total VTES system volume: 6.58 L
- Total VTES system cost: 50% of the catalytic reactor

TCS thermal conductivity is large enough for required output [86].

Fig. 6.2. Laboratory scale thermochemical energy storage experimental system for MgO/H_2O water system [86].

References

[85-87]

PROCESS DESCRIPTION	
Analyzed process	Waste heat recovery from internal combustion engine (ICE) in a diesel engine automobile
Integration goal	Waste heat used to heat a catalytic reactor for reducing exhaust gases in starting mode. Time until stable operation and fuel consumption are both reduced.
Thermal source(s)	Waste heat recovery at 300-500°C from Diesel engine ICE, 3.0 L capacity
Thermal sink(s)	Catalytic reactor with DPF for automotive exhaust gas purification
Heat transfer fluid	Exhaust gas from Diesel engine ICE
Cycle frequency	Two cycles per day (morning and afternoon)
Temperature range (°C)	220 – 350

THERMAL ENERGY STORAGE SYSTEM DESCRIPTION		
Type of storage system		Thermochemical
Technology readiness level		TRL 3 - 5
Storage capacity	kWh	0.59
Nominal power	kW	3.6
Response time of TES	minutes	10
Storage efficiency	%	90
Minimum cycle length of TES	h	2
Partial load suitability		Available
CAPEX per capacity	€/kWh	1000
CAPEX per nominal power	€/kW	170
Storage material cost per CAPEX	%	0.66

KEY PERFORMANCE INDICATORS

Stakeholder:	**Automobile company**	**Automobile owner**	**Policy maker**
KPI 1:	Material storage density	System durability	CO_2 emission reductions
KPI 2:	Heat output density	Fuel consumption reduction	
KPI 3:	System storage density		
KPI 4:	System output density		
KPI 5:	Material durability		

7 Summary and conclusions

This report has highlighted the diverse benefits that integrated TES systems can bring to different applications. As the advantages delivered by these systems become better understood, technology deployment will be advanced to ensure improved cost-effective energy management and CO_2 mitigation. To proceed toward this goal, the systematic methodology for process integration of TES systems has been developed and applied to a wide variety of benchmark and development case studies.

The methodology introduced in Chapter 1 of this report can be broken into five parts. The process analysis guidelines pave the way for a detailed evaluation of a process for integration of a TES system. Definitions on the analysis levels of a TES system provide clear boundaries for technology assessment. Furthermore, the technical parameter definitions ensure that different TES systems may be characterized in the same manner and that inter-technological comparisons are possible. The use of storage capacity costs provides a fundamental starting point when considering the investment costs of a thermal storage system. Finally, the methodology for key performance indicators identifies the critical storage parameters and benefits delivered by an integrated TES system. Inclusion of the stakeholder perspective provides a dynamic and overarching analysis of these important technologies.

Application of the methodology to both benchmark and development case studies has provided valuable insight to the different sectors in which TES systems can be integrated. Chapters 2-6 have uncovered some crucial characteristics and important differences between the presented application fields:

District heating applications can be broken down into two main categories: buffer storage and seasonal storage. Generally, conventional designs for both types are at a high TRL level and have seen deployment in a wide range of countries. R&D work focuses on improvements that address specific technical and economic issues, but are not decisive on the affordability of the storage in many applications.

The **non-residential buildings** sector is a still-nascent field that has seen several established technologies delivering both buffer and seasonal storage solutions. Novel technologies for buffer storage and process unit optimization often use low-temperature latent heat/PCM. Some systems are being tested in a real environment, while others are earlier-stage concepts. Nevertheless, more elaborate technologies remain pre-commercial. R&D work focuses on material development, system design, and system integration into processes (e.g. schools, office buildings).

Thermal energy storage in **industrial processes** is a diverse application field. Despite benchmarks being operational for over 100 years, there are few characteristic examples of integrated storage systems. Nevertheless, most applications identified in this report involve waste heat utilization, buffer storage or substitution of back-up systems. As opposed to other sectors that focus on one type of storage technology (district heating – sensible, non-residential buildings – latent), development work in industrial processes concerns sensible, latent and thermochemical storage systems. R&D work involves all levels (material, component, process integration) to optimize functionality, reduce cost and maximize benefit of storage.

The **power plant** sector comprises several well-known uses of TES systems, such as in CSP applications. Among the most common storage technologies used are molten salt (in both direct and indirect configurations) and steam accumulators. As is typical in thermal power plants, the storage temperatures are high and capacities are grid-scale. R&D work with regenerator-type storage systems is being pursued for buffer storage in cogeneration plants or in combination with compressed air energy storage. Furthermore, this work concerns the development of novel storage concepts for cost reduction, such as molten salt thermoclines with filler material or thermochemical storages for CSP.

The key performance indicator results show that TES systems operational in these different sectors have been successful in reducing CO_2 emissions, providing process flexibility, increasing energy efficiency, delivering dispatchable power, and, especially relevant for industry, reducing costs. The results presented in this report comprise a long list of benchmarks and developments in thermal energy storage systems that are delivering real benefits today. These key performance indicators have been determined by the expert research community of Annex 30. Industry consultation will be an important step for future determination of KPI.

Conclusions

Through the involvement of world-class research institutions in thermal energy storage from around the globe, this report has provided a wide range of benchmark and development cases of integrated TES systems. This variety has also shown that many new and diverse opportunities exist where TES systems can make a significant impact. The collected cases have laid out the large technical and operational variations between sectors that necessitate systematic approaches and definitions. It has also been shown how the uptake of thermal storage technologies in these sectors requires a shared understanding on concepts such as the system boundary, technical and economic parameters and identification of KPI.

The methodologies for technology assessment have been developed within Annex 30 and applied to benchmark and development cases of thermal energy storage in applications. This marks a significant first step, but in the course of this work, the evaluations have identified obstacles to technology deployment that should be addressed in future efforts.

To begin, the database of integrated cases for Annex 30 should be expanded to include many more examples across the application fields. This will provide a more precise overview of the different sectors and allow for nuanced evaluations that can potentially be either sector-specific or generalized across application fields. Further involvement of industry will be key to this step and the industrial perspective on key performance indicators is critical for delivering accurate, relevant and reliable analyses.

New technical and economic parameters of thermal energy storage should also be characterized. This concerns the concept of Technology Readiness Level, as a TES-specific definition for this property would support future discussion on commercialization of TES technologies. Economic parameters should also be defined that govern the decisiveness in costing of storage technologies. An economic analysis that follows in the footsteps of the Annex 30 methodologies is critical for supporting future uptake of these technologies.

Finally, an attempt to characterize the "added benefit" of integrated thermal storage technologies would be advantageous. An expansion of the KPI methodology could take this into consideration. With improved stakeholder involvement that advises on an added benefit, integrated storage technologies can be classified according to the additional services they deliver as well as their primary use for the process.

The methodologies developed and applied in this report have taken an important first step towards a common understanding and benefit characterization of thermal energy storage technologies integrated in processes. Expansion of the methodologies to address the aforementioned issues will deepen the structured approaches for technology development of thermal energy storage. These methods will in turn support the uptake of thermal energy storage technologies around the globe and help lead to a future energy system that is more energy efficient and sustainable.

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TES for Energy Management and CO_2 Mitigation

Abbreviations

A-CAES	Adiabatic compressed air energy storage
CCGT	Combined cycle gas turbine
CHP	Cogeneration/combined heat and power
CSP	Concentrating solar power
DH	District heating
DHC	District heating and cooling
DHW	Domestic hot water
DSG	Direct steam generation
ESC_{sys}	System storage capacity
ε_{sys}	System energy efficiency
HP/LP	High pressure/low pressure
HRSG	Heat recovery steam generation
HTF	Heat transfer fluid
ICE	Internal combustion engine
KPI	Key performance indicator
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelized cost of electricity
LHTES	Latent heat thermal energy storage
MW	Megawatt
MWh	Megawatt-hour
PCM	Phase change material
P_{nom}	Nominal power
$ReTi_{sys}$	System response time
SA	Steam accumulator
SCC_{real}	Storage capacity costs i.e. storage capacity (kWh) per CAPEX (€)
SH	Solar heating
SHTES	Sensible heat thermal energy storage
SPC_{real}	Storage power costs i.e. storage power (kWh) per CAPEX (€)
TCS	Thermochemical storage
TES	Thermal energy storage
TRL	Technology readiness level

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