Technology Collaboration Programme
by iea

energy storage

IEA Technology Collaboration Programme

International Energy Agency

Technology Collaboration Programme on Energy Storage

(ES TCP)

Task 36

Carnot Batteries

Final Report

Submitted for

the 95th ES TCP ExCo meeting, May 23-25, 2023, Vienna, Austria / Hybrid

Task Manager ES TCP Task 36:

Prof. Annelies Vandersickel

German Aerospace Center (DLR)

Germany

AUTHORS

Prof. Annelies Vandersickel

Task manager

DLR e.V.

Dr. Andrea Gutierrez
Task assistant manager
DLR e.V

Dr. Salvatore Vasta
Subtask 0 leader
ITAE CNR

Prof. Kurt Engelbrecht
Subtask A leader
DTU

Dr. Zhiwei Ma
Subtask B leader
Durham University

Prof. Yulong Ding

Subtask C leader
University of Birmingham

Dr. Benjamin Bollinger
Subtask D leader
Malta Inc

CONTRIBUTORS

Adams, Martin – MAN ES

Blandel, Karine – Hyme

Bayer, Nils – Universität Stuttgart

Bubelis, Evaldas – KIT

Canneto, Giuseppe – ENEA

Cho, Junhyun - Korea Institute of Energy Research

Dumont, Olivier – University of Liège

Ferrari, Lorenzo - University of Pisa

Frate, Guido Francesco - University of Pisa

Fuchs, Joachim – KIT

Giuliano, Stefano – DLR e.V.

Held, Tim – Echogen

Jacquemoud, Emmanuel – MAN ES

Komoszynska, Magdalena - PlanEnergi

Knobloch, Kai – Technical University of Denmark

Laterre, Antoine – UC Louvain

Lechner, Stefan – THM

Liang, Ting – University of Birmingham

Liberatore, Raffaele – ENEA

Little, Adrienne – Google [X] on behalf of Malta Inc

McTigue, Josh - NREL

Miliozzi, Adio – ENEA

Nicolini, Daniele – ENEA

Niedermeier, Klarissa – KIT

Novotny, Vaclav - Czech Technical University in Prague

Reisenbichler, Michael – AEE Intec

Reynders, Kurt – Engie

Riegler, Thomas – AEE Intec

Rohringer, Christoph – AEE Intec

Roldan Serrano, Maria Isabel – DLR e.V.

Rose, Luke – Malta Inc

Russo, Valeria – ENEA

Sciacovelli, Adriano - University of Birmingham

Schmidt, Ferdinand – KIT

Textor, Michel - THM

Thellufsen, Jakob Zinck - Aalborg University

Thiele, Elisabeth – TU Berlin

von der Heyde, Michael – Siemens Gamesa

Weller, Thilo – DLR e.V.

Weitzer, Maximilian – FAU Erlangen

Wiemer, Hans-Joachim – KIT

Zaczek, Alexander – Siemens Gamesa

Zhang, Tongtong – University of Birmingham

CONTENT

KEY MESSAGES AND POLICY RECOMMENDATIONS

The energy transition and a future dominated by fluctuating renewable energies requires affordable and decentralized storage solutions that save energy resources in the relevant order of magnitude of gigawatt hours (GWh).

Carnot Batteries are **key storage solutions** that can contribute to this challenge due to:

- their high potential to efficiently **integrate multiple energy sources into the electrical and heat sectors**, e.g. waste heat from industry and renewable electricity and heat.
- their **independence of specific geographical locations** for storing and supplying electricity and thermal energy.
- the use of a suitable combination of components to **integrate renewable electricity and heat to** specific applications, e.g. **household, industrial applications and back to the grid**.
- their high potential for **storing electricity in medium to long-term periods (> 4 h)** .
- their potential to store energy both at **large energy and power capacities at low cost with non-critical materials**.
- involvement of non-critical materials for the whole power-to-heat-to-power cycle.

These challenges can be addressed by Carnot Batteries, but they still face several **barriers to deployment**.

1. Tech to Market Transition Barriers:
   - Securing funding for R&D to advance technologies to higher TRL levels.
   - Technology risk can translate into market risk, making potential customers hesitant to commit to long-term contracts for First-of-a-Kind (FOAK) projects.
2. Commercialization Barriers:
   - Even after successfully validating through a FOAK unit, broader commercialization and widespread deployment face challenges.
   - Early stage development: Specific costs and overall efficiencies, and their integration into **future energy markets** still needs to be researched in detail.
   - Existing energy systems and markets lack incentives for deployment and adequate compensation for Carnot Battery owners/operators.

Nevertheless, based on the current barriers the following **policy recommendations** could help accelerate the development of Carnot Batteries and bring them closer to market:

1. Clarity and Fairness in Policy and Regulation: Establish clear and fair definitions of energy storage, including Carnot Batteries, within market rules and regulations. This ensures a level playing field for all technologies and facilitates efficient and cost-effective market organization.
2. Financial Support Policies: Implement public investment mechanisms such as funding research and development, providing grants, and offering tax incentives to overcome financial barriers and attract private investment in Carnot Battery development and deployment.
3. Demand-Supporting Policies: Create policies that incentivize private investment in Carnot Batteries to drive demand for deployment.
4. Valuation of Full Spectrum of Services: Work with research bodies to identify and recognize the full spectrum of services offered by Carnot Batteries

MAIN RESULTS IN A NUTSHELL

The overarching goal of Task 36 was to ease the transition from a fossil-fuel-based to a renewable source-based energy system, through the promotion of novel energy storage systems, assisting their development, deployment, demonstration and deep understanding.

Therefore, Task 36 aimed to establish a platform that brings together experts from the industry and academia, to systematically investigate, assess and strengthen the potential role of Carnot Batteries in the future energy systems gaining international attention.

This objective was overachieved and this was reflected in the number of participants attending the expert meetings and the active contribution to the deliverables in Task 36. Figure 1 shows the evolution of the number of participants from the first pre-definition meeting in 2019 to the last expert meeting in September 2022. A group of 28 institutions (20 Universities and research centers, 6 Companies and 2 agencies or public organizations) from 9 country members of the ES TCP attended the first pre-definition meeting in 2019, and 47 institutions (36 Universities and research institutions, 10 companies, 1 European organization) from 15 members countries and one sponsor attended the last expert workshop in September 2022.

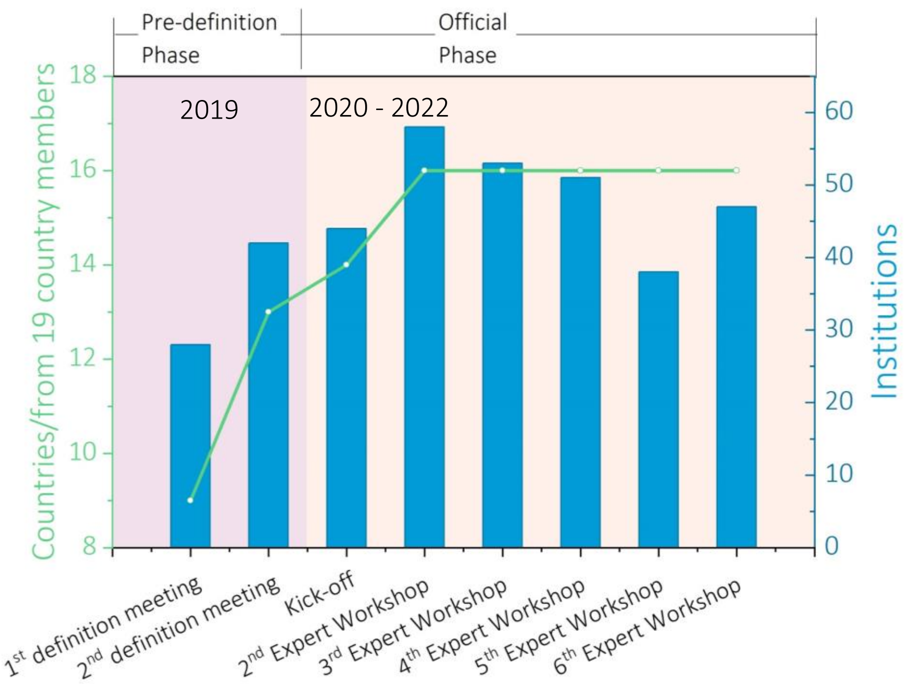


Figure 1: Overview of countries and institutions participating from 2019 to 2022.

The key objectives of the Task 36 were also overachieved, and the achievements are described as follows:

- The Carnot Battery technologies and their applications were mapped through the collection of existing information on electricity storage systems based on thermal energy storage. The information gathered were reported in three different deliverables included in this final report and also as a standalone document such as white paper on the state of the art of Carnot Batteries (see 2.1.3 and 3.2 Appendix 2), white paper on thermal energy storage methods for Carnot Batteries (see 2.1.4 and 3.3 Appendix 3), and the assessment of TRL of Carnot Battery systems and components (see 2.2.3). Based on this information a critical assessment of the R&D needs for these technologies was put together and it is reported in this document in the subsection 2.2.4.3.

- The Key Performance Indicator of the Carnot Battery systems and their key components were also discussed and systematically defined while Task 36 was being executed. The results obtained are reported in this document in the subsections 2.1.2 and 3.1 Appendix 1.
- To help technology to market and delimit its market reach by identifying the services that should/can be provided by Carnot Batteries, these technologies were systematically defined in subsection 2.1.1. In this subsection, the technologies out of the scope were also delimited. Also, a market analysis was carried out, assessing the current challenges and climate crisis, the barriers to deploy such technologies and policy recommendations were made to push the development of these technologies. The results for these points can be seen in the Subsection 2.3.
- A thorough technical description of the Carnot battery types was carried out, such Rankine and Brayton batteries, and the liquid air energy storage was chosen as an example of other concepts and configurations. This can be seen in Subsection 2.2.1. Among the participants, 18 Technical fact-sheets and 35 modelling and simulation Factsheets on Carnot Batteries and components were collected. The technical fact-sheets are summarized in subsection 2.2.1 and all the fact-sheets are included in 3.4 Appendix 3. The modelling and simulation Factsheets are summarized in subsection 2.2.2 and al the fact-sheets are included in 3.5 Appendix 5.
- As publicly available deliverables two main achievements can be cited. The Wikipedia page on Carnot Batteries was developed during Task 36 and now is available in nine different languages. More details on this can be seen in the subsection 2.1.5. Seven review papers were published by the participants of Task36. A detailed list of the review papers can be seen in the Executive Summary, in subsection 2.5.5.

EXECUTIVE SUMMARY

1 Short Description of Task 36

1.1 Objectives and Scope

The overarching aim of this Task is to ease the transition from a fossil-fuel-based to a renewable source-based energy system, through the promotion of novel energy storage systems, assisting their development, deployment, demonstration and deep understanding.

Therefore, this Task aims to establish a platform that brings together experts from the industry and academia, to systematically investigate, assess and strengthen the potential role of Carnot Batteries in the future energy systems gaining international attention.

The key objectives of Task 36 are:

- Mapping of the main Carnot Battery technologies and applications through the collection of existing information on electricity storage systems based on thermal energy storage (TES).
- Developing technology Key Performance Indicators of the Carnot Battery systems and their key components.
- Critical assessment of technological competitiveness and R&D demand.
- Help technology to market and delimit its market reach by identifying the services that should/can be provided by Carnot Batteries.
- Inform policy and provide a basis for proper regulations, based on the benefits and potential of Carnot Batteries and the requirements to assist their deployment.
- International dissemination of the technologies through workshops, white papers, open-source datasets and scientific papers.

The scope of this Task addresses two perspectives, technological and non-technological:

Technological aspects:

- definition of Carnot Batteries
- power input and output are mandatory
- power input can be consumed by a heat pump, by direct (e.g. electrical resistance) heating or by similar equipment
- heat (or cold) input and output is optional
- TES mechanism can be: sensible, latent, thermochemical

Non-Technological aspects:

- business cases
- system integration aspects
- scalability limits with respect to materials availability
- environmental aspects
- further non-technological aspects, e.g. regulations, safety, etc.

The scope of the Task is restricted to the conversion and storage of electricity in the form of thermal (sensible, latent and thermochemical) energy. Other technologies such as electrochemical and mechanical storage technologies are excluded.

1.2 Organizational Structure

The work and discussions of the Task carried out by the experts are divided in five different Subtasks as shown in Figure 2:

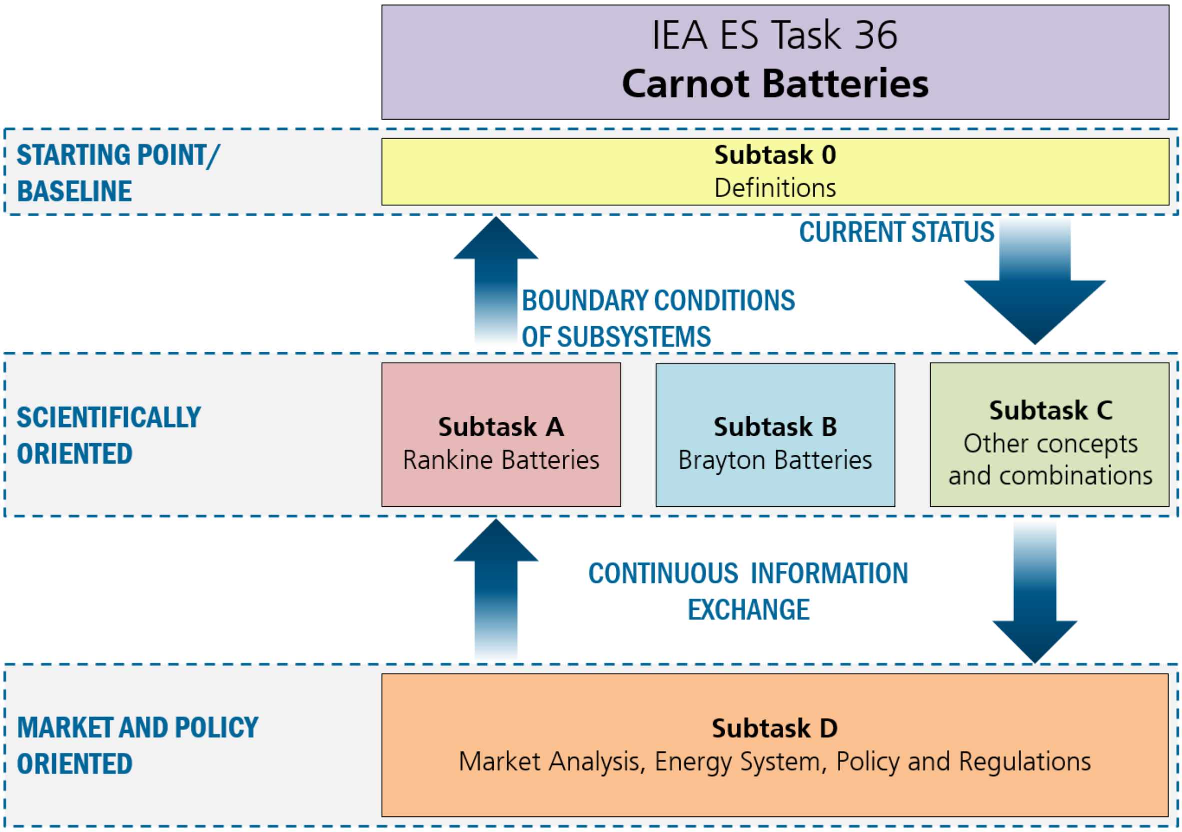


Figure 2: Structure of the IEA ES TCP Task 36.

1.3 Beginning and End of Task

The activities of Task 36 started on January 1, 2020, and have a duration of 36 months until December 31, 2022.

1.4 Experts Meetings

The official start of Task 36 was January 1, 2020. Table 1 gives an overview of the expert meetings in this Task.

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

City	Country	Date	# of Participants
Online Meeting[1]	-	March 26, 2020	51
Online Meeting[2]	-	September 17-18, 2020	65
Online Meeting[3]	-	April 15-16, 2021	93
Hybrid Meeting in Lyngby	Denmark	September 9-10, 2021	78
Hybrid Meeting in Graz	Austria	April 4-5, 2022	61

Hybrid Meeting in Stuttgart4	Germany	September 26, 2022	70

1Originally planned as an in-person workshop to be held in Birmingham on 25-26 March 2020, hosted by the University of Birmingham.

2Hosted by DLR in collaboration with the Institute for Building Energetics, Thermotechnology and Energy Storage (IGTE) from the University of Stuttgart.

3Hosted by the University of Birmingham, UK and coordinated with the support of the German Aerospace Centre (DLR e.V.), the Birmingham Centre for Energy Storage and the Supergen Energy Storage Network+.

4 Hosted by the DLR e. V., Germany combined with the exploitation Workshop of the EU- Project CHESTER (European Commission – H2020-LCE-2016-764) and took place directly before the 3rd International Workshop on Carnot Batteries that took place from September 27 – 28, 2022.

1.5 Status of Participation

15 countries and one sponsor from Spain have declared their interest in participating in the Task at the 93rd ExCo meeting in May 2022 in Rome. 47 institutions from 16 countries participated in the 6th expert meeting. Table 2 gives an overview of the organisations participating in this task and the corresponding countries.

The Subtask Managers are Salvatore Vasta from CNR-ITAE, Italy; Kurt Engelbrecht from DTU, Denmark; Zhiwei Ma from Durham University, UK; Yulong Ding from University of Birmingham, UK; Benjamin Bollinger from Malta Inc, USA.

Table 2: List of participating institutions per country.

Country	Institution	Representative (name)
Austria	AEE INTEC	Christoph Rohringer
Belgium	ENGIE-Laborelec	Kurt Reynders
	Ghent University	Stefen Lecompte
	Liege University	Olivier Dumont
	Université Catholique de Louvain	Antoine Laterre
Czech Republic	Czech Technical University in Prague	Vaclav Novotny
Denmark	Aalborg University	Peter Sorknæs
	DTU (energy and mechanical engineering)	Kurt Engelbrecht
	PlanEnergi	Magdalena Kowalska
	University of Southern Denmark	Christian Veje
	Hyme	Karine Blandel
France	CEA	Jean-François Fourmigué
Germany	Bayreuth University	Andreas König-Haagen
	Carbonclean	Jörg Strese
	DENA	Maike Irena von Krause-Kohn
	DLR e.V.	Dan Bauer
	Enolcon GmbH	Jonas Häcker
	FAU Erlangen	Bernd Eppinger
	Fraunhofer ISE	Thomas Fluri
	Fraunhofer IFAM	André Schlott
	Fraunhofer UMSICHT	Silas Heim
	Kraftblock	Martin Schichtel
	KIT	Joachim Fuchs
	Siemens Gamesa ES GmbH	Alexander Zaczek

	Spilling Technologies GmbH	Christof Fleischmann
	Stuttgart University	Harald Drück
	TU-Berlin	Elisabeth Thiele
	TU – Chemnitz	Thorsten Urbaneck
	University of Applied Science Zittau/Görlitz	Thomas Schäfer
	University of Applied Sciences Amberg-Weiden	Andreas Weiß
	University of Applied Science Mittelhessen	Stefan Lechner
	PT Jülich (observer)	Stefan Busse-Gerstengarbe
Italy	CNR-ITAE	Salvatore Vasta
	ENEA	Michela Lanchi
	Politecnico di Torino	Eliodoro Chiavazzo
	University of Bari	Marco Antonio Pantaleo (EU EIC)
	University of Pisa	Umberto Desideri
	University of Genova	Stefano Barberis
Japan	Hokkaido University	Takahiro Nomura
	Tokyo Tech	Yukitaka Kato
Netherlands	Energy transition (former ECN part of TNO)	Michel Van der Pal
South Korea	Korean Institute of Energy Research	Junhyun Cho
Sweden	Azelio	Anna Gerokostopoulou
	Climeon	Joachin Karthauser
	Rise	Roger Nordman
	KTH	Rafael Guedez
Switzerland	MAN ES	Emmanuel Jacquemoud
	University of Applied Science Luzern	Willy Villasmil
Turkey	Gazi University	Zeki Yılmazoğlu
UK	BEIS	Georgina Morris
	Durham University	Zhiwei Ma
	Highview Power	Kelvin Sim
	University of Birmingham	Yulong Ding
	University of Hertfordshire	Wenbin Zhang
USA	ARPA-E	Max Tuttman
	Echogen	Timothy Held
	Malta Inc	Benjamin Bollinger
	NREL	Joshua McTigue
Spain (Sponsor)	University of Seville	Cristina Prieto

2 Summary of Subtasks

2.1 Subtask 0: Definitions

Subtask Leader: Dr. Salvatore Vasta CNR-ITAE, **Italy**

The Subtask 0 addresses the key definitions and classification of Carnot Batteries in order to standardize the Carnot Battery “language” (definition of acronyms etc.). Furthermore, the key performance indicators (KPIs) are defined among a group of pre-defined boundaries, such as operating conditions, materials, components and systems. Technical, economic and further non-technical aspects are considered for this task. Finally, state of the art of Carnot Batteries and the determination of TES as a component suitable for Carnot Batteries are carried out following a systematic analysis. This serves as guidance for determining the missing information and requirements for the deployment of these technologies.

The outcomes generated from the work carried out in this subtask are shown in Table 3. This table also shows how this outcome will be made available, whether it will only be included in the final report, or whether it will also be available as a standalone document.

Table 3: Outcome of Subtask 0 and how they are available.

Nr	Outcome	Available	
		In the final report	As a standalone document
ST0-1	Definition of Carnot Battery	☑ (2.1.1)	☒
ST0-2	Key performance indicators	☑ (2.1.2)	☒
ST0-3	State-of-Art Carnot Batteries	☑ (2.1.3)	☑ (Appendix 2; White paper)
ST0-4	TES Methods for Carnot Batteries	☑ (2.1.4)	☑ (Appendix 3; White paper)
ST0-5	Wikipedia Page	☑ (2.1.5)	☑ (external website)

2.1.1 Definition of Carnot Battery

The definition of a Carnot Battery was discussed among all the participants of Task 36 based on the technical characteristics and services of the concept and the expert agreed on the following definition:

"A Carnot Battery is a type of energy storage system that stores electricity in thermal energy storage. During the charging process, electricity is converted into heat and kept in the heat storage. During the discharging process, the stored heat is converted back into electricity."

2.1.2 Key Performance Indicators (KPIs)

To define the KPIs for Carnot Battery, several levels were defined (see Figure 3). So KPIs were defined for the systems as roundtrip efficiency (RTE), second law efficiency (exergy efficiency, η_{II}), the ratio of electrical to thermal outputs in the discharging phase (ω_{dis}), etc. For the components, for example, technology readiness's level TRL, maintenance costs (€/year, €/cycle), maximum discharging power – TES – (MW), etc. And for materials, specifically for TES, e.g. volumetric energy density (MWh/m^3), safety and environmental aspects, and recyclability (CO_2 footprint).

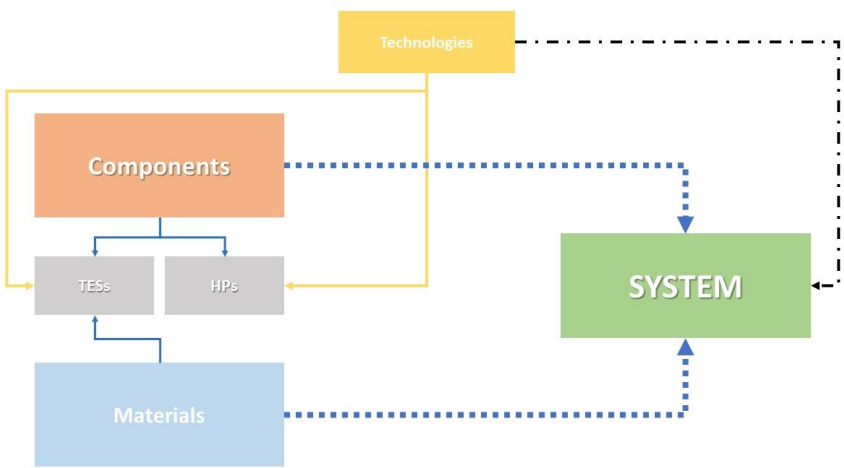


Figure 3: KPIs' structure definition.

2.1.3 State of the Art of Carnot Batteries

The state of the art of Carnot Batteries was investigated and a white paper with this information was prepared by the Czech Technical University in Prague. In this white paper a complete review of the currently available Carnot Batteries is presented, both commercial and in the research area, as well as their most important components. In addition, the technical characteristics of each of them are presented in the form of tables or graphs. This document is summarized in sub-section 2.1.3 and the complete document can be found in Appendix 2.

2.1.4 TES Methods for Carnot Batteries

The TES methods suitable for Carnot Batteries were analyzed and a white paper was prepared by AEE INTEC with this information. In this white paper a thoroughly description of the TES types is found, namely sensible heat TES, latent heat TES and thermochemical ES. Also, existing Carnot Battery facilities are shown, highlighting the TES methods used for the respective installations. The cover of the white paper is shown in Figure 4.

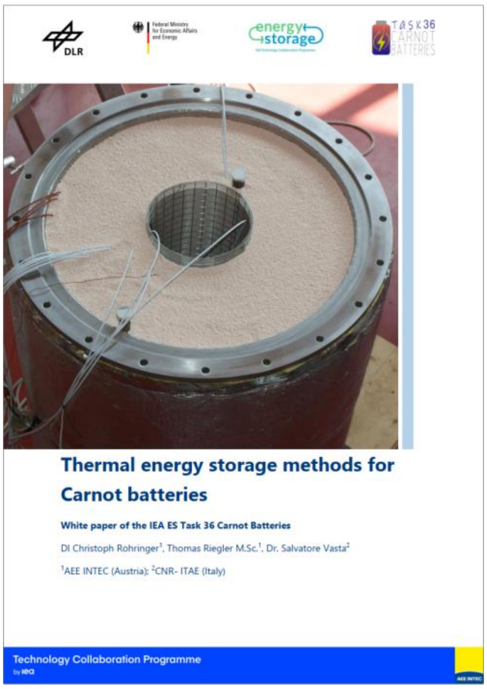
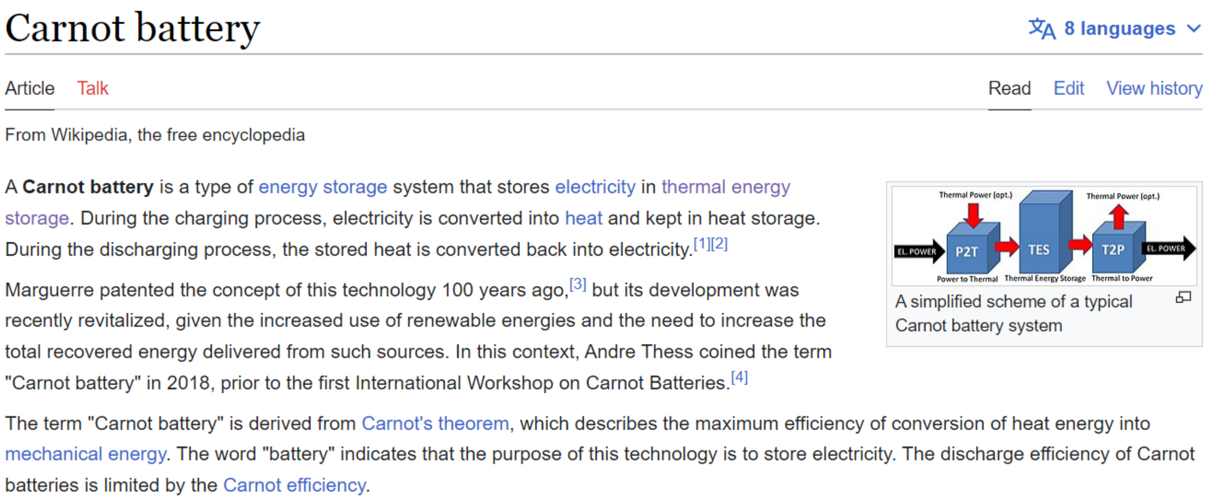


Figure 4: Cover of white paper on TES methods for Carnot Batteries.

2.1.5 Wikipedia Page

The item was created in October 2020 (see Figure 5) and it was presented in the Task 36 update report for the 90th ExCo Meeting. Since then, the views of the Wikipedia page are increasing. At the end of 2022, the pageviews are around 1,500 in per month across all languages, and the accumulated pageviews are over 32,000. The site is now available in nine languages i.e. Chinese, Czech, English, French, German, Italian, Japanese, Spanish, and Turkish.



Carnot battery

8 languages

Article Talk Read Edit View history

From Wikipedia, the free encyclopedia

A **Carnot battery** is a type of energy storage system that stores electricity in thermal energy storage. During the charging process, electricity is converted into heat and kept in heat storage. During the discharging process, the stored heat is converted back into electricity.[1][2]

Marguerre patented the concept of this technology 100 years ago,[3] but its development was recently revitalized, given the increased use of renewable energies and the need to increase the total recovered energy delivered from such sources. In this context, Andre Thess coined the term "Carnot battery" in 2018, prior to the first International Workshop on Carnot Batteries.[4]

A simplified scheme of a typical Carnot battery system

The term "Carnot battery" is derived from Carnot's theorem, which describes the maximum efficiency of conversion of heat energy into mechanical energy. The word "battery" indicates that the purpose of this technology is to store electricity. The discharge efficiency of Carnot batteries is limited by the Carnot efficiency.

Figure 5: Wikipedia site on Carnot Battery in English (https://en.wikipedia.org/wiki/Carnot_battery).

2.2 Subtask A: Rankine Batteries

Subtask Leader: Prof. Kurt Engelbrecht – DTU, **Denmark**

Subtask A assesses the state of the art of Carnot Batteries based on Rankine cycles (so-called Rankine Batteries) on a system level. Also, the identification of system configurations is carried out within this subtask, identifying the sinks and sources and the storage temperatures of Rankine Batteries. Finally, the modelling and assessment of the systems are performed to get a common understanding of efficiency, dynamic behavior, scalability and the basis for economic evaluations. Experimental data from existing systems and know-how are shared, in the form of fact-sheets.

2.3 Subtask B: Brayton Batteries

Subtask Leader: Dr. Zhiwei Ma – Durham University, **UK**

In analogy to Subtask A, Subtask B assesses the state of the art of Carnot Batteries, based on Brayton or Joule cycles (so-called Brayton Batteries), focusing on the identification of promising cycle designs, working conditions and working fluids. The experimental data and analysis of existing or planned systems as well as simulation results for promising system concepts were collected and assessed. The boundary conditions for TES are determined and provided as input for Subtask 0.

2.4 Subtask C: Other Concepts and Combinations

Subtask lead: Prof. Yulong Ding – University of Birmingham, **UK**

Subtask C investigates concepts which are not classified as Rankine and Brayton Batteries as well as combinations of different processes, e.g. the Lamm-Honigmann-Process, Liquid Air Energy Storage with TES, GT-based technologies with TES and steam generation for enhancing the GT performance, CO_2 based transcritical cycles for conversion with TES and material-based generation like thermoelectric generators. System and component level-based data for KPI definition are also provided for Subtask 0.

2.5 Outcomes of Subtasks A/B/C

Given that subtask A, B and C were scientifically oriented and there were many synergies in the results generated, these were combined and structured into four outcomes as shown in Table 4.

Table 4: Outcomes of Task A, B and C

Nr	Outcome	Available	
		In the final report	As a standalone document
STA/B/C-1	Carnot Battery technologies	☑ (2.5.1)	☒
STA/B/C-2	Modelling and simulation	☑ (2.5.2)	☒
STA/B/C-3	Assessment of TRLs	☑ (2.5.3)	☒
STA/B/C-4	R&D needs	☑ (2.5.4)	☒
Bonus	Scientific publications among the task 36 participants		☑

2.5.1 Carnot Battery technologies

In the execution period of Task 36, fact-sheets on existing Carnot Battery systems and components for these systems were collected. The Factsheets were delivered by the participants of Task 36 involved in the projects that developed the systems and components. A total of 18 Factsheets were collected and they are shown in Appendix 4. A summary is shown in Table 5.

Table 5: Summary of Systems and components Factsheets

Nr	Country	Type	Name	Institution
1	Denmark	Component	Rock bed TES test concept	DTU
2	Denmark	Component	Rock bed TES Pilot plat	DTU
3	Denmark	System	CO_2 Carnot Battery with water storage	DTU
4	Denmark	System	CHESTER system in the management of electricity	PlanEnergi
5	Germany	System	Enolcon OPTES Battery	Enolcon
6	Germany	Component	STORASOL HT TES	Enolcon
7	Germany	System	HiTES	Fraunhofer UMSICHT
8	Germany	System	HiTES-Steam	Fraunhofer UMSICHT
9	Germany	Component	THERESA	HSZG
10	Germany	System	TMS - Battery	HSZG – Spilling Technologies
11	Germany	System	CHESTER	EU Project (DLR)
12	Germany	System	ETES	Siemens Gamesa
13	Switzerland	System	MAN CO_2 ETES System	MAN ES
14	UK	System	Isentropic	Durham University
15	Belgium	System	BETRENEW	University of Liège
16	Italy	System	Hybrid TES	ENEA
17	UK	Component	Sensible TES	New Castle University
18	UK	System	LAES	HighviewPower
19	UK	Component	LHTES	Malta Inc / Siemens

2.5.2 Modelling and Simulation

Factsheets on modelling and simulation were also gathered among the participants of Task 36. A total of 35 fact-sheets were submitted by 20 participants of Task 36. The models were focused on component, system and grid level. These models were at the same time classified based on the change of external conditions e.g. static and dynamic. Quasi-static models are considered as dynamic for this analysis. A summary of this distribution is shown in Figure 6.

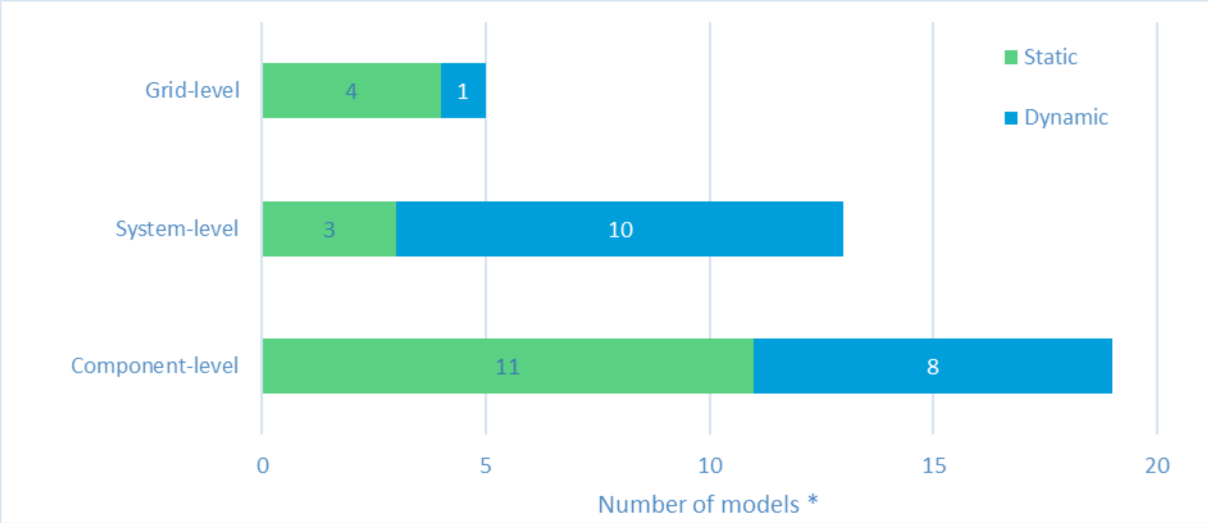


Figure 6: Overall categorization of models from gathered Factsheets.
* Please note that the sum of these numbers is above 35 since some models were categorized by two model levels.

The three most common software/programming language chosen by Task 36 participants reflected on the Factsheets was Matlab (10 users), followed by Dymola (5 users) and COMSOL (4 users). The reason why the user chooses certain software or programming language is very diverse, such as familiarity, availability, compatibility with other languages, etc. a thorough analysis of all the Factsheets is shown in sub-section 2.2.2, and the full Factsheets are shown in Appendix 4.

2.5.3 Assessment of TRLs

A detailed assessment of TRL of Carnot Batteries has been carried out in this subsection, citing also the developer either of the systems or components. One example of the technologies cited in this sub-section is the Rankine-based Carnot Battery developed by Siemens Gamesa -ETES- battery charged with an electrical resistance, which has reached a TRL 5-7. As for the Rankine-based Carnot Batteries charged by heat pumps that are under development, several examples can be cited. The CHESTER prototype was developed in the frame of an EU H2020 project, Echogen ETES, MAN ETES, which has reached a TRL from 3 to 5.

In the case of the Brayton-based Carnot Batteries, some demonstrations in the MW scale are under construction. Here the demonstrator of Stiesdal and GridScale can be cited. So far, the existing prototypes have mainly achieved up to TRL 5.

In the category of other concepts and combinations the liquid air energy storage (LAES) system is found. A LAES pilot plant in the kW power scale and MWh storage scale has been designed, constructed and tested over the past 10 years at the University of Birmingham. Currently, several commercial-scale LAES plants are under development. Overall, this technology has reached a TRL 7-9.

2.5.4 R&D Needs

As mentioned in subsection 2.5.3 the are currently several demonstrators and pilot plants under development, some of these are even commercial installations, but there are still some research and development needs to be addressed to bring these technologies to market. This subsection analyzes the needs from different perspectives and gives some recommendations to continue the progress in the development of Carnot Batteries.

In order to analyze the future development path and R&D needs of Carnot Batteries, the members of IEA Task 36 have conducted a survey in which they provide their current view of the most challenging obstacles and associated solutions. In subsection 2.2.4 the extended results of the analyses are shown, here we will show only one example from the Component-level, system-level and material-level and non-technical barriers and solutions for the development of Carnot Batteries.

Table 6: Examples of component-, system-, material- and non-technical barriers and solutions for the development of Carnot Batteries.

	Challenges/barriers/comments	Potential solutions/suggested R&D pathways
Component - level	**Overall problems:** • High temperature and high-pressure condition (non-standard condition) poses challenges to system components, especially compressors; • It lacks methods/standards to select components for Carnot Batteries.	1. Develop components (compressors, heat exchangers, heat store etc.) for high pressure and temperature applications; 2. Investigate the behaviors and performance of the related components for high-temperature/high-pressure applications; 3. Develop intelligent strategies to select the components of Carnot Batteries based on the system capacity; 4. Develop efficient components for different system scales.
System - level	**System operation:** • There is a lack of understanding of the dynamic behaviors of Carnot Batteries. • Operating strategy/dynamic control of Carnot Batteries needs to be well designed. • The services that Carnot Batteries can provide currently and in the future need to be identified.	1. Build the dynamic model and conduct experiments to investigate the dynamic behaviors of Carnot Batteries (e.g., response time, start-up/shut-down behaviors etc.); 2. Develop advanced control strategies to provide flexibility in the response; 3. Develop a storage management system by using AI, machine learning and big data technologies; 4. Collaborate with large companies to conduct an experimental demonstration of innovative management systems/control systems; 5. Understand the requirements and cost of grid ancillary services (e.g., peak load shifting etc.), figure out the capabilities of Carnot Batteries to engage in these services, and demonstrate Carnot Batteries on the actual utility market.

Material-level	Thermal storage materials: • The database for suitable energy storage materials for different temperature levels and different types of Carnot Battery systems needs to be improved, especially for very high and very low temperature levels.	1. Detailed characterization of all fields of thermal storage materials (e.g., thermal conductivity, phase change enthalpy, usable temperature range, chemical stability, availability, corrosion tests, production costs, environmental impact of using a certain storage material, etc.), including sensible, latent, thermochemical etc.; 2. Development of new promising/new/challenging energy storage materials/ compounds /mixtures/ sorbents, such as magnetite, liquid metal and MOFs etc.; 3. Long-term experiments for mechanical as well as thermophysical properties, and finalization of standardized procedures to characterize materials compatibility and stability (lifetime testing); 4. More projects on building and improving long-term thermal storage materials database and making the database more accessible.
Non-technical level	Cost of materials: Cost for the TES materials needs to be reduced	1. Analysis of the compatibility of storage materials with low-cost structural materials; 2. Focus on the abundant and cost-effective storage materials; 3. Screening of global resources of natural (mines) and non-natural origin (waste industry material) for storage materials; 4. Including companies/manufacturers in the consortium and cooperating with industrial fields for mass production; 5. Drawing guidelines to select materials in terms of both technical and cost aspects (as well as environmental aspects etc.).

2.5.5 Bonus - Scientific publications among the task 36 participants

Seven reviews on Carnot Batteries and related topics were published within the Task 36 execution time by participants of Task 36. In Table 7 the detailed information about the reviews is summarized.

Table 7: List of reviews published by the participants during the Task 36

Title	Authors	Journal	Year	DOI	Task 36
Carnot Battery technology: A state-of-the-art review	O. Dumont, G. F. Frate, A. Pillai, S. Lecompte, M. De paepe, V. Lemort	Journal of energy storage	2020	10.1016/j.est.2020.101756	☑
Rankine Carnot Batteries with the Integration of Thermal Energy Sources: A Review	G.F. Frate, L. Ferrari, U. Desideri,	Energies	2020	10.3390/en13184766	☑
Liquid air energy storage (LAES): A review on technology state-of-the-art, integration pathways and future perspectives	A. Vecchi, Y. Li, Y. Ding, P. Mancarella, A. Sciacovelli	Advances in Applied Energy	2021	10.1016/j.adapen.2021.100047	☑

Progress and prospects of thermo-mechanical energy storage – a critical review	A.V. Olympios, J.D. McTigue, P. Farres-Antunez, A. Tafone, A. Romagnoli, Y. Li, Y. Ding, W.D. Steinmann, L. Wang, H. Chen	Progress in Energy	2021	10.1088/2516-1083/abdbba	☑
Review of Carnot Battery Technology Commercial Development	V. Novotny, V. Basta, P. Smola, J. Spale	Energies	2022	10.3390/en15020647	☑
Key components for Carnot Batteries: technology review, technical barriers and selection criteria	T. Liang, A. Vecchi, K. Knobloch, A. Sciacovelli, K. Engelbrecht, Y. Li, Y. Ding	Renewable and Sustainable Energy Reviews	2022	10.1016/j.rser.2022.112478	☑
Carnot Batteries (CB): A State-of-the-art Review of CB System Performance and Applications	A. Vecchi, K. Knobloch, T. Liang, H. Kildahl, A. Sciacovelli, K. Engelbrecht, Y. Li, Y. Ding	Journal of Energy Storage	2022	10.1016/j.est.2022.105782	☑

2.6 Subtask D: Market Analysis, Energy System, Policy and Regulations

Subtask lead: Dr. Benjamin Bollinger – Malta Inc, **USA**

Subtask D focuses on promoting commercial acceptance of Carnot Batteries, by identifying market requirements for these technologies, assisting cost modelling and analyzing the Tech-to-Market transition. In addition, it supports policy and regulations as well as (non-scientifically focused) dissemination activities. Through education, lobbying and advertising, it builds support with hearts & minds.

Based on the discussions and analyses of the barriers and needs to deploy Carnot Batteries, the key aspects were identified and put together in the report of Subtask D. This report has three main parts and these are shortly described as follows:

2.6.1 Climate Crisis and Decarbonization Challenges

The current climate crisis has led local and international government agencies to set ambitious targets for the decarbonization of the energy system to stop the consequences caused by climate change.

With the European Climate Law, the European Commission is proposing a legally binding target of zero net greenhouse gas emissions by 2050.[1] According to the Federal Climate Protection Law, which was adapted in 2021, Germany must be climate-neutral by 2045[2]. Similarly, other countries in the world are heading in the same direction. One of the solutions proposed is to electrify the energy supply, from heat supply for households to industry.

Electricity generation from renewable sources has grown enormously in recent years and will continue to do so, but the reactivation of the post-pandemic economic system and the conflicts in Eastern Europe that led to the gas crisis have led to the prioritization of energy generation from any energy source to ensure supply for industry and households. This makes it even more challenging to achieve the goals set for the coming decades.

Carnot Batteries could accelerate the energy transition while building energy resilience. Carnot Batteries store electricity as thermal energy, which is later used to generate steam and thus electricity

[1] Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law').

[2] *Klimaschutzgesetz: Generationenvertrag für das Klima* Klimaschutzgesetz: Klimaneutralität bis 2045 | Bundesregierung

when demand requires. Carnot Batteries can convert Variable Renewable Energy into on-demand, around-the-clock power, meeting the accelerating need for power without worsening the dependency on fossil energy. Industry uses large amounts of natural gas to create heat. Carnot Batteries can discharge clean heat when charged with VRE. Buildings use fossil energy to keep families warm. Carnot Batteries can discharge heat into district energy systems to achieve the same goal. Most areas of the developed world face some combination of these three challenges.

2.6.2 Barriers to Deployment

Carnot Batteries are not broadly deployed today outside of concentrated solar power (CSP) plants. In CSP, TES is integrated with the solar-thermal systems to allow the plants to provide power 24 hours per day. Standalone Carnot Batteries, where electricity is stored from integrated generation facilities (e.g., solar PV, wind, etc.) or from the electric grid, can address the intermittency and flexibility challenges of VRE but face several barriers to deployment.

<u>Tech to Market Transition Barriers</u>

Some Carnot Batteries are still early in development with significant research and development needs. Funding to advance these technologies to higher TRL is challenging to secure.

Technology risk can lead to market risk, with potential customers being unwilling to commit to long-term contracts for FOAK projects. Without a long-term contract, securing financing for projects is even more challenging. This has been termed the "Valley of Death" for technology start-ups.

New, clean technologies are also inherently more expensive than their GHG-emitting alternatives. At the apex of their cost-down curves, new technologies must compete with fossil-economy technologies with decades of deployments, refinements, and cost savings measures. Bill Gates terms this the "green premium:" the additional cost of clean technology over a polluting alternative.

<u>Commercialization Barriers</u>

For Carnot Battery developers who are able to build a FOAK unit to validate a technology's operational and financial viability, market barriers make broader commercialization and widespread deployment challenging. Current energy systems and markets are insufficiently designed to incentivize deployment and appropriately compensate Carnot Battery owners and/or operators for all the services the technology can provide. Many markets have discriminatory policies in place that make bidirectional energy storage uneconomic.

2.6.3 Policy Recommendations

The drivers for deployment of Carnot Batteries and energy storage technologies in general are akin to the drivers for renewable energy: adoption of policy support packages to traditional market frameworks that were created to accommodate the conventional generation industry. Globally, power market laws, rules, and regulation vary by jurisdiction. There is no one-size-fit-all solution to removing barriers to and fostering support for Carnot Batteries. However, there are a host of mechanisms that could be drawn as inspirations and guidance for how the most suitable support mechanism(s) could operate in specific markets and geographies.

Carnot Batteries are a diverse technology class with solutions at all technology readiness levels. Collectively, all Carnot technologies would benefit from clarity and fairness in policy and regulation. Only through fair competition on a level playing field will transitioning markets organize efficiently and cost effectively.

Public investment in the development and deployment Carnot Batteries can help to overcome both tech-to-market barriers and commercialization barriers, namely funding Research and Development, grants, tax incentives, support for performance guarantees and warranties.

3 Comprehensive Results and Recommendations for Deployment

- Carnot Batteries and their components were defined in this working group. *"A Carnot Battery is a type of energy storage system that stores electricity in thermal energy storage. During the charging process, electricity is converted into heat and kept in the heat storage. During the discharging process, the stored heat is converted back into electricity"*.
- It was further defined explicitly which charging, storage and discharging methods are used in a Carnot Battery. Charging methods (power-to-heat): heating with an electric resistance or with a heat pump run by -preferably- excess renewable electricity, through different thermodynamic cycles such as Rankine, Brayton and joule. Thermal energy storage is carried out by any of the three methods, namely, sensible heat TES, latent heat TES or thermochemical storage. The discharging method (heat-to-power) is carried out based on reversible thermodynamic cycles, again Rankine and Brayton processes.
- The key performance indicators at system, component and material levels have been clearly defined. Thus, the system-level-KPI was defined as RTE, η_{II}, ω_{ch}, ω_{dis} etc. The component-level- KPI were defined as technology readiness's level TRL, maintenance costs (€/year, €/cycle), maximum discharging power – TES – (MW), etc. And for materials, specifically for TES, e.g. volumetric energy density (MWh/m^3), safety and environmental aspects, and recyclability (CO_2 footprint).
- An in-depth literature review was conducted to compile the state-of-the-art of Carnot Batteries, including commercial systems under development, pilot plants and components for Carnot Batteries. This is included in the final report, but also as a white paper that is available as a stand-alone document.
- A brief but very comprehensive description was elaborated to explain the mechanisms of thermal, sensible, latent and thermochemical storage as a white paper. This includes examples of Carnot batterie facilities, highlighting the type of thermal energy storage they use.
- The Wikipedia site on Carnot Battery was successfully released during the Task 36 execution. So far it is available in nine languages and can be further edited by task participants or externally. This allows an efficient and easy dissemination of the Carnot Batteries topic since Wikipedia sites are available globally and free of charge.
- Clear definitions of Rankine Batteries, Brayton Batteries and examples of other concepts and combinations have been provided in the final report. Including the technical operating conditions and limitations. This is also supported by the extended information in the 18 Factsheets on Carnot Battery systems and components delivered by the participants of Task 36.
- Similarly, the simulation tools used by the participants were collected in the form of Factsheets. A total of 35 Factsheets were submitted by 20 participants. They were analysed to provide a clear overview of which Software/programming languages the participants prefer. Also, some specific cases have been thoroughly exhibited in the final report, to communicate clearly what are the methods on which the simulations are based and what information can be obtained from them.
- The Subsection on R&D needs clearly communicates what is the current status of the Carnot Batteries installed today, the demonstrator, whether commercial or pilot plants. In overall, this

subsection shows tremendous technical advantages for the different Carnot Battery configurations, however, more research and development are still needed to experimentally confirm all these advantages. In addition, alternatives need to be found for the more expensive components in order to reduce the investment costs of the technologies.

- Clear definitions of the Carnot Batteries and their components – especially storage definitions - need to be stated, to facilitate the understanding by the public outside the technical area, and thus accelerate the development of regulations that facilitate the implementation of these technologies.
- Public funding in the form of projects, grants and subsidies for medium- and large-scale systems are some of the tools that can help Carnot Batteries to be deployed faster so that the dynamic operation of these technologies can be better understood and experimentally dominated.
- In addition to the two pre-definition meetings and six expert workshops held during the task execution period, webinars and workshops with the industry were also held. Below is a list of the additional events and their attendees:
    - The 2nd Expert Workshop of Task 36 held online was combined with the 2nd International Workshop on Carnot Batteries held online on September 15-16, 2020 and organized by the DLR, KIT and the University of Stuttgart.
    - Webinar organized between the IEA Energy Storage Task 36 and the Supergen Energy Storage Network+ *"Carnot Batteries – Academia meets Industry"*. It took place on January 28-29, 2021, with about 70+ internal and external participants.
    - The industrial workshop on Carnot Batteries was held as a hybrid events at the Technical University of Denmark (DTU) in the Lyngby-Campus, Denmark on September 10, 2021.
    - The 6th Expert Workshop of Task 36 held as a hybrid event in Stuttgart was combined with:
        - Exploitation workshop of the EU H2020 – CHESTER project, held as the last session of the expert workshop and moderated by PNO, partner of the CHESTER consortium.
        - The 3rd International Workshop on Carnot Batteries was held online on September 27-28, 2022 and organized by the DLR, KIT and the University of Stuttgart.

FINAL REPORT

1 Objectives, Structure, and Approach of Task

1.1 Objectives

The overarching aim of this Task is to ease the transition from a fossil-fuel-based to a renewable source-based energy system, through the promotion of novel energy storage systems, assisting their development, deployment, demonstration and deep understanding.

Therefore, this Task aims to establish a platform that brings together experts from the industry and academia, to systematically investigate, assess and strengthen the potential role of Carnot Batteries in the future energy systems gaining international attention.

The key objectives of Task 36 are:

- Mapping of the main Carnot Battery technologies and applications through the collection of existing information on electricity storage systems based on thermal energy storage (TES).
- Developing technology Key Performance Indicators of the Carnot Battery systems and their key components.
- Critical assessment of technological competitiveness and R&D demand.
- Help technology to market and delimit its market reach by identifying the services that should/can be provided by Carnot Batteries.
- Inform policy and provide a basis for proper regulations, based on the benefits and potential of Carnot Batteries and the requirements to assist their deployment.
- International dissemination of the technologies through workshops, white papers, open source datasets and scientific papers.

1.2 Scope

The scope of this Task addresses two perspectives, technological and non-technological:

Technological aspects:

- definition of Carnot Batteries
- power input and output are mandatory
- power input can be consumed by a heat pump, by direct (e.g. electrical resistance) heating or by similar equipment
- heat (or cold) input and output is optional
- TES mechanism can be: sensible, latent, thermochemical

Non-Technological aspects:

- business cases
- system integration aspects
- scalability limits with respect to materials availability
- environmental aspects
- further non-technological aspects, e.g. regulations, safety, etc.

The scope of the Task is restricted to the conversion and storage of electricity in the form of thermal (sensible, latent and thermochemical) energy. Other technologies such as electrochemical and mechanical storage technologies are excluded.

1.3 Structure and Approach

The work and discussions of the Task carried out by the experts are divided into five different Subtasks as shown in Figure 7. Subtask 0 is responsible for standardizing the information used for the Carnot Batteries, such as terminology, key performance indicators, and which electricity storage concepts are included and which are not.

The subtasks A, B and C were scientifically oriented and responsible for assessing the state of the art of the respective Carnot Batteries; Subtask A Rankine Batteries, Subtask B Brayton Batteries, Subtask C Other concepts and combinations. Within these Subtasks is analyzed which configurations would fit the respective concepts, including their operating conditions. Also, the modelling tools used for the different concepts and components were assessed here.

Finally, in Subtask D the market and policy perspectives are brought into the game. Within this Subtask, the current climate challenges are analyzed and the main hurdles to deploy technologies such as Carnot Batteries in the current scenario are discussed. At the end of section 2.3, some policy recommendations and paths to push the development of Carnot Batteries closer to the market are discussed.

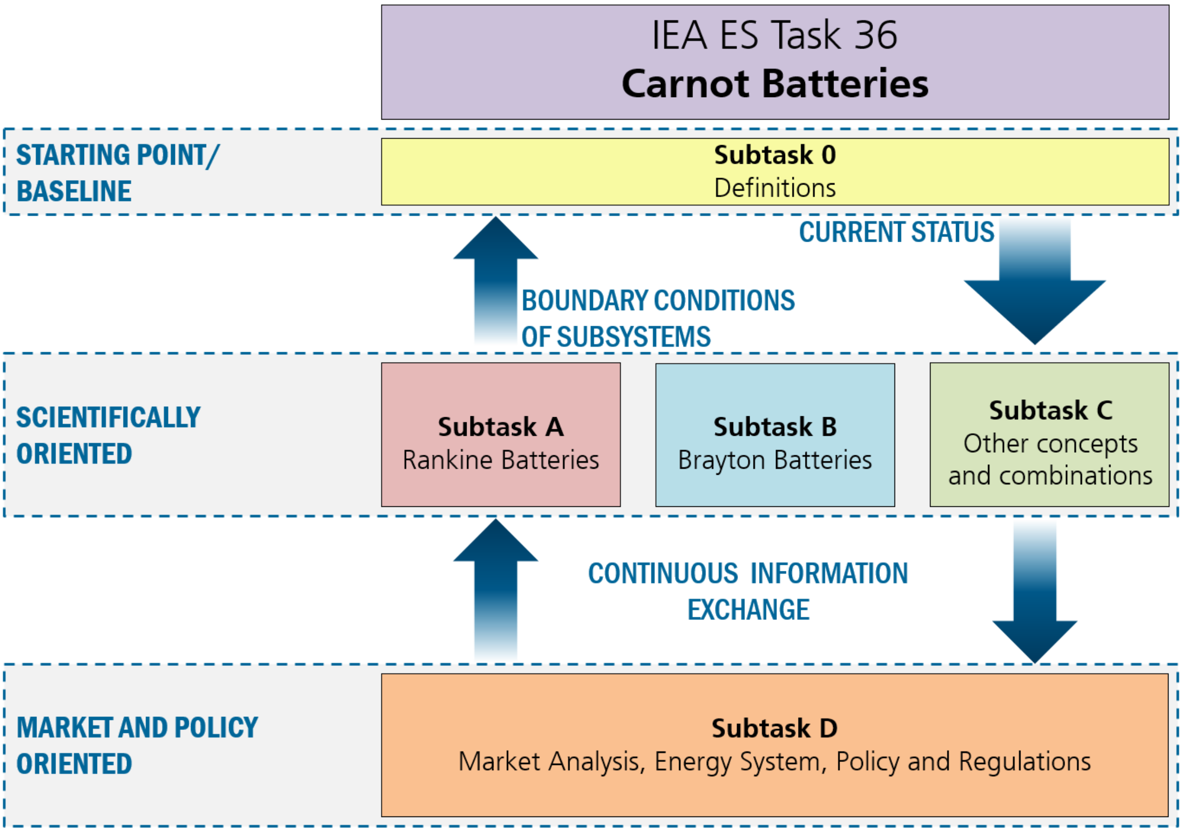


Figure 7: Structure of the IEA ES TCP Task 36

1.4 Meetings and Participating Countries/TCPs

The official start of the Task 36 was January 1, 2020. Table 8 gives an overview of the expert meetings in this Task.

Table 8: Details about the date and location of each expert meeting.

City	Country	Date	# of Participants
Online Meeting[1]	-	March 26, 2020	51
Online Meeting[2]	-	September 17-18, 2020	65
Online Meeting[3]	-	April 15-16, 2021	93
Hybrid Meeting in Lyngby	Denmark	September 9-10, 2021	78
Hybrid Meeting in Graz	Austria	April 4-5, 2022	61
Hybrid Meeting in Stuttgart[4]	Germany	September 26, 2022	70

[1]Originally planned as an in-person workshop to be held in Birmingham on 25-26 March 2020, hosted by the University of Birmingham.
[2]Hosted by DLR in collaboration with the Institute for Building Energetics, Thermotechnology and Energy Storage (IGTE) from the University of Stuttgart.
[3]Hosted by the University of Birmingham, UK and coordinated with the support of the German Aerospace Centre (DLR e.V.), the Birmingham Centre for Energy Storage and the Supergen Energy Storage Network+.
[4] Hosted by the DLR e. V., Germany combined with the exploitation Workshop of the EU- Project CHESTER (European Commission – H2020-LCE-2016-764) and took place directly before the 3th International Workshop on Carnot Batteries that took place from September 27 – 28, 2022.

1.4.1 Status of Participation

15 countries and one sponsor from Spain have declared their interest in participating in the Task at the 93rd ExCo meeting in May 2022 in Rome. 47 institutions from 16 countries participated in the 6th expert meeting. Table 9 gives an overview of the organisations participating in this task and the corresponding countries.

The Subtask Managers are Salvatore Vasta from CNR-ITAE, Italy; Kurt Engelbrecht from DTU, Denmark; Zhiwei Ma from Durham University, UK; Yulong Ding from University of Birmingham, UK; Benjamin Bollinger from Malta Inc, USA.

Table 9: List of participant countries and their representatives.

Country	Institution	Representative
Austria	AEE INTEC	Christoph Rohringer
Belgium	ENGIE-Laborelec	Kurt Reynders
	Ghent University	Steven Lecompte
	Liege University	Olivier Dumont
	Université Catholique de Louvain	Antoine Laterre
Czech Republic	Czech Technical University in Prague	Vaclav Novotny
Denmark	Aalborg University	Peter Sorknæs
	DTU (energy and mechanical engineering)	Kurt Engelbrecht
	PlanEnergi	Magdalena Kowalska
	University of Southern Denmark	Christian Veje
	Hyme	Karine Blandel
France	CEA	Jean-François Fourmigué
Germany	Bayreuth University	Andreas König-Haagen
	Carbonclean	Jörg Strese
	DENA	Maike Irena von Krause-Kohn
	DLR e.V.	Dan Bauer
	Enolcon GmbH	Jonas Häcker
	FAU Erlangen	Bernd Eppinger

	Fraunhofer ISE	Thomas Fluri
	Fraunhofer IFAM	André Schlott
	Fraunhofer UMSICHT	Silas Heim
	Kraftblock	Martin Schichtel
	KIT	Joachim Fuchs
	Siemens Gamesa ES GmbH	Alexander Zaczek
	Spilling Technologies GmbH	Christof Fleischmann
	Stuttgart University	Harald Drück
	TU-Berlin	Elisabeth Thiele
	TU – Chemnitz	Thorsten Urbaneck
	University of Applied Science Zittau/Görlitz	Thomas Schäfer
	University of Applied Sciences Amberg-Weiden	Andreas Weiß
	University of Applied Science Mittelhessen	Stefan Lechner
	PT Jülich (observer)	Stefan Busse-Gerstengarbe
Italy	CNR-ITAE	Salvatore Vasta
	ENEA	Michela Lanchi
	Politecnico di Torino	Eliodoro Chiavazzo
	University of Bari	Marco Antonio Pantaleo (EU EIC)
	University of Pisa	Umberto Desideri
	University of Genova	Stefano Barberis
Japan	Hokkaido University	Takahiro Nomura
	Tokyo Tech	Yukitaka Kato
Netherlands	Energy transition (former ECN part of TNO)	Michel Van der Pal
South Korea	Korean Institute of Energy Research	Junhyun Cho
Sweden	Azelio	Anna Gerokostopoulou
	Climeon	Joachin Karthauser
	Rise	Roger Nordman
	KTH	Rafael Guedez
Switzerland	MAN ES	Emmanuel Jacquemoud
	University of Applied Science Luzern	Willy Villasmil
Turkey	Gazi University	Zeki Yılmazoğlu
UK	BEIS	Georgina Morris
	Durham University	Zhiwei Ma
	Highview Power	Kelvin Sim
	University of Birmingham	Yulong Ding
	University of Hertfordshire	Wenbin Zhang
USA	ARPA-E	Max Tuttman
	Echogen	Timothy Held
	Malta Inc	Benjamin Bollinger
	NREL	Joshua McTigue
Spain (Sponsor)	University of Seville	Cristina Prieto

2 Outcomes of the Task 36

2.1 Basics

2.1.1 Definition of Carnot Batteries

Carnot Battery definition is a power-to-heat-to-power system, an energy conversion system that stores excess electricity as heat and then converts that heat back into electricity when needed. This process increases the overall efficiency and stability of the energy grid by reducing the fluctuations in energy demand and supply.

According to the description above, Carnot Battery is a multi-step energy conversion unit whose process involves the conversion of electrical energy into thermal energy and then back into electrical energy. This process can be used in a district heating system where a central heating plant provides heat to a large area or community through a network. To better define the operation, three different stages can be distinguished:

Step 1: Power-to-Heat Conversion: The first step of a Carnot Battery is the conversion of electrical energy into thermal energy. This is achieved by using an electric heater, such as an electric resistance heater, or a heat pump (more details in the following sections) which converts the electrical energy into heat energy. This "converter" is powered by electricity, preferably excess electricity, from renewable sources such as wind and solar, but hydro power can be also used as a backup.

Step 2: Heating the TES: The thermal energy generated from the electric converter is then used to heat-charge the TES unit. The share of the heat generated in Step 1 that doesn't have an adequate temperature level to the stored in the TES unit, can be also circulated through a network of pipes and distributed to different buildings or homes within the district (sector coupling). Heat in the TES unit is stored for different periods, according to the TES technology and application/grid requirements.

Step 3: Heat-to-Power Conversion: The final step in the power-to-heat-to-power system is the conversion of thermal energy back into electrical energy. This is achieved by using a heat-to-power conversion device based on different thermodynamic cycles, such as Steam Rankine Cycle, Organic Rankine Cycle, and Brayton Cycle among others, that converts the heat energy into electrical energy. The generated electrical energy can then be used for various applications or fed back into the grid in case the electricity transmission is needed.

In conclusion, a Carnot Battery is an innovative solution that supports the decarbonization of the electricity grid to ensure the supply of renewable power in a reliable, resilient and affordable way.

According to the details above, TASK 36's experts agreed on the following shared definition:

> *"A Carnot Battery is a type of energy storage system that stores electricity in thermal energy storage. During the charging process, electricity is converted into heat and kept in the heat storage. During the discharging process, the stored heat is converted back into electricity."*

Such a definition is reported on the Wikipedia Page created within the activities of the IEA-ECES Task 36[3].

[3] https://en.wikipedia.org/wiki/Carnot_battery

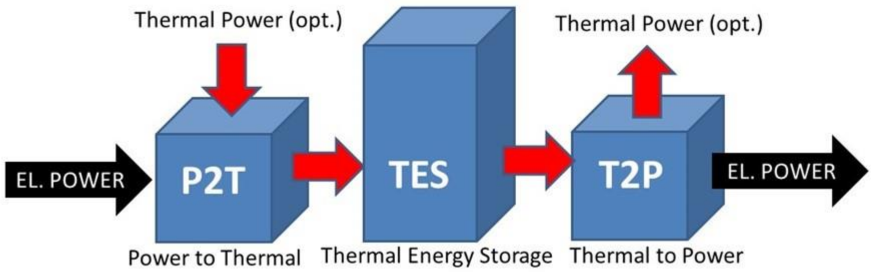


Figure 8: A simplified scheme of a typical Carnot Battery system.

Prof. Andre Thess invented the term *"Carnot Battery"* in 2018, before the first International Workshop on Carnot Batteries. The name *"Carnot Battery"* comes from Carnot's theorem, which describes the maximum efficiency of converting heat into mechanical energy. The word *"Battery"* indicates that the purpose of this technology is to store electricity. The discharge efficiency of Carnot Batteries is limited by the Carnot efficiency.

2.1.2 Key Performance Indicators

2.1.2.1 System Level

Various indicators can characterize a Carnot Battery's performance. The most commonly used performance indicator for a Carnot Battery as an Electrical Energy Storage (EES) technology is the round-trip efficiency (RTE), which is calculated as the ratio of net electrical energy output (E_{out}) to gross electrical energy input (E_{in}). The terms "net" and "gross" indicate that the electrical energy input and output undergo losses in components such as generators, motors, converters, inverters and transformers. Gross input includes these losses, while net output is after they have taken place. The RTE is defined as:

$$RTE = \frac{E_{out}}{E_{in}} \tag{2.1}$$

The RTE can be greater than 1 if waste heat is taken into account (as will be further explained). It would be more accurate to refer to this as the "electrical energy ratio" instead of "efficiency." However, for consistency with the majority of existing literature, this Task will continue to use the term "efficiency".

Most Carnot Batteries can be considered, in most cases, as composed of a series of heat pumps, to convert power into heat for the charging phase, a TES, to keep the thermal energy, and a heat engine to convert the stored thermal energy into power for the discharging phase. In this case, the RTE can be related to the performance indicators of the heat pump (COP), the TES (η_{tes}, which accounts for the thermal leakages) and the heat engine (η_{he}).

When fully reversible heat pumps and heat engines are used, and the heat transfer to the storage systems is reversible, with no temperature difference, RTE=1. In practical cycles involving various irreversibility forms, RTE is less than 1. This can be attributed to the exergy content of heat. Although energy is conserved during any conversion process, the work that can be produced from a heat flow is limited by its exergy. This is true for all systems without external heat input. If additional energy (heat) is added to the system, it can provide an additional exergy stream that can offset the losses due to irreversibilities.

When a non-ideal energy storage system is utilized, heat accumulates as internal energy, which hinders the system's ability to cycle correctly and restore its initial conditions after a full charge and discharge cycle. Two auxiliary components, typically two heat exchangers, are added to the energy storage system to address this issue. This allows excess heat removal from both the high-temperature (HT) and low-temperature (LT) reservoirs, thereby restoring the CB's initial conditions before the next charge/discharge cycle. A commonly proposed solution is to design the system so that all the excess heat is accumulated in only one of the two reservoirs, eliminating the need for one of the two additional components. However, the decision on which reservoir to store the excess heat in has consequences for the expression of RTE as a function of COP and η_{he}, and for the numerical value of RTE itself, as one configuration is more efficient than the other.

If the heat accumulates in the LT reservoir, meaning that the thermal energy stored in the HT reservoir is fully exploited, the following can be written[4]:

$$RTE = COP \cdot \eta_{tes} \cdot \eta_{he} \qquad (2.2)$$

Instead, if the heat from irreversibilities accumulates in the HT reservoir, meaning that the thermal energy stored in the HT reservoir remains partly unused while the LT is filled up, receiving all the thermal energy it can accumulate, the RTE reads[4] :

$$RTE = (COP - 1) \cdot \eta_{tes} \cdot \frac{\eta_{he}}{\eta_{he} - 1} \qquad (2.3)$$

In the previous formulas, Carnot Batteries with thermal reservoirs at a temperature higher and/or lower than the environment are considered. In both cases, the most rigorous framework to investigate the storage performance is to consider that thermal exergy is stored at temperatures higher or lower than the environment[5] . From this standpoint, it is possible to consider the impact of heat leakages in the storage by dropping the adiabatic reservoir hypothesis, introducing the η_{tes}. If the thermal reservoir at temperatures higher than the environment is considered, η_{tes} considers the heat that is lost to the environment. If the considered thermal reservoir is colder than the environment, η_{tes} accounts for heat that leaks from the environment into the reservoir. In both cases, the reservoirs lose a portion of the stored exergy during energy conservation, which leads to a reduced ability to produce electric energy during the discharge.

The decisions on where to store excess heat have an impact on system performance. According to the equations, it is more efficient to store the heat in the LT reservoir. However, in some cases, it may be more practical to store the heat in the HT reservoir due to lower costs and ease of extraction. This is because high-temperature heat is easier to extract. However, if the LT reservoir is only partially at lower temperatures than the environment, the excess heat storage can still be removed without needing an auxiliary heat pump. Some authors suggest using only one heat reservoir, making it obvious to determine which reservoir should be emptied at the end of the charge/discharge cycle and use the appropriate expression for RTE.

Lastly, it can be noted that both expressions of RTE equal 1 in the case of ideal systems. This occurs when the thermal reservoirs are adiabatic and COP and η_{he} are the exact opposite of each other, meaning that there are no heat or pressure losses and only isentropic machines are used during the thermodynamic cycle.

Carnot Batteries with the integration of additional heat sources

The definitions provided above for the RTE can be readily applied to the case in which the Carnot Battery absorbs additional heat sources during the charge or discharge, improving COP and η_{he} and, thus, RTE. In this case, many authors showed that the RTE could go beyond 1[5], which would be impossible without resorting to external energy streams in addition to the charging energy input.

A thermally integrated CB can indeed have a high RTE, stemming from high first-law efficiency, but it is unfair to consider the heat from the additional heat sources and the input electrical energy as equally valuable. Furthermore, the RTE is focused on the electric input and outputs and is not suitable for measuring the impact of the potential production of heat during discharge.

---

[4] Dumont, O., Frate, G. F., Pillai, A., Lecompte, S., De paepe, M., and Lemort, V. (2020). Carnot battery technology: A state-of-the-art review. J. Energy Storage 32, 101756. DOI:10.1016/j.est.2020.101756

[5] Frate, G. F., Antonelli, M., and Desideri, U. (2017). A novel Pumped Thermal Electricity Storage (PTES) system with thermal integration. Appl. Therm. Eng. 121, 1051–1058. DOI:10.1016/j.applthermaleng.2017.04.127

A second-law efficiency, also known as exergy efficiency, can be used to account for the difference in thermodynamic quality between thermal and electrical inputs. By considering all the heat in input and output as useful energy, the second-law efficiency can be defined based on the assumption that all the heat absorbed and produced could be converted into electricity through an infinite number of infinitesimal Carnot cycle[6] (, 1985):

$$\eta_{II} = \frac{E_{dis}+Q_{dis}\cdot\left[1-\frac{T_0}{\Delta T_{sink}}\cdot ln\left(\frac{T_{sink,out}}{T_{sink,in}}\right)\right]}{E_{ch}+Q_{ch}\cdot\left[1-\frac{T_0}{\Delta T_{source}}\cdot ln\left(\frac{T_{source,in}}{T_{source,out}}\right)\right]} \tag{2.4}$$

Where, Q_{ch} and Q_{dis} are the heat amounts absorbed and produced during the charging and discharging phase, respectively. Q_{dis} is used to heat a thermal sink from the temperature $T_{sink,in}$ to $T_{sink,out}$, with $\Delta T_{sink} = T_{sink,out} - T_{sink,in}$. Q_{ch}, instead is the available heat from the heat source by cooling it down from a temperature $T_{source,in}$ to $T_{source,out}$, with $\Delta T_{source} = T_{source,in} - T_{source,out}$. Finally, T_0 is the reference environment temperature.

Two cases can be considered for Q_{ch}. In the first case, η_{II} is calculated using the available heat input, implying that any part not captured by the Carnot Battery is considered waste (a typical scenario for waste heat recovery). In this case, $T_{source,out} = T_0$. In the second case, Q_{ch} represents the actual heat input absorbed by the Carnot Battery, meaning $T_{source,out} \geq T_0$.

The classification of a thermally integrated Carnot Battery as either an electricity storage system or a waste heat recovery system is not always clear-cut and may depend on the ratio between heat and electrical energy input, which may be up to 1/10[7], depending on the operating fluids and the temperature level of the heat source. Additionally, it is worth noting that the direct conversion of waste heat into electricity, regardless of how low the temperature may be, will always be more efficient than any Carnot Battery using such thermal resources.

For the charging phase, the ratio of the electrical to thermal input is[7];

$$\omega_{ch} = \frac{E_{ch}}{Q_{ch}} = \frac{1}{COP-1} \tag{2.5}$$

For the discharging phase, the ratio of the electric to the thermal output can be written as follows (Frate et al., 2020):

$$\omega_{dis} = \frac{E_{dis}}{Q_{dis}} = \frac{\eta_{he}-1}{\eta_{he}} \tag{2.6}$$

Since to achieve satisfactory RTE, both high COP and η_{he} are desired, it is straightforward to understand that $\omega_{ch} \ll 1$, meaning that large heat flows are required to have an impact on systems with large electric charging capacities. Similarly, the larger η_{he} is the lower ω_{dis} becomes, meaning that efficient discharge systems reduce the Carnot Battery's capability of producing additional heat outputs.

Technical and economic key performance indicators

In addition to RTE, second-law efficiency, and the ratio between electric and thermal inputs and outputs, which are specific to Carnot Batteries, other indicators commonly used to evaluate the performance of storage technologies can also be applied to characterize the performance of a Carnot Battery.

---

[6] Kotas, T. J. (1985). “Chapter 2: Basic exergy concepts,” in The Exergy Method of Thermal Plant Analysis (Elsevier), 29–56. doi:10.1016/B978-0-408-01350-5.50009-X

[7] Frate, G. F., Ferrari, L., and Desideri, U. (2020). Rankine Carnot Batteries with the Integration of Thermal Energy Sources: A Review. Energies 13, 4766. DOI:10.3390/en13184766

These indicators include energy and power compactness γ_e and γ_w in kWh/m^3 and kW/m^3, often called also electric energy and power density[8], which are defined as the ratio of the electric inputs to the TES volume (V_{tes}) and can be based on the charging or discharging energy and power inputs/outputs[4]:

$$\rho_{e,ch} = \frac{E_{ch}}{V_{tes}} \quad (2.7)$$

$$\rho_{e,dis} = \frac{E_{dis}}{V_{tes}} = \frac{E_{ch} \cdot RTE}{V_{tes}} \quad (2.8)$$

$$\rho_{w,ch} = \frac{E_{ch}}{\tau_{ch} \cdot V_{tes}} \quad (2.9)$$

$$\rho_{w,dis} = \frac{E_{dis}}{\tau_{dis} \cdot V_{tes}} \quad (2.10)$$

where τ_{ch} and τ_{dis} is the nominal charging and discharging durations in hours. It is worth noting that energy and power compactness are defined based on *electric* inputs/outputs and do not coincide with *thermal* energy and power compactness (or density). If thermal inputs and outputs are used, the resulting compactness indices must be multiplied by the charging and discharging efficiencies to account for losses from electricity conversion to heat.

Other indicators useful to compare Carnot Batteries with different storage technologies are[8]: the Technology Readiness Level (TRL), the operating lifetime (L) in years, the specific cost of capacity (γ_e) in € or $ per kWh, and the specific cost of charging and discharging rates (γ_w) in € or $ per kW.

The specific costs can be defined based on the charged or discharged electric inputs and outputs. The capacity cost can be written as follows:

$$\gamma_{e,ch} = \frac{\sum_i C_{tes,i}}{E_{ch}} \quad (2.11)$$

$$\gamma_{e,dis} = \frac{\sum_i C_{tes,i}}{E_{dis}} = \frac{\sum_i C_{tes,i}}{E_{ch} \cdot RTE} \quad (2.12)$$

where $C_{tes,i}$ is the cost of the *i*-th of the TES component. The cost summation usually includes the TES materials, the related containers and the auxiliary devices required to operate the TES.

Similarly, for the power-specific cost, it can be written as follows:

$$\gamma_{w,ch} = \frac{\sum_i C_{ch,i} + \sum_j C_{dis,j}}{E_{ch}/\tau_{ch}} \quad (2.13)$$

$$\gamma_{w,dis} = \frac{\sum_i C_{ch,i} + \sum_j C_{dis,j}}{E_{dis}/\tau_{dis}} = \frac{\sum_i C_{ch,i} + \sum_j C_{dis,j}}{E_{ch} \cdot RTE/\tau_{dis}} \quad (2.14)$$

where $C_{ch,i}$ is the cost of the *i*-th component of the charging system, while $C_{dis,j}$ is the cost of the *j*-th component of the discharging system. The cost summation usually includes the charging and discharging systems' machines (compressors and turbines), heat exchangers, and the auxiliary devices required to operate the charging and discharging devices.

The KPIs defined in this Annex to measure the Carnot Batteries' performance are summarised in Table 10.

Table 10: Summary of KPIs relevant to Carnot Batteries.

Nomenclature	Full name	Unit measure
RTE	Roundtrip efficiency	(-)
η_{II}	Second law efficiency (exergy efficiency)	(-)

[8] Frate, G. F., Ferrari, L., and Desideri, U. (2021). Energy storage for grid-scale applications: Technology review and economic feasibility analysis. Renew. Energy 163, 1754–1772. DOI:10.1016/j.renene.2020.10.070

ω_{ch}	Ratio of electrical to thermal inputs in the charging phase	(-)
ω_{dis}	Ratio of electrical to thermal outputs in the discharging phase	(-)
ρ_e	Energy compactness*	(kWh·m^{-3})
ρ_w	Power compactness*	(kW·m^{-3})
γ_e	Specific capacity cost*	(€ or $/kWh)
γ_w	Specific power cost*	(€ or $/kW)
L	Operating life time	(years)
TRL	Technology readiness level	(-)
*It can be related either to the charging or discharging phase		

2.1.2.2 Component Level & Material Level

The KPIs defined for the component and material levels are shown in 3.1 Appendix 1.

2.1.3 State of Art of Carnot Batteries

This section gives a summarized overview of the current state of the art of Carnot Batteries. Including the classification of Carnot Batteries and the experimental and commercial developments of Carnot Batteries. The extended white paper can be seen in Appendix 2.

2.1.3.1 Introduction

Carnot Batteries (CB) are an emerging solution for large-scale, flexible, and cost-effective electricity storage, based on thermal energy and conversion systems between power and heat. As the demand for energy storage increases with the growing penetration of renewable energy sources in the grid, CBs present a promising alternative to other electrical storage systems like pumped storage hydropower plants and electrochemical batteries. This paper explores the current state of the art in CB technology, examining the various methods and technologies competing in the market and academia.

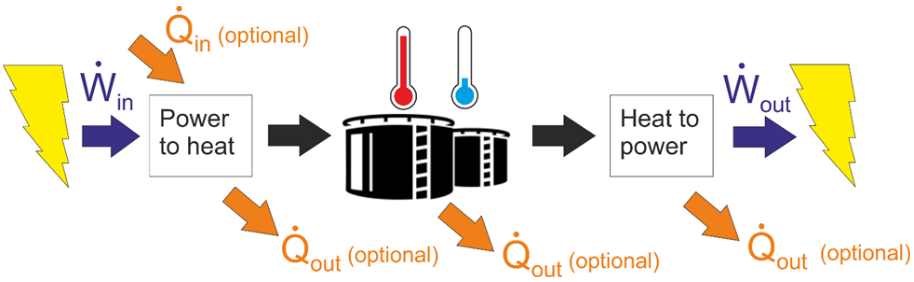


Figure 9: General principle of Carnot Battery systems.

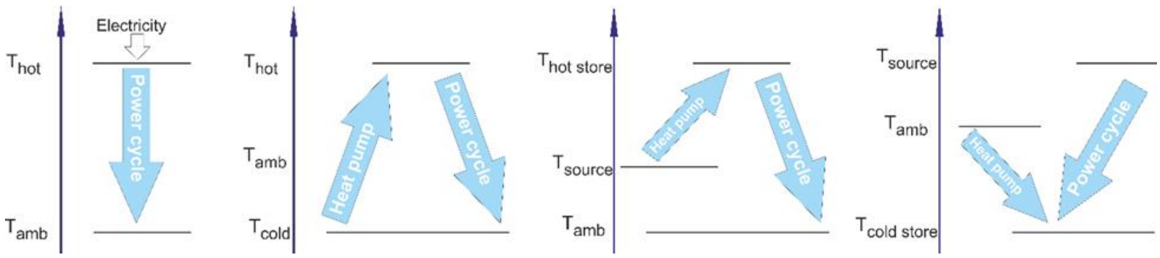


Figure 10: CB concept for thermal integration of heat sources and conversion systems.

2.1.3.2 Classification of Carnot Batteries

Carnot Batteries can be categorized based on factors such as charging and discharging methods, thermal energy storage technology, and the type of conversion system used. In this paper, the classification system used focuses on the discharging system, specifically Rankine cycle systems, Brayton cycle systems, and other hybrid systems, in accordance with the categories established by the IEA Task 36 on Carnot Batteries.

2.1.3.3 Bibliometric Study and Theoretical Analyses

The term *"Carnot Battery"* has gained increasing attention in recent years, as evidenced by the growth in the number of scientific publications on the topic. **Theoretical analysis** of CB systems highlights the importance of real component efficiency and the impact of temperature differences and pressure losses during heat exchange on overall roundtrip efficiency. According to the literature on theoretical analyses, typical roundtrip efficiency values range between 40% and 65%.

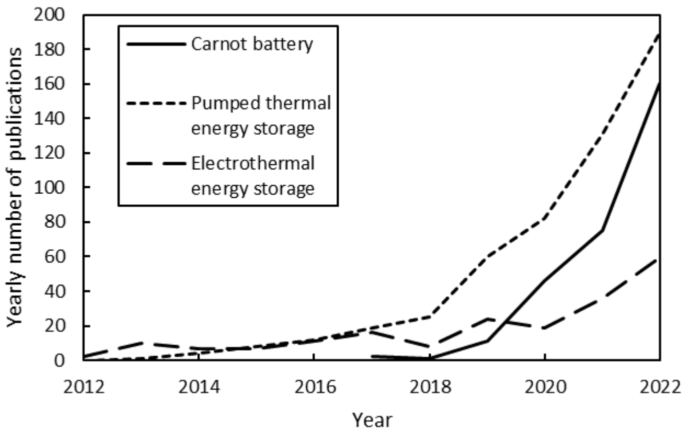


Figure 11: Yearly number of scientific publications with main CB keywords.

2.1.3.4 State of the Art in Experimental and Commercial Development

The development of CB technology spans from early experimental works and commercialization trials to more recent advancements driven by the need for large-scale economically feasible electricity storage. Planned commercial CB systems can be roughly distinguished into three groups: Rankine cycle-based, Brayton cycle-based, and hybrid systems.

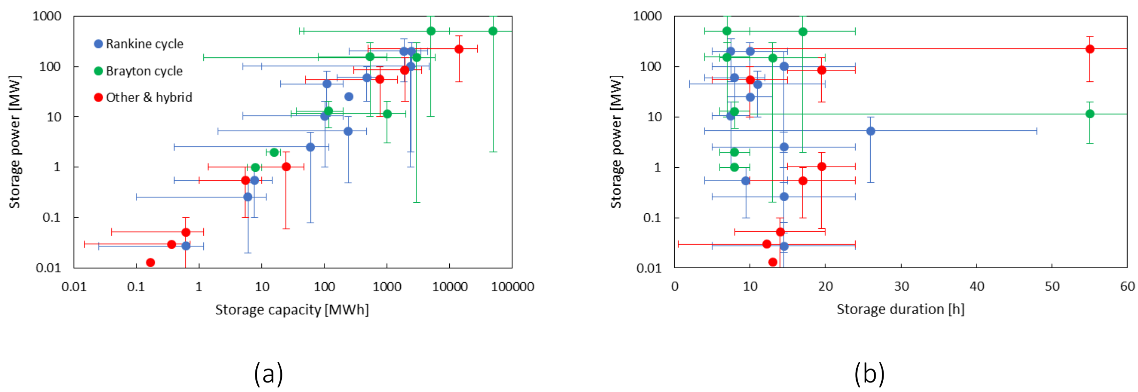


Figure 12: Storage power output and capacity (a) and discharge duration (b) for the commercially developed CB systems.

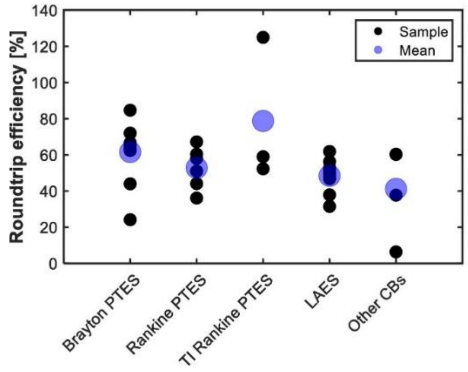


Figure 13: Overview of CB efficiency in published scientific papers[9].

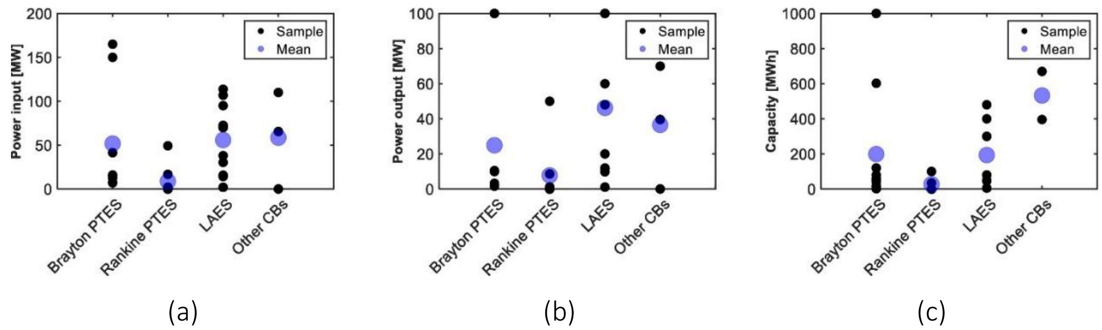


Figure 14: Storage systems performance from scientific studies regarding (a) power input, (b) power output and (c) system capacity[9].

2.1.3.5 Challenges and Future Perspectives

Several challenges need to be addressed for CB technology to become a widely adopted large-scale energy storage solution:

a. Technology maturity: Many CB systems are still in the experimental or pilot stages, requiring further development to demonstrate reliability and cost-effectiveness at full scale.
b. Component efficiency: Improving the efficiency of key components such as compressors and expanders is crucial for enhancing overall system performance.
c. Thermal energy storage: Developing cost-effective, high-performance thermal storage materials and technologies is essential for the success of CB systems.
d. System integration: The integration of CB systems with renewable energy sources and the grid will require advancements in control and optimization strategies.
e. Market and regulatory barriers: The widespread adoption of CBs will depend on supportive policies, regulations, and market structures that encourage investment and deployment.

In conclusion, Carnot Battery technology is in the early stages of development but undergoing rapid growth and fast evolution. Driven by the growing demand for flexible large-scale cost-effective electricity storage and ancillary grid services, CBs have the potential to become a key component of future renewable-based energy systems. As the technology matures and overcomes the challenges outlined above, CBs are expected to play a significant role in the transition to a sustainable and resilient energy future.

---

[9] Vecchi A, Knobloch K, Liang T, Kildahl H, Sciacovelli A, Engelbrecht K, et al. Carnot Battery development: A review on system performance, applications and commercial state-of-the-art. J Energy Storage 2022;55:105782. https://doi.org/10.1016/J.EST.2022.105782

2.1.4 TES Methods for Carnot Batteries

This section gives an overview of different types of storage materials for Carnot Batteries, their benefits and drawbacks as well as an outline of the interaction between the TES and the overall Carnot Battery system. The presented content is based on the outcome ST0-3 which can be found in full length in Appendix 3 of the final report.

2.1.4.1 Thermal Storage Principles and Materials

TES is a key component of every Carnot Battery system. It is located between the power-to-heat and heat-to-power systems, so its discharging and charging operations must be adapted to these systems for optimal operation. In the following sections, various TES technologies are discussed in the context of Carnot Batteries[10] [11]. A detailed description of the main types of thermal storage technologies can be found in [12][13], where they can be divided into three groups:

2.1.4.1.1 Sensible-type Heat Storage

This class of TES uses a change in material temperature to store thermal energy. The material temperature changes during charging and discharging, resulting in higher losses at higher temperature differences to the ambient.

2.1.4.1.2 Latent-type Heat Storage

It utilizes the melting or evaporation heat of certain materials (PCMs) to store thermal energy. During a phase change, the material temperature changes negligibly, resulting in lower overall temperatures compared to sensible storage at the same energy intake. (see Figure 15b).
Additionally, by properly selecting the material to phase change at the desired mean operation temperature, the material temperature does not change and provides a constant temperature level during charge and discharge.

2.1.4.1.3 Thermochemical-type Heat Storage

It stores heat as a thermochemical potential between two components. The major upside to this storage principle is that virtually no storage losses occur as soon as the two reactants are separated. If combined again (e.g. during ab- or adsorption) the stored thermal energy can be released at the desired time.

---

[10] Hasnain, S. M. (1998). Review on sustainable thermal energy storage technologies, Part I: Heat storage materials and techniques. Energy Conversion and Management, 39(11), 1127–1138. https://doi.org/10.1016/S0196-8904(98)00025-9

[11] Sarbu, I., & Sebarchievici, C. (2018). A Comprehensive Review of Thermal Energy Storage. Sustainability, 10(1), 191. https://doi.org/10.3390/su10010191

[12] Alva, G., Liu, L., Huang, X., & Fang, G. (2017). Thermal energy storage materials and systems for solar energy applications. Renewable and Sustainable Energy Reviews, 68, 693–706. https://doi.org/10.1016/j.rser.2016.10.021

[13] Hauer, A. (2011). Storage Technology Issues and Opportunities, International Low-Carbon Energy Technology Platform. In Proceedings of the Strategic and Cross-Cutting Workshop “Energy Storage—Issues and Opportunities”, Paris, France, 15 February

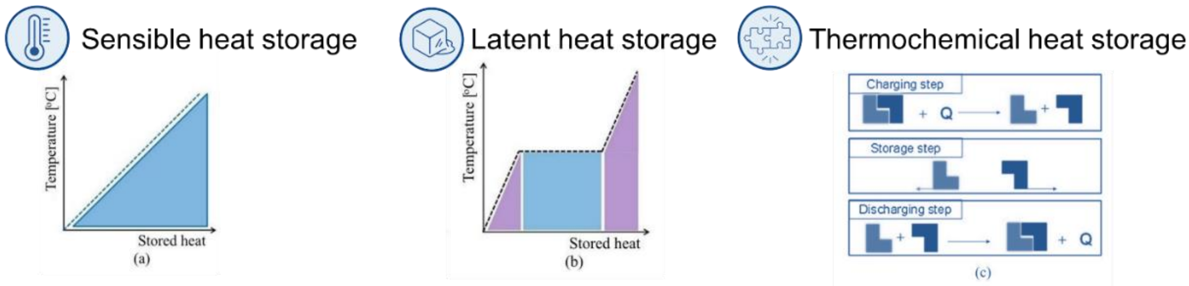


Figure 15: Methods for thermal energy storage: (a) sensible heat; (b) latent heat; (c) thermo-chemical, based on Sarbu & Sebarchievici, 2018[11].

To minimize exergetic losses during energy conversion from electricity to heat and vice versa, the temperature profiles of the deployed conversion technologies and thermal storage need to match during charge and discharge. Since sensible storage changes its temperature when taking in thermal energy, conversion technologies with similarly changing temperature profiles are desired. The most common process with such a profile is the so-called Joule-Brayton cycle, with the classic gas turbine or CO_2 heat pumps as one example. In Novotny et al., 2022[14], detailed descriptions of storage materials for Carnot Batteries with Brayton cycles are available.

2.1.4.2 Storage Materials for Carnot Batteries

2.1.4.2.1 Sensible

The most common example of Sensible Heat TES (SHTES) with a liquid medium is water, while with a solid medium, it could be rock. Both have the advantage of being cheap, abundantly available and non-toxic storage materials. The specific heat capacity of water is about four times that of rock material. However, the increase in water vapor pressure with temperature makes it more difficult to handle and more costly. When using rock as a storage material reaching temperatures of 700 °C can be easily carried out, without phase change or change in the chemical structure within the expected operating temperature range. A detailed list of the different materials can be found in several papers published on this topic, e.g. Sarbu & Sebarchievici, 2018[11].

One real-scale example of sensible-based Carnot Batteries is the ETES: Base System deployed by Siemens Gamesa in Germany. It is a sensible rock storage charged with high-temperature air flow (direct resistance heating, matching temperature profile for the sensible storage, up to 750 °C storage temperature). The system contains around 1.000 t of volcanic rocks and can store about 130 MWh of thermal energy for about a week depending on ambient conditions. The conversion back to electricity is carried out by an off-the-self steam turbine which can dispatch up to 30 MWh of electrical energy using the full storage capacity. The storage capacity did not significantly change with time and the increasing number of charging and discharging cycles, showcasing the durability of the chosen storage material over several cycles.

[14] Novotny, V., Basta, V., Smola, P., & Spale, J. (2022). Review of Carnot Battery Technology Commercial Development. Energies, 15(2), 647. https://doi.org/10.3390/en15020647

Figure 16: TES: Base System built by Siemens Games in cooperation with TU Hamburg and Hamburg Energy in 2019, source: IEA ES Task 36 Fact-sheets (left) and Google Maps (right).

2.1.4.2.2 Latent

Latent Heat TES (LHTES) is advantageous in specific heat capacity compared to SHTES but requires much higher investment costs. Prototypes that provide LHTES in Carnot Batteries can be found for example in (Active Energy systems[15], melting ice and Malta [16], molten salt, however, there are a variety of phase change materials available covering a wide range of phase change temperatures to be deployed for different uses. Figure 17 showcases the distribution of different PCMs over temperature levels and material classes as well as their specific advantages and disadvantages.

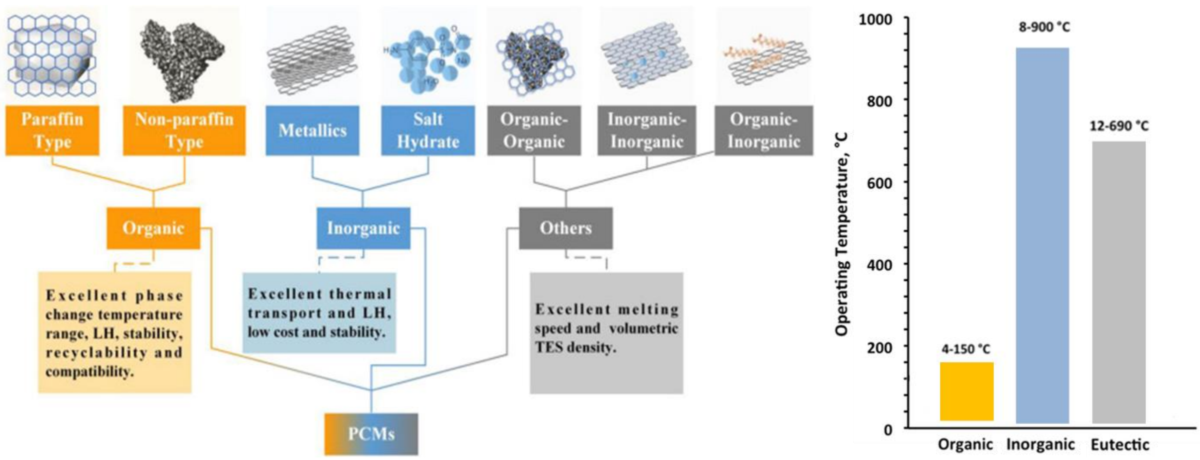


Figure 17: Different classes of phase change material and their advantages and disadvantages for thermal energy storage, as well as the respective temperature ranges for operation, based on Dumont et al., 2020[4]; Maha, 2021[17]; Qiu et al., 2019[18].

"MAN Energy Solutions" is currently developing and marketing a Carnot Battery system called MAN ETES, containing not only sensible storage (pressurized hot water for heat storage at 150 °C max) but also a latent storage system based on ice (cold storage) as well as a transcritical CO_2 heat pump. The ice storage allows for very space-efficient storage of the cold generated during charge by the heat pump

[15] Active Energy Systems. (o. J.). Abgerufen 11. März 2022, von https://www.activeenergysystems.com/
[16] Malta. (o. J.). accessed 11. März 2022, von https://x.company/projects/malta/
[17] Maha, T. (2021). Recent frontiers in solar energy storage via nanoparticles enhanced phase change materials: Succinct review on basics, applications, and their environmental aspects
[18] Qiu, L., Ouyang, Y., Feng, Y., & Zhang, X. (2019). Review on micro/nano phase change materials for solar thermal applications. Renewable Energy, 140, 513–538. https://doi.org/10.1016/j.renene.2019.03.088

and utilized during discharge for the expansion. MAN is planning also to use heat and cold not only for electricity storage and conversion but also for combined heat/cold and power applications, using the assets to their maximum and increasing the efficiency of the overall system instead of focusing only on electrical storage efficiency. The system is therefore not only an electrical battery but also an efficient tool for sector coupling. The proposed system should be able to store about 150 MWh of heat and 110 MWh of cold.

2.1.4.2.3 Thermochemical

The main benefit of this type of heat storage is, that virtually no storage losses occur during the storage period since the majority of the heat is provided by the reaction. Additionally, since exothermic reactions can provide a significant amount of energy per unit of volume or mass, these storage systems have higher volumetric or gravimetric energy densities than sensible storage systems. However, most of the reactants are usually more costly than simple sensible or latent storage materials, resulting in TCTES systems being the most expensive of the three thermal storage principles on average. Depending on reactants and their thermal stability as well as the ideal reaction temperature, CTES can be realized for a range of temperature levels. Sorption-based systems (absorption, adsorption) are more suited for low-grade heat while non-sorption-based reactants are utilized for higher-temperature applications. An overview of common thermochemical reactant pairs and their associated temperature levels is provided in Figure 18.

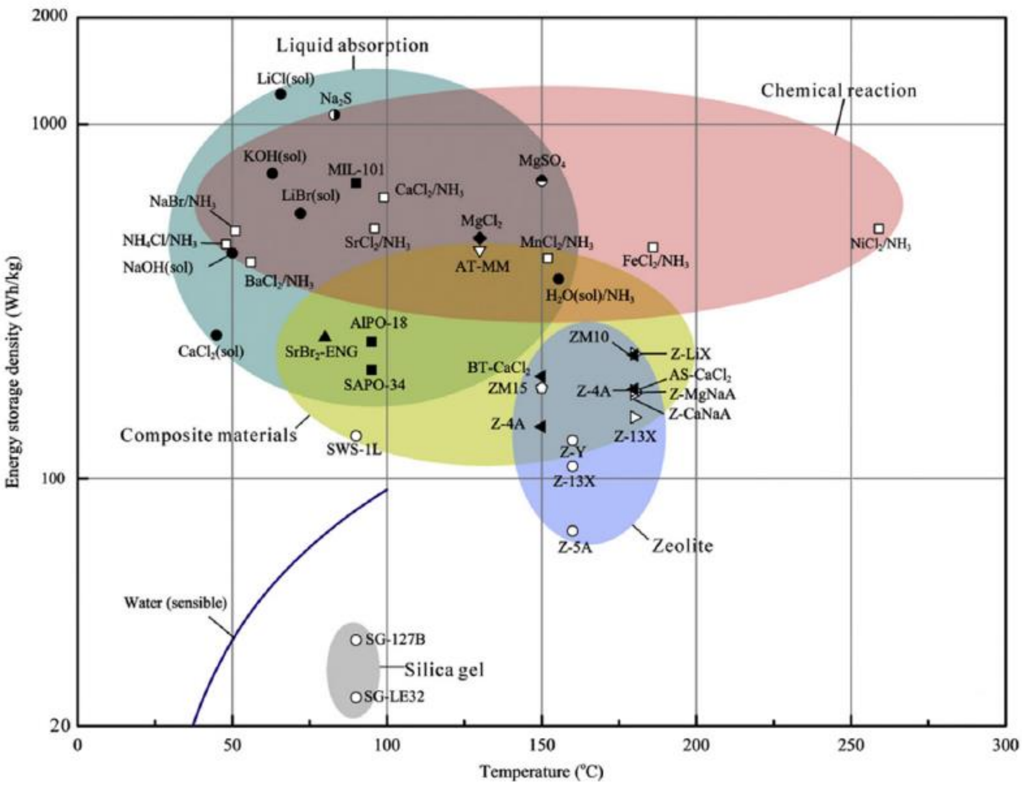


Figure 18: Overview of common thermochemical reactant pairs, their associated temperature levels and energy storage densities. Based on Aydin et al., 2015[19].

During the Task 36 duration, no TCES-based Carnot Batteries were identified within the industry sector and only individual ones at the prototype stage in the research sector. However, the mitigation of storage losses and high volumetric and gravimetric energy densities coupled with a broad range of

[19] Aydin, D., Casey, S. P., & Riffat, S. (2015). The latest advancements on thermochemical heat storage systems. Renewable and Sustainable Energy Reviews, 41, 356–367. https://doi.org/10.1016/j.rser.2014.08.054

temperature levels suggest a high implementation potential for TCES systems in future Carnot Battery concepts.

2.1.5 Wikipedia Page/Dissemination

The Wikipedia page of Carnot Batteries was first created by the partners in Task 36 to increase the exposure to the public. The first page was created in English in October 2020, and then later extended to nine different languages until December 2022, i.e., Italian, German, Chinese, Turkish, Czech, Japanese, French, and Spanish (in the order by the created date). At the end of 2022, the pageviews are around 1,500 in a month across all languages, and the accumulated pageviews are over 32,000.

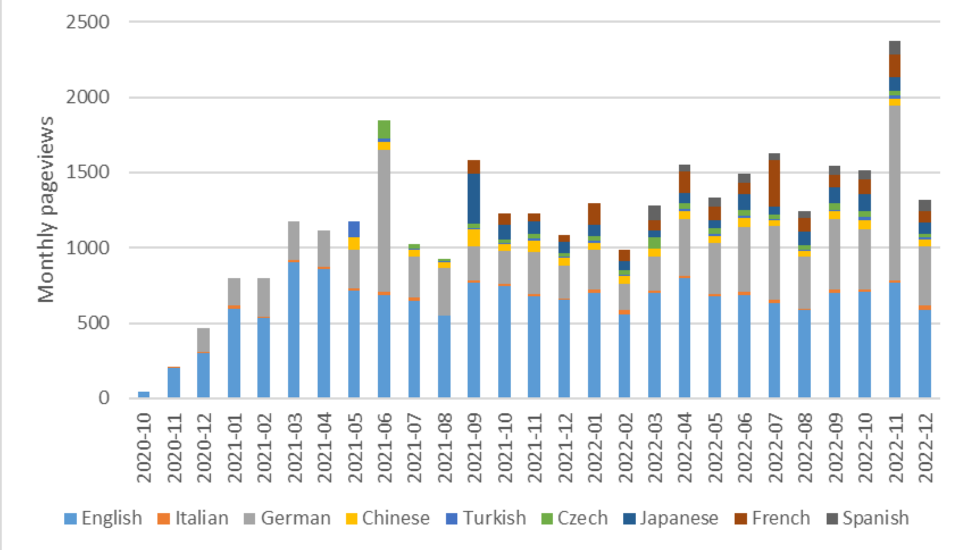
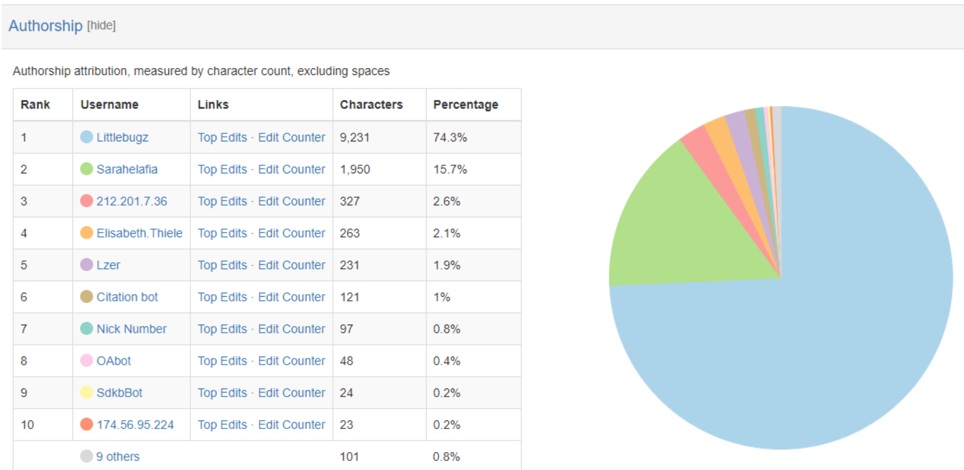


Figure 19: Wikipedia pageviews of Carnot Batteries in different languages (Oct. 2020 - Dec. 2022).

Wikipedia is a top 10 most visited website in the world and the content of the Wikipedia pages is likely to be the first results from search engines. Therefore, creating Wikipedia pages is an effective way to introduce Carnot Batteries to the public. Although the Wikipedia page of Carnot Batteries is initiated by the members of the IEA ES Task 36 – “Carnot Batteries”, the contributors to the pages can be done by anyone in the world. Based on the statistics of the authorship for the page in English, there are a total of 19 users that have contributed to the page (see Figure 20).



Authorship [hide]

Authorship attribution, measured by character count, excluding spaces

Rank	Username	Links	Characters	Percentage
1	Littlebugz	Top Edits · Edit Counter	9,231	74.3%
2	Sarahelafia	Top Edits · Edit Counter	1,950	15.7%
3	212.201.7.36	Top Edits · Edit Counter	327	2.6%
4	Elisabeth.Thiele	Top Edits · Edit Counter	263	2.1%
5	Lzer	Top Edits · Edit Counter	231	1.9%
6	Citation bot	Top Edits · Edit Counter	121	1%
7	Nick Number	Top Edits · Edit Counter	97	0.8%
8	OAbot	Top Edits · Edit Counter	48	0.4%
9	SdkbBot	Top Edits · Edit Counter	24	0.2%
10	174.56.95.224	Top Edits · Edit Counter	23	0.2%
	9 others		101	0.8%

Figure 20: Contributors to the Wikipedia page in English.

The Carnot Batteries Wikipedia page has generally six parts: introduction, background, system configuration (i.e. electricity-to-heat, heat storage, heat-to-electricity), advantages and disadvantages, application, and list of projects. The publications and reports related to Carnot Batteries are linked or referenced on the page, and therefore more people can find the latest works in this area. The pages of related topics (e.g. Lamm-Honigmann process) are also created while improving the content of the page. This Carnot Batteries page has also been linked to other Wikipedia pages such as energy storage and thermal energy storage pages to increase public visibility.

There is room to improve the content on the Wikipedia page. For example, more technical details can be added to provide information about the costs and technical characteristics of different Carnot Battery technologies. The comparison between Carnot Batteries and other energy storage technologies in various aspects such as storage duration and cost per storage capacity can provide a clear picture of the position and potential role of each storage technology.

The list of Wikipedia page contributors from the annex: Alexander Zaczek, Barton Chen, Cristina Prieto, Elisabeth Thiele, Jean-Francois Formigue, Karin Edel, Maike von Krause-Kohn, Noelia Martinez, Salvatore Vasta, Takahiro Nomura, Yukitaka Kato, Zeki Yilmazoglu, Zhiwei Ma.

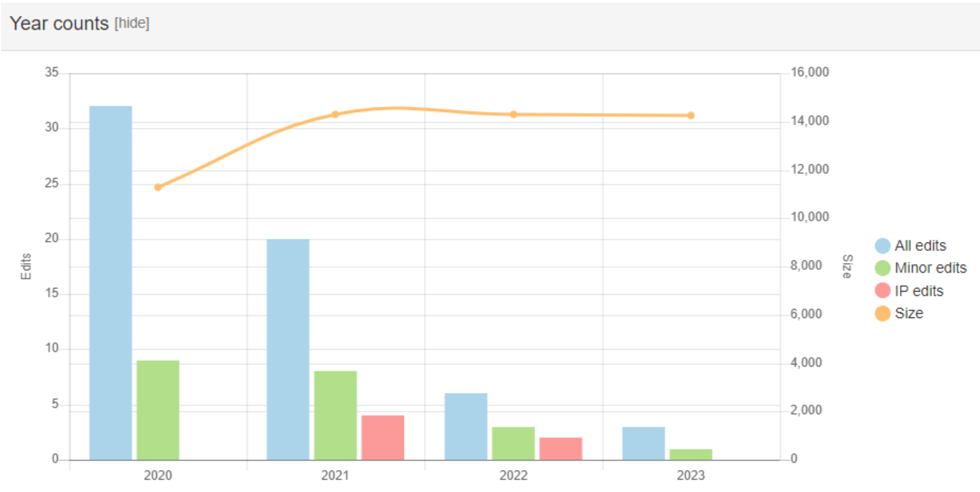


Figure 21: Summary of editions over the years of the Wikipedia page on Carnot Batteries.

2.2 An In-Depth Look at Carnot Batteries

Since subtasks A, B and C were scientifically oriented and many of the discussions and definitions overlapped, the generated outputs were combined and structured into four outcomes/sub-sections; 2.2.1 Carnot Battery Technologies, 2.2.2 Modelling and Simulation, 2.2.3 The assessment of TRLs, 2.2.4 R&D Needs.

2.2.1 Carnot Battery Technologies

In this section, the information of the gathered Factsheets on Carnot Battery systems and components is summarized and shown in Table 11. Also, the Rankine battery and Brayton battery are technically described, and in both cases, a real case is shown as an example. A LAES system has been selected to thoroughly explain a concept outside Rankine and Brayton batteries.

Table 11: Summary of existing Carnot Battery systems and components, supplied by Task 36 participants.

Nr	Country	Type	Name	Institution
1	Belgium	System	BATRENEW	University of Liège
2	Denmark	Component	Rock bed TES test concept	DTU
3	Denmark	Component	Rock bed TES Pilot plat	DTU
4	Denmark	System	CO2 Carnot Battery with water storage	DTU
5	Germany	System	Enolcon OPTES Battery	Enolcon
6	Germany	Component	STORASOL HT TES	Enolcon

7	Germany	System	HiTES	Fraunhofer UMSICHT
8	Germany	System	HiTES-Steam	Fraunhofer UMSICHT
9	Germany	Component	THERESA	HSZG
10	Germany	System	TMS - Battery	HSZG – Spilling Technologies
11	Germany	System	CHESTER	EU Project (DLR)
12	Germany	System	ETES	Siemens Gamesa
13	Italy	System	Hybrid TES	ENEA
14	Switzerland	System	MAN CO2 ETES System	MAN ES
15	UK	System	Isentropic	Durham University
16	UK	Component	Sensible TES	New Castle University
17	UK	System	LAES	HighviewPower
18	UK	Component	LHTES	Malta Inc / Siemens

2.2.1.1 Rankine Battery

In a Carnot Battery based on the Rankine process, the refrigerant/working fluid undergoes a phase change, which makes it suitable to operate at quasi-constant temperatures. In the charging process (see Figure 22) the low-pressure fluid is evaporated at constant temperature (1-2) and then is mechanically compressed to reach high temperatures (2-3). The vapor releases thus high temperature sensible heat (3-4) followed by latent heat at constant temperature (4-5), finally, the remaining sensible heat is released at relatively low temperatures (5-1).

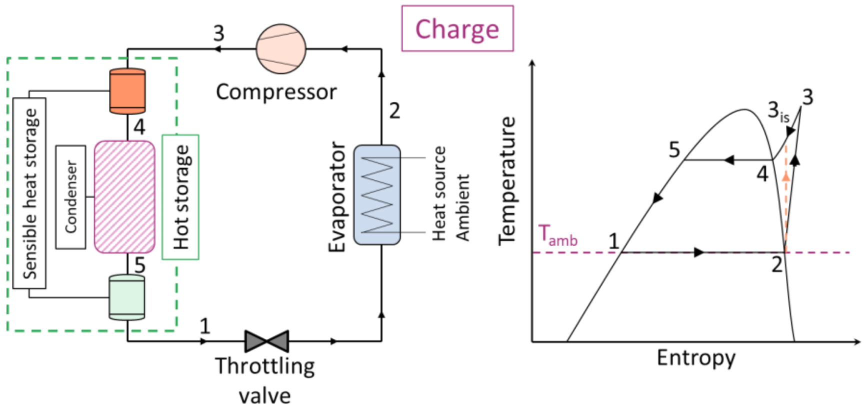


Figure 22: Scheme of the charging process of a Rankine based Carnot Battery (left) and the associated T-s diagram (right).

In the discharging process (see Figure 23) the heat transfer fluid in the liquid state is pumped to the hot reservoir where it is heated up absorbing sensible heat (1-2) and the latent heat evaporating at constant temperature (2-3), afterwards the gas is superheated in a sensible heat area (3-4), this superheated gas is then used to run a turbine/expander (4-5) and finally the low temperature gas, after the expansion, is condensed at relatively low temperature.

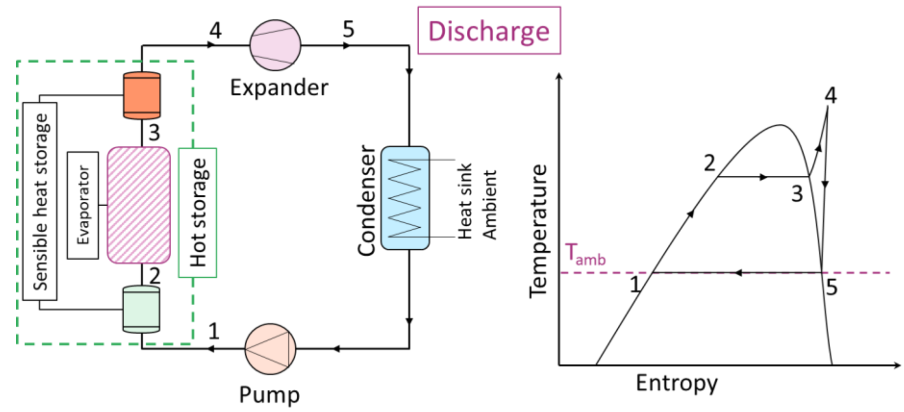


Figure 23: Simplified scheme of the discharging process of a Rankine based Carnot Battery (left) and the associated T-s diagram (right).

The Rankine based Carnot Batteries include several types of cycles, namely the steam Rankine cycles, organic Rankine cycles and trans-critical CO_2 cycles[20].

In the frame of the EU H2020 Project CHESTER – *Compressed Heat Energy Storage for Energy from Renewable sources* a first-of-its-kind Rankine based Carnot Battery was developed, built and experimentally tested at DLR in Stuttgart.

CHESTER is based on an advanced concept of indirect thermo-mechanical storage of power. In charging mode surplus electricity and low-temperature heat (40-100 °C) are converted into high-temperature heat (~140 °C) by using a heat pump. The high-temperature heat is stored in a high temperature TES system, which is a cascade of a latent and sensible heat TES. The Latent heat thermal energy storage (LH-TES) has a thermal storage capacity of ~200 kWh, and uses a PCM with a melting point ~133 °C. The sensible heat thermal energy storage (SH-TES) consists of a pressurized two-tank water storage system. When the demand requires so, the stored thermal energy can be converted back into electricity by an organic Rankine cycle and fed into the grid. In Figure 24 a simplified diagram of the CHESTER is shown and in Figure 25 two pictures of the real installation at DLR in Stuttgart can be seen.

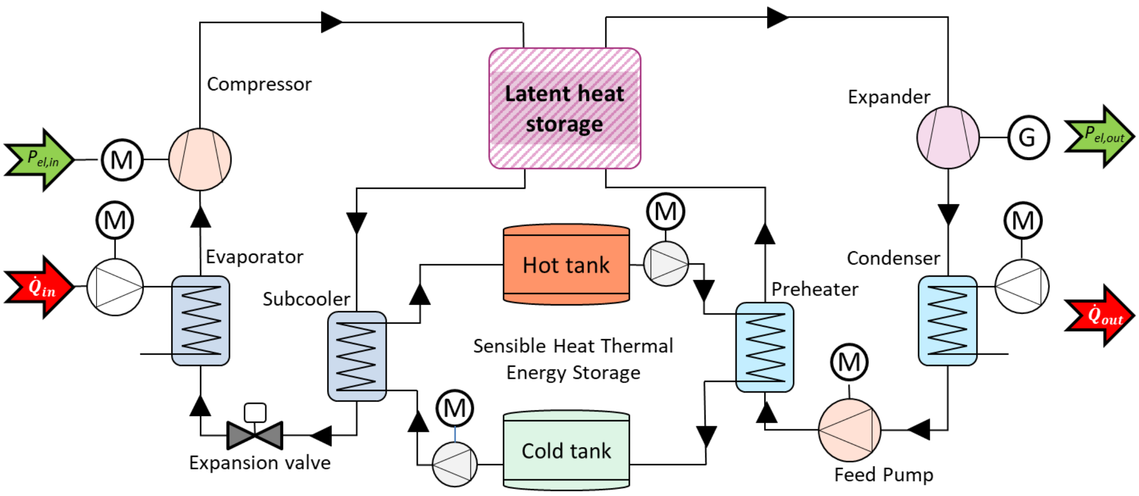


Figure 24: Simplified laboratory diagram of the CHESTER installation.

[20] Liang, T., Vecchi, A., Knobloch, K., Sciacovelli, A., Engelbrecht, K., Li, Y., Ding, Y. (2022). Key components for Carnot Battery: Technology review, technical barriers and selection criteria. Renewable Sustainable Energy Rev. DOI: 10.1016/j.rser.2022.112478

Figure 25: CHESTER installation at DLR Stuttgart. Heat pump, latent heat and sensible heat thermal energy storage (left) and latent heat thermal energy storage and ORC (right). © DLR (CC BY-NC-ND 3.0).

2.2.1.2 Brayton Battery

A Carnot Battery based on Brayton processes, well known as Brayton Battery, uses reverse-Brayton and Brayton cycles to charge and discharge electricity, respectively, as shown in Figure 26 and Figure 27. The system consists of a compressor, an expander, a hot storage tank and a cold storage tank, and two heat exchangers. The hot and cold storage tanks are normally packed bed type heat storage with particle-shape storage medium inside. The cycle is explained in the following content by using argon as working gas and 12 bar high pressure (P_H) and 1 bar low pressure (P_L).

As shown in Figure 26, during the energy storage process, argon at ambient temperature T_{amb} (e.g. 25 °C) and pressure of P_L (1 bar) are compressed to high temperature T_H (533 °C by an isentropic compression process) and P_H (12 bar, point 2_{is} or 2). Then the sensible heat of argon is released and stored by heating the storage medium inside the hot bed. The argon is chilled down to the ambient temperature (point 3) at the early stage of the charging process; at the late stage of the charging process, the temperature of the outlet argon from hot bed is possibly higher than the ambient temperature due to the non-perfect heat storage of packed bed, therefore a heat exchanger (HX1) is needed at the downstream of hot bed to ensure the argon entering the expander returns to ambient temperature level (point 4), otherwise, the system will get hotter and hotter. The argon at P_H and T_{amb} expands in the expander to P_L and low temperature T_L (−163 °C by an isentropic expansion process, point 5_{is}, or a non-isentropic process to point 5). The cold energy is released and stored in the cold bed and the argon returns to ambient temperature (point 6). For the same reason of using HX1, another heat exchanger HX2 is needed downstream of cold bed to ensure the temperature at the inlet of the compressor returns to T_a. In practice, the non-isentropic compression/expansion leads to higher outlet temperature, as compared by points 2_{is} and 2, 5_{is} and 5.

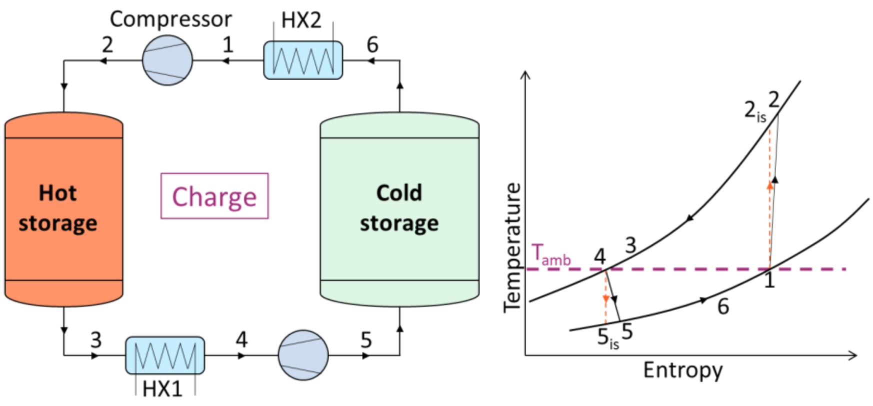


Figure 26: Charging process diagram (left) and T-s diagram (right) of a Brayton battery.

The cycle is reversed for energy discharge as shown in Figure 27. The hot and high-pressure argon (point 2) leaving the hot tank expands in the expander to generate electricity. Due to the non-isentropic process, the exhaust gas from the expander (point 1) has a higher temperature than T_{amb}, so HX2 is used to bring the temperature down (point 6). The Argon at T_{amb} and P_L is then cooled by the cold bed, potentially to the storage temperature (point 5). Thereafter the gas is compressed to P_H and the temperature increases to higher than ambient temperature due to the non-isentropic (point 4(3)), in this case, HX1 shall be bypassed (in some studies, the argon was cooled down to ambient temperature by HX1 to counter irreversibility throughout the cycle). The gas enters the hot tank to absorb the stored heat and its temperature reaches the storage temperature of the hot bed (point 2).

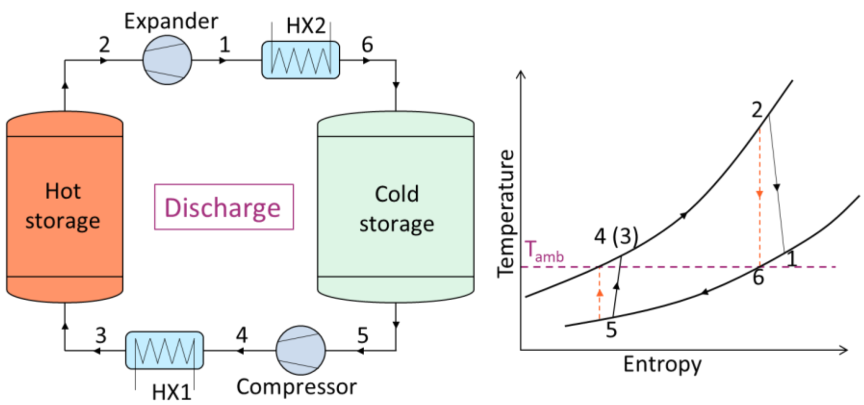


Figure 27: Discharge process diagram (left) and T-s diagram (right) of a Brayton battery.

A first-of-its-kind Brayton based Carnot Battery was developed, built and experimentally tested by Isentropic Ltd in the UK, which was later acquired by Durham University. Figure 28 shows the real installation of the system in the UK. The system uses Argon as working fluid, piston cylinders-type compressor and expander, and packed-bed type thermal storage using magnetite as storage material. Novel layer control was applied to the thermal storage to ensure a flat thermal front. In the charging cycle, surplus electricity is converted into high-temperature heat (~500 °C) and low-temperature cold (~-160 °C) by using a reverse Brayton cycle, with low and high system pressures at 1 bar and 12 bar. In the discharging cycle, heat and cold energy are converted back to electricity through the Brayton cycle. The nominal system capacity is 150 kW and 600 kWh.

Figure 28: 150 kW Brayton Carnot Battery demonstrator built at Hampshire, UK.

2.2.1.3 Other Concepts and Combinations: Liquid Air Energy Storage

In a Liquid Air Energy Storage (LAES) system, air or nitrogen can be used as the working fluid and storage medium, which is liquefied during charging by consuming electricity to store energy in cryogenic form, and is pressurized, regasified and expanded to convert the stored energy back into electricity.

In the charging process (i.e. air liquefaction process, see Figure 29), purified air is first compressed to high pressure (1-2), then cooled down to a low temperature (2-3), and finally expands to produce liquid air (3-4), with heat generated during air compression harvested and stored (hot storage) for later utilization in the discharging process. Specifically, Liquid Air Energy Storage can adopt different types of liquefaction cycles, including Linde-Hampson cycle, Claude cycle, Kapitza cycle, Heylandt cycle, and Collins cycle etc.

In the discharging process (see Figure 29), the stored liquid air is pumped to a high pressure first (5-6), evaporated with ambient heat and then superheated to a high temperature by the stored compression heat (6-2), and finally expands in the air turbine to generate electricity (2-1), with cold released during air evaporation recovered and stored (cold storage) for reuse in the liquefaction process to enhance the liquid yield and hence the round efficiency.

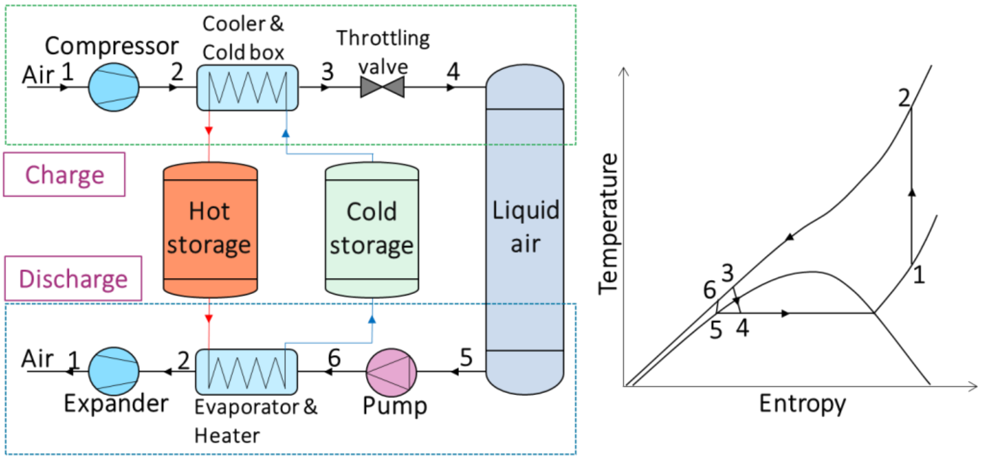


Figure 29: Charging and discharging process diagram (left) and T-s diagram (right) of the liquid air energy storage concept.

The world's first LAES pilot plant (350 kW/2.5 MWh) was designed, built, and trialed from 2005 to 2012 by Highview Power in collaboration with the University of Leeds[21]. This pilot plant was donated to the University of Birmingham for further research in 2013, as shown in Figure 30. This pilot plant was decommissioned and demolished in 2023. This milestone marks the beginning of the commercial deployment stage. Highview Power commissioned the first pre-commercial plant of the LAES (5 MW/15 MWh) in Manchester, United Kingdom, between 2018-2020 [22] The first large-scale commercial plant (50 MW/300 MWh) is currently under construction at a decommissioned thermal power station in North of England[23].

Figure 30: World's first LAES pilot plant donated to University of Birmingham. Decommissioned in 2023.

[21] Brett G, Barnett M. The application of liquid air energy storage for large scale long duration solutions to grid balancing. EPJ Web Conf 2014; 79:03002. doi:10.1051/EPJCONF/20137903002

[22] Coyne B. 15MWh liquid air energy storage plant opens, owners plot world domination. The Energyst 2018. https://theenergyst.com/15mwh-liquid-air-energy-storage-plant-opens/

[23] EMILY HOLBROOK. World's Largest Liquid-Air Energy Storage Construction to Begin. Environ Energy Lead 2021. https://www.environmentalleader.com/2021/04/construction-to-begin-on-worlds-largest-liquid-air-energy-storage-project/ (accessed 2 January 2022).

2.2.2 Modelling and Simulation

Researchers in the Carnot Battery field use models for the same reasons as other topics: to assess the technology, predict the limits of system performance, size components, optimize system design and related purposes. The most important subsystems of Carnot Batteries from the modelling standpoint are the heat-to-power components, power-to-heat components, thermal storages, heat exchangers, fans, pumps, valves and system integration. For the most part, the subsystems are based on off-the-shelf components or existing technologies adapted for the specific application. From a modelling perspective, the main challenge is to determine what the most important performance aspects of the overall Carnot Battery system, which are also discussed in Section 2.1.2, will be and how to couple the different subsystems in the best way. The development of reliable system models is an important aspect of the roll-out of Carnot Battery technologies because for the technology to become widespread, it will be crucial for its characteristics to be well known and predictable over a wide range of operation conditions.

On a component level, existing models can be adapted and coupled to the subcomponents specific to Carnot Battery applications. An example could be a heat pump used to charge a cold reservoir and a hot reservoir at the same time. Typical operation of such a heat pump might see a nearly constant cold reservoir from which the heat pump extracts heat. However, in the Carnot Battery example, the cold reservoir temperature may decrease while the hot reservoir temperature increases during the entire charge process. This specific operating condition for a heat pump coupled to a Carnot Battery may favour specific heat pump designs or refrigerants that would not be the best choice for a system with less variable conditions. The transient nature of Carnot Battery operation will also likely put an emphasis on the need for dynamic models that require more detailed characterization of the system subcomponents. Coupling all the subcomponents into a full system model that gives accurate predictions for overall system performance is a major challenge going forward for Carnot Battery modelling.

From a system perspective, modelling is used to predict performance and optimize and choose subcomponents and is a powerful tool to assess different applications of Carnot Batteries. For example, retrofitting coal or similar fired power plants with a TES and power-to-heat system is a potentially attractive application of a Carnot Battery. Here, the CAPEX is reduced by reusing some of the most expensive components, such as the heat-to-power equipment and the grid connection. Models can predict the performance of such a system and can be used to evaluate the commercial viability of a particular application. Since TES is the most unique feature of Carnot Batteries, there is a potential that TES models developed for Carnot Battery applications will be useful for similar applications, including power-to-heat operation coupled with industrial processes. There is a high potential that the efforts in this Task will be useful to a number of other research fields through models developed and made available to the public.

Since Carnot Batteries are either near the market or possibly already commercialized, grid-level integration and techno-economic analysis are important to guide the rollout and potential of the technology. For grid-level models, Carnot Batteries must be simplified to just a few equations or a table that can be interpolated by the model due to the complexity of the overall system. For techno-economic modelling, accurate models of the system operation are needed and they must be coupled to price functions for each component. Accurate techno-economic figures are needed to assess the economic feasibility of Carnot Batteries, which is one of the major barriers to widespread implementation.

Within the IEA Task framework, an in-depth screening of modelling and simulation approaches used for Carnot Battery (related) systems by means of a participant survey took place. While subsection 2.2.2.1 evaluates 35 model factsheets submitted by 20 participants mostly quantitatively, subsection 2.2.2.2 includes unique insights into the application of six selected models covering a wide range of models as well Carnot Battery types.

2.2.2.1 Evaluation of Model Factsheets

20 participants submitted a total of 35 model factsheets within the timeframe of May 2021 to November 2022, see Table 12. As Figure 31 illustrates, more than half of all factsheets stem from participants affiliated with a university (60%).

Table 12: Overview of the model factsheet collection.

# Participants	20
# Factsheets	35
Time frame	May 21 – Nov 22

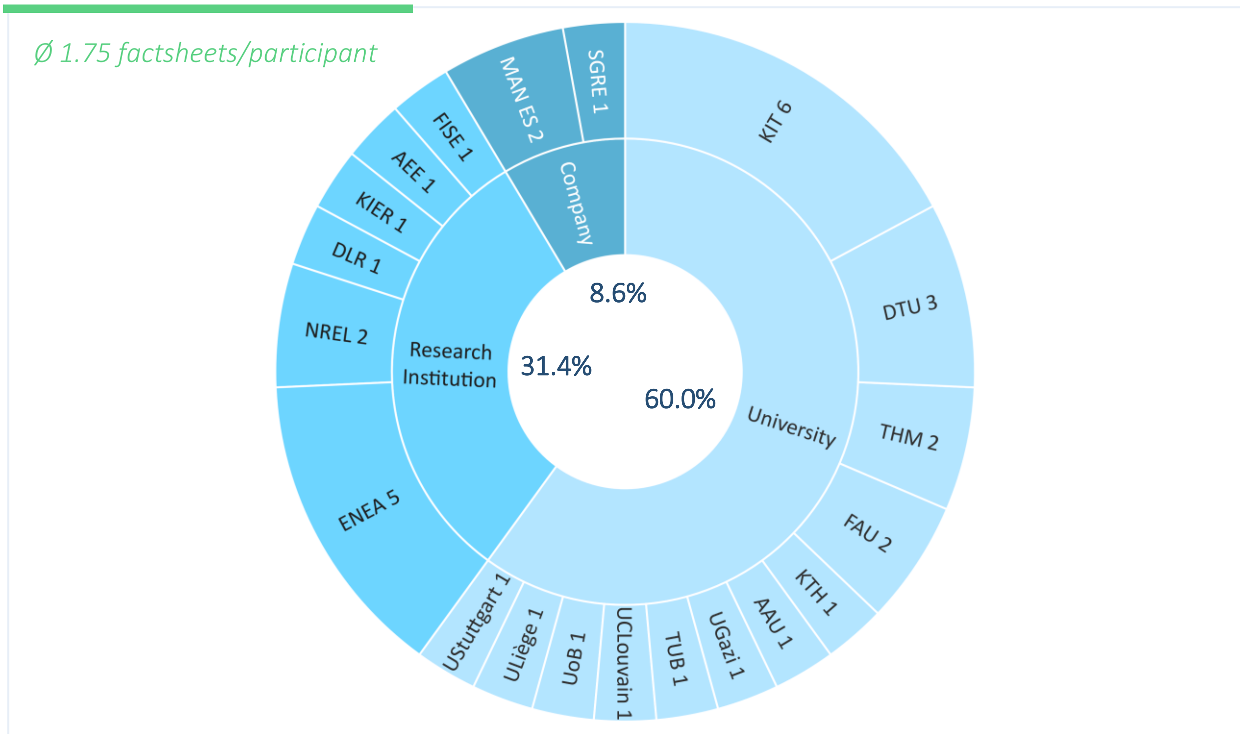


Figure 31: Affiliation of survey participants.

The two most typical ways to classify models are by their level (e.g. component, system, grid) or by their change of external conditions (e.g. static, quasi-static, dynamic). Quasi-static models are considered as dynamic for the purpose of this survey. While the number of static and dynamic models collected in the survey are nearly identical overall, nearly half of the models (48.7%) focus on one or more component(s) and hence represent the most detailed model level, as illustrated in Figure 32. Higher abstraction levels contain a lower number of models: 13 system-level (33.3%) as well as 5 grid-level models (12.9%). In that context, it can also be concluded that static models dominate the highest and lowest abstraction levels, whereas more than half of all dynamic models (52.6%) are developed for investigations on the system level.

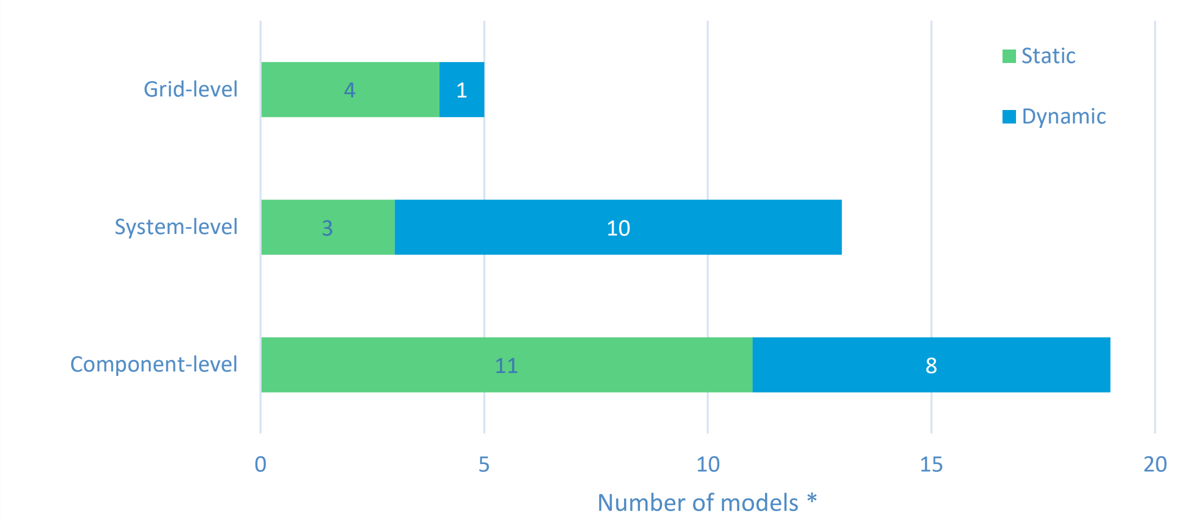


Figure 32: Overall categorization of models. * Please note that the sum of these numbers is above 35 since some models were categorized by two model levels.

Even though dynamic, component-level models are indisputably candidates for high computational efforts and hence long runtimes in general, the number of dimensions considered in each model turns out to have the largest influence on the runtime. While one of the 0-D models is characterized by the highest maximum runtime of up to 3 days on a single, personal, state-of-art computer, the highest average runtime of roughly 8 hours is found for the 3-D models. Not taking the 0-D models into account, a trend of higher maximum as well, as average runtimes for higher numbers of considered dimensions, can be observed in Figure 33.

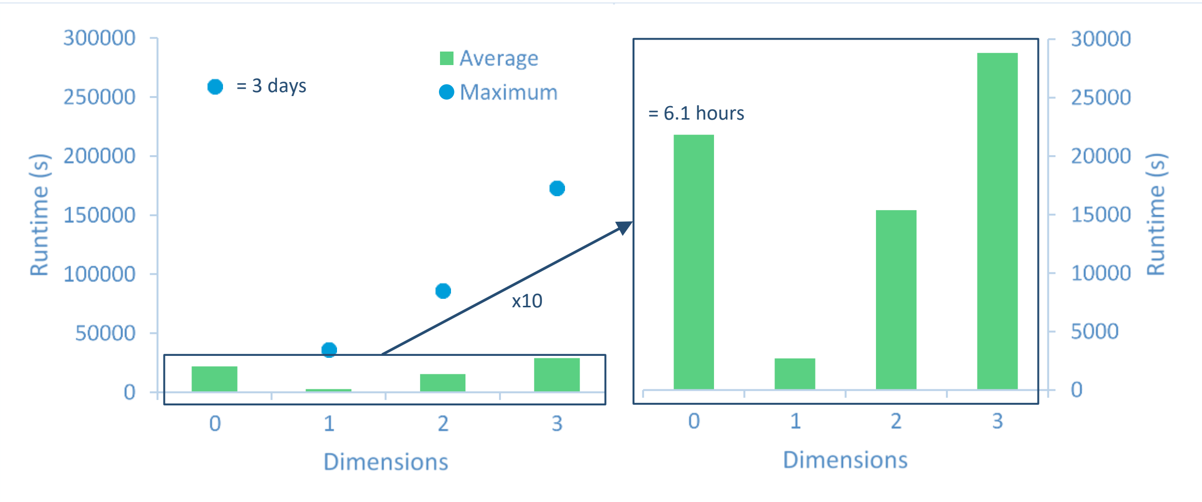


Figure 33: Average and maximum runtime of models categorized by dimensions considered by each model. The total numbers of considered models per dimension were 7 for 0-D, 15 for 1-D, 7 for 2-D and 3 for 3-D.

Figure 34 illustrates that the choice of software/programming language is as diverse as the reasons for each choice. Irrespective of whether the choice is based on e.g. familiarity, availability or acceptance in the field, most models (51.7%) are fully available within the IEA Task 36 framework, predominantly only setting a citation as a condition, as summarized in Figure 35. For only three models (9.7%), sharing is unconditionally ruled out.

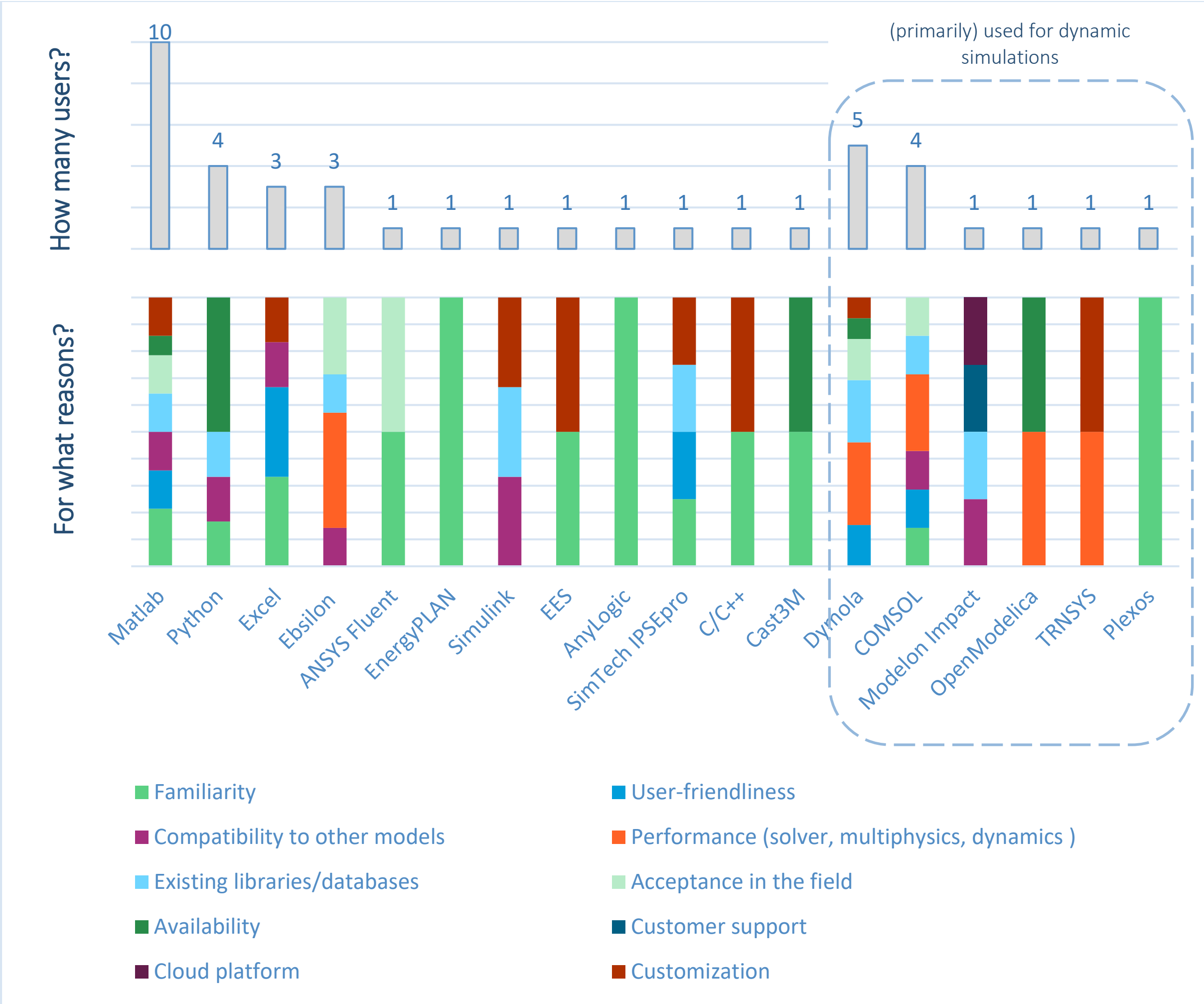


Figure 34: Number of users as well as stated reasons for each of the 18 software/language choices.

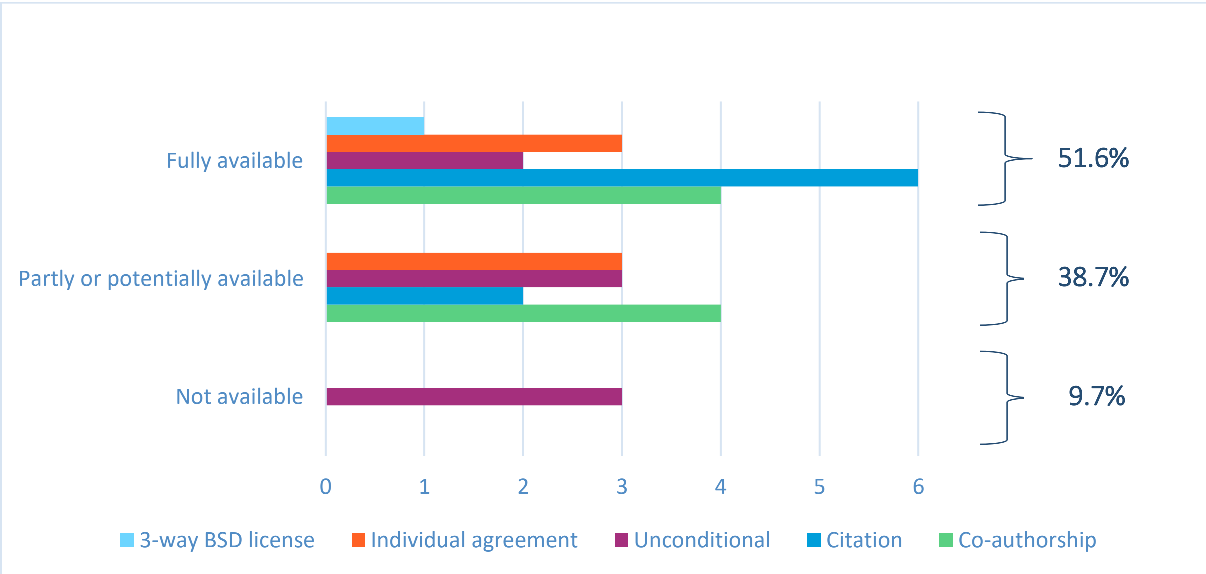


Figure 35: Availability of models within the IEA framework.

2.2.2.2 Application of Selected Models

Table 13 provides an overview of the models selected for the following application presentation.

Table 13: Overview of selected models.

Subsection	Institution	Model type	(Predominantly) used for
2.2.2.2.1	THM	Component	Static and dynamic simulation as well as validation of a Carnot Battery with electric heating and gas turbine
2.2.2.2.2	TUB	Component	Dynamic process simulation for charging and discharging of Lamm-Honigmann Carnot Batteries
2.2.2.2.3	FAU	Component / System	Static simulation and parameter variation of different configurations based on heat pump and ORC cycles
2.2.2.2.4	KTH	System	Techno-economic performance assessment of especially power-to-heat solutions
2.2.2.2.5	AAU	Grid	Hourly simulation of energy systems, typically country level

2.2.2.2.1 Technische Hochschule Mittelhessen (THM)

The direct charging process of the Carnot Battery HTS600 is based on resistive heating elements that are vertically inserted into the TES. At a maximum operating temperature of 1200 °C, the highly exergetic heat is stored in the ceramic material of the storage core, which is a refractory concrete (corundum-mullite). An open, externally heated gas turbine process turned out to be a suitable option to allow an ambient pressure storage design and efficient reconversion of stored heat[24]. The HTS600 demonstrator has an electrical charging power capacity of 600 kW, a maximum storage temperature of 1200 °C and a thermal storage capacity of 8 MWh. The externally heated gas turbine process with a modified micro gas turbine (generator output = 30 kW) is set up as the reconversion unit[25].

The overall model of the Carnot Battery consists of several sub models and is shown in Figure 36.

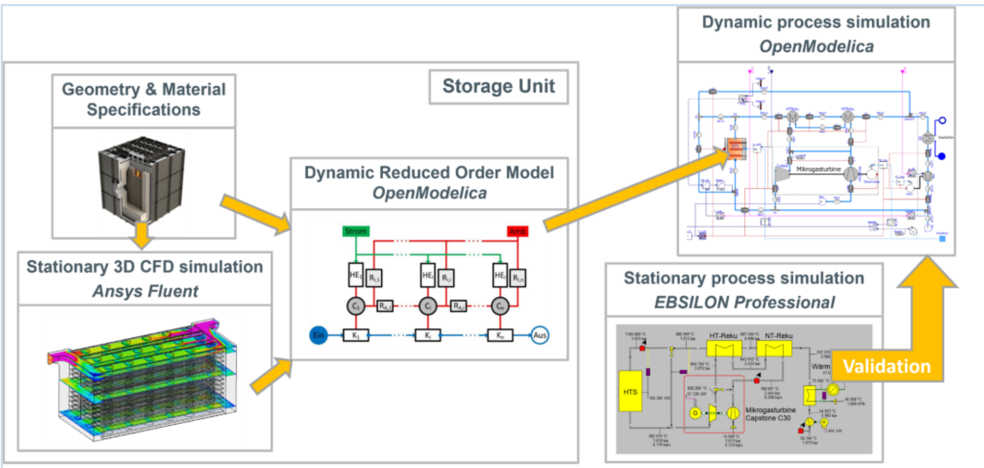


Figure 36: Modelling overview from THM with Ansys Fluent, OpenModelica and Ebsilon Professional.

---

[24] F. Holy, M. Textor and S. Lechner, "Gas turbine cogeneration concepts for the pressureless discharge of high temperature thermal energy storage units," Journal of Energy Storage, vol. 44, p. 103283, 2021

[25] F. Holy, A. Paul, M. Textor, S. Lechner, M. Metka and F. Klaus, "Sensibler Hochtemperaturspeicher bis 1200°C mit extern beheiztem Gasturbinenprozess - Entwicklung und Simulation einer neuartigen Carnot-Batterie zur dezentralen Sektorenkopplung," in 54. Kraftwerkstechnisches Kolloquium, Dresden, 2021

The hydraulic and thermal steady-state behavior of the TES is determined using computational fluid dynamics (CFD) in ANSYS Fluent. In a variant study, the uniformity of the air distribution within the storage core was first investigated and optimized under design conditions[25]. Based on this study, flow resistors are introduced in the flow channels in order to realize a uniform discharge behavior over the whole cross-sectional area. The CFD simulations provide the average specific heat fluxes between the solid wall and the air stream, as well as the average air temperatures at the outlet of the reservoir. The absolute pressure losses across the storage unit are also recorded. From this, regression functions can be derived for the Nusselt number and the pressure loss coefficient depending on the Reynolds number.

Using the CFD results, a transient 1-D model of the TES is developed in OpenModelica. The thermal-hydraulic model considers the heating power of the integrated electrical resistance heating elements, the thermal capacity and thermal conductivity of the storage material and the insulation. According to Xu et. al[26], the geometry of the flow channels which surrounds the solid storage material is approximated as a hollow cylinder model, which is a very good approximation for Biot numbers < 1.

The design and steady-state modeling of the reconversion unit is initially performed with EBSILON®Professional. For the dynamic simulation of the Carnot Battery, the transient model of the TES is coupled with the reconversion model. For this purpose, the process cycle is also modeled in OpenModelica and validated at the design point with the steady-state results from EBSILON® Professional[24].

The first simulation results show that a round-trip efficiency of approx. 22% is achieved with the cyclic operation of the CB. Considering the usable thermal power, the overall efficiency can be increased to over 71%[25]. This system is only a test plant with an electrical generator output of approx. 30 kW. In a scale-up, lower specific heat losses and much higher efficiency in the reconversion process can be expected, so a significant increase in overall efficiency can be achieved. The overall dynamic model of the Carnot Battery represents an important tool for the design, evaluation, and optimization of operation management. The demonstration plant is currently being set up in the FlexQuartier in Giessen. The first test results are expected in the summer of 2023, so the simulation can be validated.

2.2.2.2.2 Technische Universität Berlin (TUB)

The Lamm-Honigmann thermochemical storage has been modelled at the TUB as a component-based system and simulated for dynamic mechanical charging and discharging. The full model is built via Modelica/Dymola. It is based on previous work by Jahnke[27] and several qualification works (master and bachelor thesis) supervised by Jahnke and Thiele[28]. In a simplified overview of the current model structure is shown in Figure 37. The main components, inputs and simplifications are listed.

The central components of the system are the vessels (absorber/desorber (A/D) and evaporator /condenser (E/C)), and the machine (M) (an expander (EM) or a compressor (CM) for discharging or charging the storage, respectively). Several types of expansion devices are modelled, so that optionally a simplified turbine[27], a generic volumetric expander model from the Thermal Cycle Library[29], a rotary vane expander[30] or a reciprocating piston expander[31] can be integrated into the system. The

[26] X. Ben, L. Pei-Wen and C. C. Lik, "Extending the validity of lumped capacitance method for large Biot number in thermal storage application," Solar Energy, vol. 84, pp. 1709-1724, 2012

[27] A. Jahnke et al., "First cycle simulations of the Honigmann process with LiBr/H2O and NaOH/H2O as working fluid pairs as a thermochemical energy storage," International Journal of Low-Carbon Technologies, vol. 8, 2013

[28] Berlin, Website of the research project at TU, [Online]. Available: https://www.eta.tu-berlin.de/menue/energie_forschung/projekte/thermochemische_energiespeicherung/.

[29] "Thermal Cycle Library," [Online]. Available: https://github.com/thermocycle/Thermocycle-library

[30] L. Kaune, Modellierung der Expansionsmaschine für den Honigmann-Prozess, Master Thesis, Berlin Institute of Technology, 2017

[31] M. Lorenzo, Modellierung und Simulation einer zweistufigen Kolbendampfmaschine zur Produktion mechanischer Energie im Lamm-Honigmann Prozess, Bachelor Thesis, Berlin Institute of Technology, 2021

components are connected through the mass exchange (water vapor) as well as thermally connected either directly via a lumped thermal resistance or via an external circuit (EC). Heat is transferred from the absorber to the evaporator and optionally to the expander during discharge, and from the condenser and optionally from the compressor to the desorber during charge. Additionally, an external heat source or sink can be integrated into the heat transfer circuit. The model calculates the transient mass and energy balances within each component and the interaction between them.

The inputs of the model include technical aspects of operation and design as well as the libraries required for the determination of the thermodynamic properties of the working fluid pairs. Design aspects include component masses and materials of the vessels and machine (and thus their thermal masses), as well as a simplified geometry of the volumetric expansion/compression machine. The configuration of the heat exchanger within each vessel (e.g., counter-flow) can also be considered by lumped parameters. All this permits the study of several designs, dimensions (scaling up and down), configurations and working pairs.

Operational aspects include the thermodynamic initial states such as temperature and masses of water and working fluid, mass fraction of the latter, and the mass flow rate of water in the external circuit. For the volumetric machines, the power output/input of the storage can be controlled in the model by setting either the rotational speed of the machine or its electrical input/output directly. All this allows the identification of adequate operational conditions and control strategies depending on the design aspects.

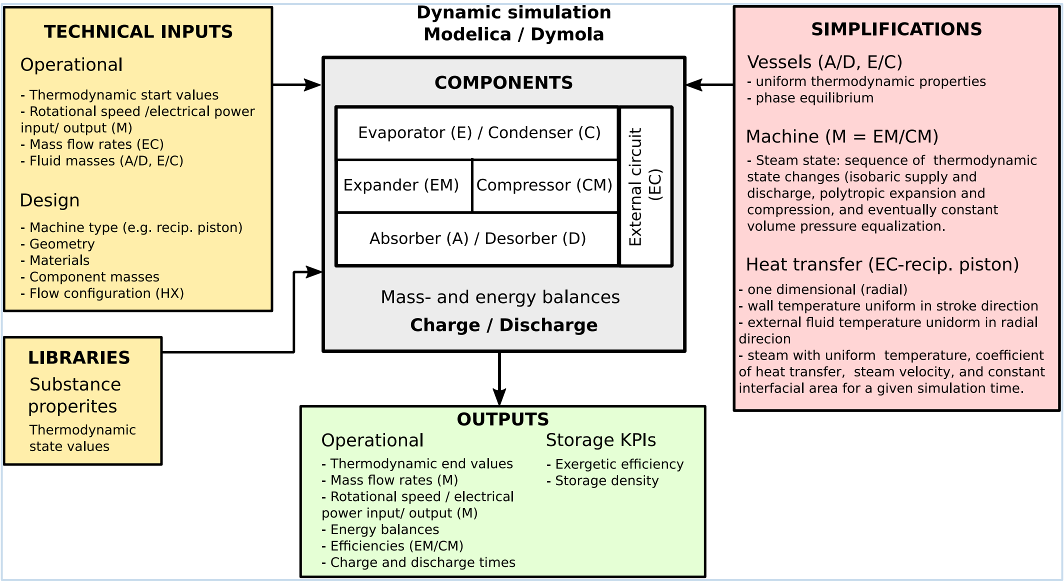


Figure 37: Simplified model structure of the Lamm-Honigmann system. Main components, inputs, simplifications, and outputs.

The model is built on several simplifications of heat and mass transfer phenomena. The fluids within the vessels are considered to be homogeneous and in phase equilibrium. The state changes in the volumetric machines are modelled as a sequence of thermodynamic state changes. Heat transfer between the machine and the external circuit is modelled with the help of the LMTD method using lumped heat resistance parameters. For the reciprocating piston machine, a more detailed heat transfer model has been developed (see Figure 37).

The outputs of the system are the thermodynamic states of the working fluids, the heat and mass transfer between the components, the rotational speed or the electrical power input/output of the machine, as well as the energy efficiencies of the components. Electricity consumption of liquid pumps etc. is not considered. Storage key performance indicators such as exergetic efficiency and storage density are also calculated.

Intensive research on the Lamm-Honigmann process by other groups has not been found and is unknown to the TUB group. Punctual publications on the process were made by some researchers[32] [33]. Earlier publications by Thiele and Jahnke show the influence of operational and design inputs on storage density and efficiencies. Results have been summarized in Thiele, 2022[34]. All the described models consider the dynamic nature of the process. A quasi-stationary analytical model for the mechanical discharging and charging process to predict the power output depending on the system state is shown in Thiele and Ziegler, 2022[35]. Results for the refined heating and cooling model of the reciprocating piston machine, described here, will be published soon.

2.2.2.2.3 University of Erlangen-Nürnberg (FAU)

At the Chair of Energy Process Engineering at the University of Erlangen-Nürnberg the commercial software system IPSEpro by Simtech is utilized for the simulative investigation of Carnot Batteries.

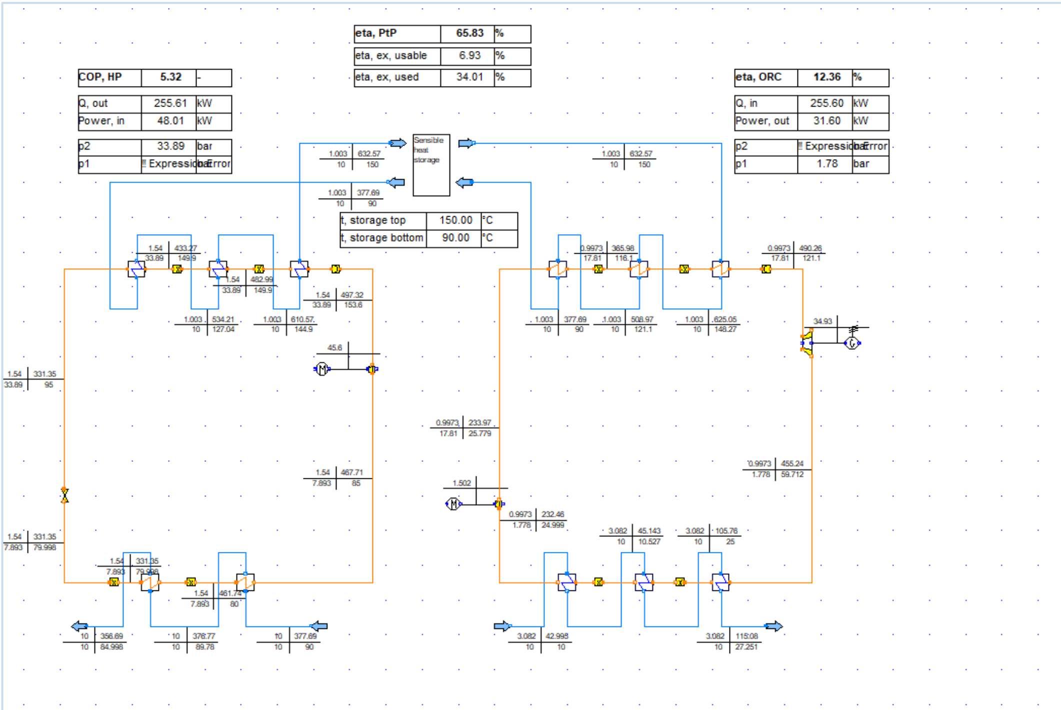


Figure 38: Illustration of the IPSEpro Carnot Battery model.

IPSEpro comprises a set of modules for creating process models and calculating thermodynamic cycles. These modules are used to numerically calculate processes in design and off-design conditions, validate measurements and optimize plant performance. Dedicated ready-to-use model libraries are available, e.g. for power plants and low temperature processes. However, IPSEpro is not restricted to the capabilities of these libraries. The Model Development Kit allows to individually create tailored

[32] N. Isshiki, "Study on the concentration difference energy system," Journal of Non-Equilibrium Thermodynamics, vol. 2, pp. 85-107, 1977

[33] M.J. Tierney et al., "Analysis of sorption cycles with integrated absorber-evaporators," *Heat Transfer Research,* vol. 46, pp. 233-249, 2015

[34] E. Thiele and F. Ziegler, "Thermal operation map for the mechanical discharging process of the Lamm-Honigmann Energy Storage - A Quasi-Stationary Model for Process Analysis," Processes, vol. 10, p. 977, 2022

[35] E. Thiele and F. Ziegler, "Thermal operation map for the mechanical discharging process of the Lamm-Honigmann Energy Storage - A Quasi-Stationary Model for Process Analysis," Processes, vol. 10, p. 977, 2022

component models and libraries[36]. Fluid properties originate from the Refprop database[37]. To solve the equation system, IPSEpro uses the Newton-Raphson method which implies starting values and linearization of the functions at the starting value in an iterative approach.

So far, IPSEpro was mainly used to calculate static Carnot Batteries in terms of heat pump – ORC processes, see Figure 38. In a first parameter study, Weitzer et al.[38] compared different cycle configurations including flash cycles. This work was extended by implementing more detailed part-load component models in a second study[39] investigating the effect of two-phase expansion processes in off-design conditions. IPSE's Model Development Kit allows to implementation of the part-load component models for this study. Once the model is set up, automated parameter variations can be conducted. The generated results are directly written into an Excel file. Moreover, the latest version IPSEpro 8.0 is equipped with a module for dynamic simulation and an online module which enables live monitoring and closed-loop control of real plants.

Although the approach of static cycle simulation is quite straightforward and commonly used in literature, IPSEpro offers several advantages compared to other software environments. This includes the flexibility of defining and programming component models, simple arrangement of process models, short implementation time, a graphical user interface and a uniform environment for static/dynamic simulations, optimizations and online monitoring. IPSEpro provides comparable tools and a similar numerical approach to the Energy Equation Solver (EES)[40] [41].

2.2.2.2.4 KTH Royal Institute of Technology

Figure 39 shows a summary of the modelling structure and simulation approach including the key inputs, outcomes, and performance indicators considered for each step. The full model is built via Excel VBA macros and Python scripts, while CoolProp has been exploited for the thermodynamic properties. This modelling approach as well as the key results obtainable have been fully described in Trevisan et al.,2022 [42]. At first, the main technical inputs describing the key components (i.e. TES tank geometry, type of heat transfer fluid, effectiveness of the steam generation unit (SGS), efficiency of the electric heater (EH), power cycle efficiency) as well as the system's requirements (i.e. thermal and power load) and boundary conditions (i.e. electricity prices) are defined. The operation of the system is evaluated by means of a dedicated dispatch optimization algorithm, which considers the main technical and operational inputs of the system. This step provides the main operational variables (i.e. power consumption at the EH and state of charge of the TES) aiming at fulfilling the load whilst minimizing the operational costs. Additional technical and operational inputs together with the identified optimal dispatch input to the thermodynamic model of the proposed system. This model provides the specific hourly-based thermodynamic outputs, based on which technical and energy related key performance indicators (KPI) are calculated. A parallel bottom-up economic model, based on cost functions gathered from literature and direct industrial data, is implemented and exploited to assess the specific economic

---

[36] "Simtech GmbH (online), "IPSEpro," 2022," [Online]. Available: https://www.simtechnology.com/cms/ipsepro-menu/ipse-pro.

[37] E. Lemmon, M. Huber and M. McLinden, "NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 9.1.," Natl Std. Ref. Data Series (NIST NSRDS), National Institute of Standards and Technology, Gaithersburg, MD, 2013. [Online]. Available: https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=912382.

[38] M. Weitzer, D. Müller, D. Steger, A. Charalampidis, S. Karellas and J. Karl, "Organic flash cycles in Rankine-based Carnot batteries with large storage temperature spreads," Energy Convers. Manag., vol. 255, p. 115323, 2021

[39] M. Weitzer, D. Müller and J. Karl, "Two-phase expansion processes in heat pump – ORC systems (Carnot batteries) with volumetric machines for enhanced off-design efficiency," Renew. Energy, vol. 199, pp. 720-732, 2022

[40] S. Eyerer et al, "Experimental and numerical investigation of direct liquid injection into an ORC twin-screw expander," *Energy,* vol. 178, pp. 867-878, 2019

[41] C. Arpagaus, F. Bless, M. Uhlmann, J. Schiffmann and S. Bertsch, "High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials," Energy, vol. 152, pp. 985-1010, 2018

[42] S. Trevisan, B. Buchbjerg and R. Guedez, "Power-to-heat for the industrial sector : Techno-economic assessment of a molten salt-based solution," Energy Conversion and Management, vol. 272, p. 116362, 2022

performance of the proposed solution. Techno-economic KPIs such as the nominal levelized cost of heat (LCoH) and electricity (LCoE) and the operational expenditure (OPEX) are derived from the previous steps and exploited to benchmark the techno-economic performance of the proposed power-to-heat solution against reference business as usual (BAU), such as non-flexible electric boilers and fossil fuel-based alternatives. LCoH and OPEX can be exploited also as the main objectives in the system sizing optimization step, aimed at identifying optimal EH nominal power and TES capacity.

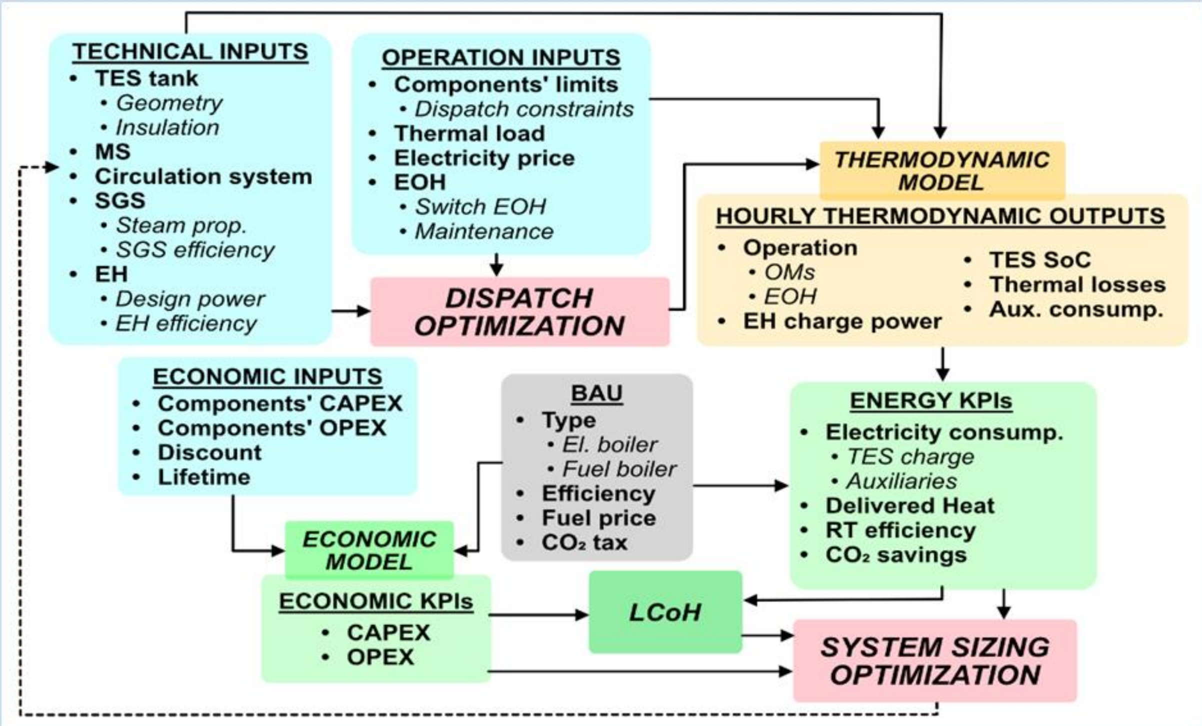


Figure 39: Illustration of the KTH model.

The described modelling approach has been rarely exploited and applied to industrial heat electrification and Carnot Batteries applications, similar examples can be found in Cirocco et al., 2022[43] and in Pee et al., 2018[44]. However, the general methodology is common to different energy applications and fields, such as solar thermal power plants[45] and hydrogen production units[46].

2.2.2.2.5 Alborg University (AAU)

EnergyPLAN (https://www.energyplan.eu/) is a holistic energy system model that simulates the hourly energy balances for an entire energy system including all energy demands, which includes: electricity, cooling, heating, transport and industrial processes[47]. The simulation includes conversion technologies and storages, including technologies that allow for sector coupling between different energy sectors. EnergyPLAN has been used to understand the potential of Carnot Batteries in energy systems based on variable renewable sources including the competing flexibility solutions. This is done by simulating

[43] L. Cirocco, P. Pudney, S. Riahi, R. Liddle, H. Semsarilar, J. Hudson and F. Bruno, “Thermal energy storage for industrial thermal loads and electricity demand side management,” Energy Conversion and Management, vol. 270, p. 116190, 2022

[44] A. d. Pee, D. Pinner, O. Roelofsen, K. Somers, E. Speelman and M. Witteveen, “Decarbonization of industrial sectors: the next frontier,” McKinsey & Company, 2018.

[45] 2.2.2.2.2 R. Guedez, M. Topel, L. Conde, F. Ferragut, L. Callaba, J. Spelling, Z. Hassar, D. Perez-Segarra and B. Laumert, “A Methodology for Determining Optimum Solar Tower Plant Configurations and Operating Strategies to Maximize Profits Based on Hourly Electricity Market Prices and Tariffs.,” Journal of Solar Energy Engineering, vol. 138, p. 021006, 2016

[46] T. Grube, J. Reul, S. C. M. Reuß, N. Monnerie, R. Schlatmann, C. Sattler, M. Robinius and D. Stolten, “A techno-economic perspective on solar-to-hydrogen concepts through 2025,” Sustainable Energy and Fuels, vol. 4, p. 5818–5834, 2020.

[47] H. Lund, J. Thellufsen, P. Østergaard, P. Sorknæs, I. Skov and B. Mathiesen, “EnergyPLAN – Advanced analysis of smart energy systems,” Smart Energy, vol. 1, 2021

Carnot Batteries in different future 100% renewable energy system scenarios for a national energy system where all energy sectors are included, as illustrated in Figure 40.

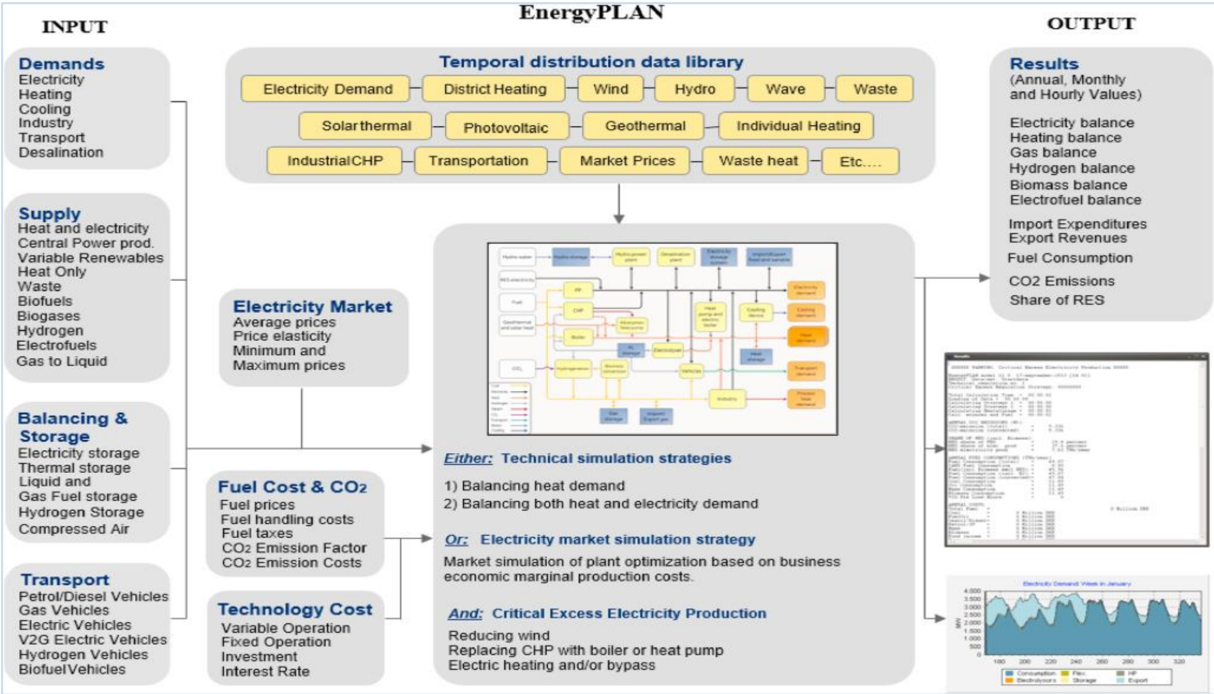


Figure 40: Illustration of the EnergyPLAN model developed by AAU.

Denmark is used as a case study in our work. Each scenario has a different expectation for how a future 100% renewable Danish energy system could be structured. The implementation of Carnot Batteries in these energy system scenarios is tested using a range of different configurations, referring to storage capacities, charge capacities, discharge capacities and round-trip efficiencies. The main output of the simulations is to identify what the energy system benefits could be for different configurations of Carnot Batteries in different energy system scenarios. Thus, the analyses identify potential energy system benefits in a national energy system context instead of only focusing on a single district or city that only assesses a single sector. The benefits include effects on costs and primary energy supply in the entire energy system. The results can be used to identify what LCOE should be targeted for Carnot Batteries at different configurations, and what size of Carnot Batteries would be most suitable for the national energy system.

The results from the 100% renewable scenario show that Carnot Batteries can be used to reduce the use of power plants, and thereby reduce the use of renewable fuels for these. The Carnot Batteries are found to have between 3 and 32 yearly charge cycles depending on the capacities of the storage with smaller storages having more yearly charge cycles than larger. The main cost reduction of Carnot Batteries in the system is the reduction in fuel used in the power plants. In the used scenario the power plants are gas-fired utilizing upgraded biogas. Thereby the economic gains of the Carnot Batteries is in the scenario found to be directly connected to the international price of gas. The gas price used in the scenario is 9.2 EUR/GJ incl. transport, which shows LCOEs of Carnot Batteries in the range of 63-76 EUR/MWh_e discharged.

2.2.3 The assessment of TRLs

2.2.3.1 Technology Readiness Levels (TRLs)

Technology Readiness Levels (TRLs) are indicators for assessing and communicating the maturity extent of a technology. Originally developed by NASA for space exploration technologies in the 1970s, TRLs have been used globally across a wide range of sectors including government and industry.

The TRL system has nine levels (see Figure 41), split into three broad groups:

- TRLs 1-3 (least mature) indicate an early stage of research to demonstrate proof of concept.
- TRLs 4-6 indicate early technology development stages including small and pilot system demonstration.
- TRLs 7-9 (most mature) indicate an advanced development stage including full commercial demonstration.

More detailed definitions and descriptions of the TRL system are given in Appendix 5, which will be used to assess the TRL of Carnot Battery technologies in this report.

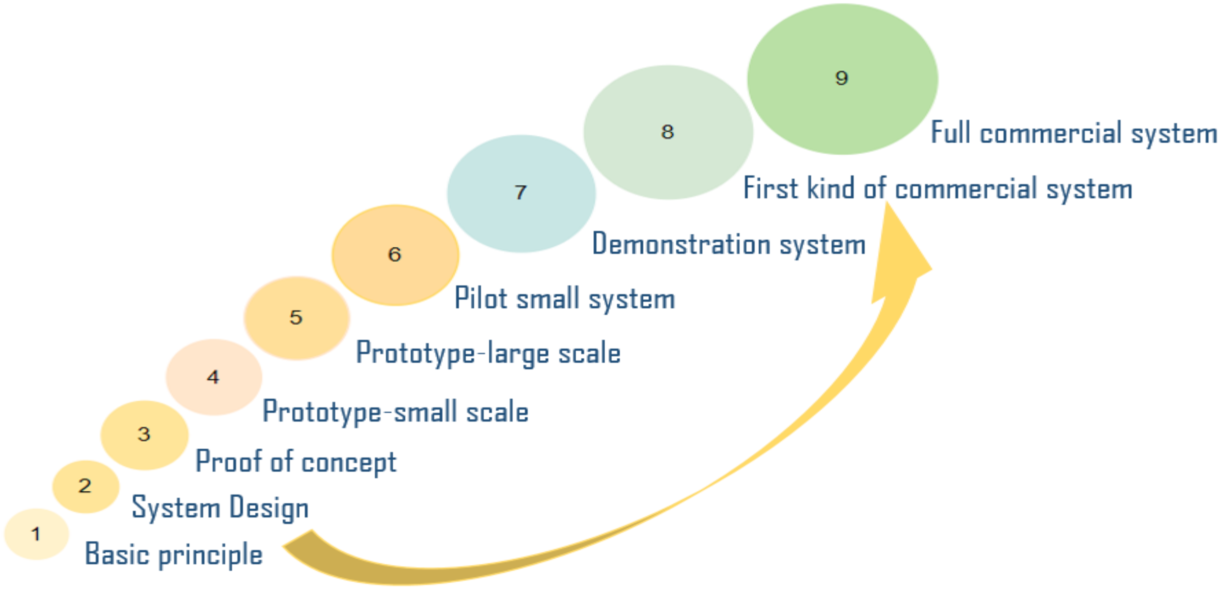


Figure 41: Technology readiness level (TRL) ranking system illustration.

2.2.3.2 The Assessment of TRLs of Carnot Batteries

The TRLs of different Carnot Batteries (CBs) are assessed and summarized in Table 14. The assessment is based on their state of technology development (technology maturity at both components and whole system levels), and advances in technology demonstration (prototype, pilot plant, or commercial plant). Section 2.2.4 will provide more details.

Table 14: TRLs assessment of different Carnot Batteries.

Carnot Battery types		Basis of assessment for TRLs	
CB technology (discharging method)	Charging method	TRL	Details
Rankine Battery	Resistive heating	TRL 5-7	The resistive heating-based Rankine Batteries use resistive heaters for producing steam to generate power via Rankine cycles (a mature technology). The resistive heating-based Rankine Battery technology has been demonstrated by Siemens Gamesa[48] [49] [50] and E2S Power [51] [52]. Siemens Gamesa has completed a test at pre-commercial scale (4 MW/130 MWh). E2S Power has validated its technology on a lab scale and is currently developing several pilot-scale projects.
	Heat pumps	TRL 4-6	Heat pumps-based Rankine Batteries are currently undergoing the process of moving from lab-scale validation to pilot-scale validation.

48 Gamesa S, Energy R. ETES – Electric Thermal Energy Storage – Technology and Commercial Proposition n.d.
49 Wind S, Gmbh P. Electric Thermal Energy Storage (ETES) Transition of energy supply Increasing penetration of renewable energy in the energy grid to achieve emission reduction targets 2017.
50 Mai S, Schumacher M. ETES Electric Thermal Energy Storage 2019
51 Our Product | E2S Power n.d. https://e2s-power.com/our-product/ (accessed July 18, 2022)
52 Thermal energy storage TWEST secures production of CO2 free electricity in thermal power plants n.d. https://balkangreenenergynews.com/thermal-energy-storage-twest-enables-co2-free-electricity-production-at-thermal-power-plants/ (accessed August 15, 2022)

			Several projects are ongoing to demonstrate the technology, including CHESTER [53] [54], FutureBay[55] [56], Echogen, ETES[57] and MAN/ABB[58] [59] [60] etc. Several lab-scale prototypes have been built and tested, and FutureBay[54] [55] has delivered a small-scale demonstrator for real application.
Brayton Battery	Resistive heating	TRL 3-5	Resistive heating-based Brayton Batteries use resistive heaters and a gas turbine cycle. Although gas turbine power generation is a mature technology, cost-effective, high-power, long-lifespan and high-temperature electrical heating (>1000 °C) technology at a large scale still faces challenges. Several designs have been proposed[61] [62] [63]. Among them, 1414 Degree [63] has commissioned a small commercial scale system, which is only for testing purpose. Peregrine Turbine Technologies[64] [65] [66] proposed the use of sCO_2 (supercritical CO_2) Brayton cycle for discharging. A prototype sCO_2 Turbo-compressor has been tested for such purpose.

[53] First experimental results from the prototypes of CHEST technology » CHESTER Project n.d.
[54] Important MILESTONE: Status of the CHEST development and experiments » CHESTER Project n.d. https://www.chester-project.eu/news/status-of-the-chest-technology-and-experiments/ (accessed August 15, 2022)
[55] Technology | FutureBay n.d. https://futurebay.uk.com/technology (accessed July 19, 2022).
[56] OTTO Simon by ProactivePublications - Issuu n.d. https://issuu.com/proactivepublications/docs/otto_simon_sus_ (accessed August 15, 2022)
[57] ECHOGEN, Held TJ, Systems EP. Low-cost, long-duration electrical energy storage using a CO 2-based Electro Thermal Energy Storage (ETES) system Delivering long-duration electrical energy storage with low-cost, environmentally safe, domestically-sourced materials 2021
[58] MAN ETES: a cool technology that's heating up sector coupling - Modern Power Systems n.d. https://www.modernpowersystems.com/features/featureman-etes-a-cool-technology-thats-heating-up-sector-coupling-7314754/ (accessed August 15, 2022).
[59] MAN ETES (Electro Thermal Energy Storage) - Solar Impulse Efficient Solution n.d. https://solarimpulse.com/solutions-explorer/man-etes-electro-thermal-energy-storage (accessed August 15, 2022)
[60] ETES CO2 Heat pump MAN Energy Solutions n.d. https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2022/07/man-es-etes-co2-hthp-system.pdf (accessed August 15, 2022)
[61] Heat2Power Turbine - 247Solar, Inc. n.d. https://247solar.com/sustainable-solar-solutions-products/heat2power-turbine/ (accessed July 20, 2022).
[62] 247Solar launches HeatStorE™ a long duration thermal battery - Business Focus Magazine n.d. https://www.businessfocusmagazine.com/2021/06/24/new-thermal-battery-and-solar-tech-help-mining-companies-get-rid-of-diesel-247solar/ (accessed August 16, 2022)
[63] Parham J, Vrettos P, Levinson N. Commercialisation of ultra-high temperature energy storage applications: the 1414 Degrees approach. Ultra-High Temp Therm Energy Storage, Transf Convers 2021:331–46. https://doi.org/10.1016/B978-0-12-819955-8.00013-2
[64] Technology - Peregrine Turbine Technologies Info n.d. https://www.peregrineturbine.com/technology/ (accessed July 20, 2022)
[65] Miscibility Gap Alloy (MGA) Based Thermal Energy Storage (TES) Systems n.d. https://www.peregrineturbine.com/wp-content/uploads/2021/03/PTT_TES.pdf (accessed August 16, 2022)
[66] Experimental Testing of a 1MW sCO2 Turbocompressor n.d. https://www.osti.gov/servlets/purl/1642057 (accessed August 16, 2022)

	Heat pumps	TRL 3-5	Several designs of heat pump-based Brayton Battery technology have been proposed. This includes the use of a reversible Brayton cycle[67 68 69 70], and two separate Brayton cycles [71 72 73]. Prototypes of some key components (e.g. heat pump, turbomachinery, TES unit) and a lab-scale system have been built and tested to validate the technology. A full-scale demonstration plant (4 MW for charging / 2 MW for discharging with a capacity of 10 MWh) is under construction (Stiesdal, GridScale[71 72]).
Other CB – Carnot Battery with Stirling engine	\	TRL 5-7	Several conceptual designs have been proposed. Lab-scale technology validation has been completed. There are reports on multiple demonstrators commissioned and tested[63 74 75 76 77 78 79 80]
Other CB – Liquid Air Energy Storage (LAES)	Air liquefaction	TRL 7-9	A LAES pilot plant (350 kW/2.5 MWh) was designed, constructed, and tested over 10 years ago, and is currently located at the University of Birmingham. A pre-commercial LAES plant (5MW/15MWh) was designed, constructed, and tested. A 50MW/300MWh commercial plant is under construction. Multiple commercial-scale LAES plants are under development[81 82].

[67] Howes J. Concept and development of a pumped heat electricity storage device. Proc IEEE 2012;100:493–503. https://doi.org/10.1109/JPROC.2011.2174529
[68] Breakthrough in Energy Storage: Isentropic Energy | Greentech Media n.d. https://www.greentechmedia.com/articles/read/breakthrough-in-utility-scale-energy-storage-isentropic (accessed August 16, 2022).
[69] Newcastle University connects first grid-scale pumped heat energy storage system n.d. https://www.theengineer.co.uk/content/news/newcastle-university-connects-first-grid-scale-pumped-heat-energy-storage-system (accessed August 16, 2022)
[70] Isentropic - Press Office - Newcastle University n.d. https://www.ncl.ac.uk/press/articles/archive/2017/11/isentropic/ (accessed August 16, 2022)
[71] The GridScale technology explained | Stiesdal n.d. https://www.stiesdal.com/storage/the-gridscale-technology-explained/ (accessed July 20, 2022).
[72] GridScale Energy storage system. n.d.
[73] Schneider G, Maier H, Häcker J, Siegele S. Electricity Storage With a Solid Bed High Temperature Thermal Energy Storage System (HTTES) - A Methodical Approach to Improve the Pumped Thermal Grid Storage Concept. Proc 14th Int Renew Energy Storage Conf 2020 (IRES 2020) 2021;6:26–33. https://doi.org/10.2991/AHE.K.210202.005
[74] Start page - Azelio n.d. https://www.azelio.com/ (accessed June 30, 2022)
[75] Com A, Tespod /, Lindquist T, Fjällborg M, Wallmander -Azelio J. Performance validation data from Azelio TES.POD 1.0 test rig in Sweden. n.d.
[76] "World's first working thermal battery" promises cheap, eco-friendly, grid-scalable energy storage n.d. https://newatlas.com/cct-silicon-energy-battery-thermal-energy-storage/59098/ (accessed June 30, 2022)
[77] CCT Energy | Thermal Energy Storage Specialists n.d. https://www.cctenergystorage.com/ (accessed June 30, 2022)
[78] TECHNOLOGY - TEXEL n.d. https://www.texeles.com/technology/ (accessed July 5, 2022)
[79] Projects Energy Storage: FH Aachen n.d. https://www.fh-aachen.de/en/research/solar-institute-juelich/focus-areas/projects-energy-storage (accessed June 30, 2022)
[80] Green Visit Multi-Tess Store | district association Düren n.d. https://gruene-dueren.de/2020/09/gruene-besichtigen-multi-tess-speicher_20381.html (accessed August 18, 2022)
[81] Liquid Air Energy Storage - Pumped Hydro Capability, No Geographical Constraints. 2017
[82] Plants | Highview Power n.d. https://highviewpower.com/plants/ (accessed August 19, 2022)

Other CB – Lamm-Honigmann energy storage	Lamm-Honigmann-process (thermochemical energy storage)	TRL 2	\

2.2.4 R&D Needs

2.2.4.1 Demonstration Plants

Before analyzing the R&D needs of Carnot Batteries, it is important to understand the development status of different types of Carnot Batteries, which are related to the TRLs. In Section 2.2.3, the TRLs of various Carnot Batteries are suggested based on their development stages. More details are provided in this section.

2.2.4.1.1 Rankine Batteries

Table 15 shows a list of the demonstration plants and ongoing projects of Rankine Batteries. One can see that the Rankine Batteries with resistive heaters for charging can achieve a high storage temperature (700 °C+). It is therefore recommended for use through combining with existing equipment (e.g., steam turbines) of traditional fossil fuel power plants, transforming such plants into storage stations. This resistive heating based Rankine Batteries is a relatively developed technology, and both lab-scale prototypes and small-scale demonstrators for field tests have been reported in the last 5-10 years[48-52].

Comparatively speaking, Rankine Batteries with a heat pump-based charging process can only be used for low temperature applications, often below ~200°C[83], though some more recent work aims for a higher temperature of 300°C[84]. Because the thermal energy is produced by the heat pump and is usually stored, the Rankine Battery can be used not only for combined heating and power supply [53,54], but for combined cooling, heating and power applications[55, 60]. Among lab-scale demonstrators commissioned and tested include the ones by MAN Energy and ABB, who demonstrated CO_2 heat pumps, showing their suitability as the charging unit of the Rankine Batteries[58,60].

[83] Dumont O, Frate GF, Pillai A, Lecompte S, De paepe M, Lemort V. Carnot battery technology: A state-of-the-art review. J Energy Storage 2020;32:101756. https://doi.org/10.1016/J.EST.2020.101756

[84] DLR. High-temperature heat pump ready for operation n.d. https://www.dlr.de/content/en/articles/news/2022/03/20220908_cobra-supports-the-thermal-transition-in-industry.html (accessed December 15, 2022)

Table 15: Demonstration projects of Carnot Batteries based on Rankine cycle for discharging.

Charging cycle	Discharging cycle	Thermal energy storage (TES)	Suggested scale for commercialization	Round trip efficiency (RTE)	Current status of the technology/ project	Company/project and reference
Resistive heating	Steam Rankine cycle	Volcanic rock bed up to 800 °C	10-100 MW and higher 100-2000 MWh and higher	25-40%	Test for various storage concepts, materials and setups in operation since 2014: 0.7 MW/5 MWh Demonstrator - Inauguration and connection to the Hamburg grid, commissioned in 2019: 5.4 MW/130 MWh	Siemens Gamesa, ETES[48-50]
Resistive heating	Steam Rankine cycle	Graphite-aluminium alloy at near 700 °C	1–100s MW 8+ hours	25-40% (design value)	Lab scale, proof of concept Three pilot projects are being developed at Montenegrin power plant Pljevlja, EP Power Europe, and a US utility	E2S Power[51,52]
Heat pump	ORC	Both latent and sensible TES (~140 °C)	N/A	RTE_{CCHP} ≥100%	Lab scale, proof of concept at DLR laboratory, commissioned and initial testing completed	CHESTER[53,54]
Heat pump (organic fluid)	ORC	Water (hot) and PCM (cold)	Grid scale: capable of delivering 12 MW electricity for 6 hours and 70MWh cooling.	N/A	Demonstrator capturing waste heat from a data centre and delivering 1.2 MWh cooling whilst simultaneously delivering stored electricity	FutureBay[55,56]
CO_2 heat pump	CO_2 Rankine cycle	Sand (hot) and ice/water (cold)	Full scale: 10-100 MW, 10-100 hours	60% (concept)	Lab scale, proof of concept – design, fabrication, and commissioning: ~100 kWh thermal, 2-3 hours storage duration	Echogen, ETES[57]
CO_2 heat pump	CO_2 Rankine cycle	Water and ice at 0-150 °C	Suitable for mid- to large-scale thermal and electrical consumers	~50-65%	Pilot CO_2 heat pump successfully tested in Zurich in 2020: 5MW heat supply capacity Two CO_2 heat pumps are to be installed in Denmark in 2022 for replacing a current coal-fired power plant for district heating: overall thermal supply capacity of ~50 MW	MAN/ABB, ETES[58-60]

Notes: 1) RTE – Electricity to electricity round trip efficiency; RTE_{CCHP} – Combined cooling, heating and power efficiency; PCM: phase change material; 2) Concept design, feasibility study projects, as well as projects in planning stage are not included.

2.2.4.1.2 Brayton Batteries

Table 16 summarizes demonstration plants and ongoing projects of Brayton Batteries. One can see several demonstrations of Brayton Batteries using resistive heaters for charging. It should be noted that the heat storage temperature in such a combination of electrical heating and gas turbine cycle is high, often over 1000 °C, whereas their round-trip efficiencies are relatively low (≤45-50%[83]). Besides, the high temperature represents challenges in the selection of both electrical heaters and thermal storage materials. Thus, different heating methods, such as solar collectors [14,15] and biogas combustion (1414 Degree[63,85]), have been proposed for the charging process to achieve high temperatures. For the use of heat pumps for thermal energy production, two areas of development have been reported. One is that both charging and discharging processes share one Brayton cycle (a reversible Brayton cycle). Isentropic Ltd built three lab-scale heat pump prototypes using a reciprocating reversible piston machine capable of working as both compressor and expander before the company was dissolved in 2017[67]. The subsequent development and tests were done by Newcastle University first, then Durham University after 2019 [67-70]. The other development is the use of two separate Brayton cycles, consisting of two compressors and two expanders with one working forward for power generation and the other working backwards as a heat pump for heat/cold generation. The requirements and selection for the components (compressor and turbine) for such a system are relatively much simpler than those for the reversible cycle. Besides, WindTP proposed a Brayton Battery design, whereby the heat pump is powered by the mechanical power of the wind turbine shaft and/or the electricity from the grid[86]. In other words, in their design, primary compressors and secondary compressors used in the heat pump and Brayton cycle are driven directly by wind turbine rotors and grid respectively. To realize this design, a specific multistage slow speed piston compressor concept was proposed, which is currently in experimental development[87].

2.2.4.1.3 Carnot Batteries Based on Hybrid or Other Cycles

In parallel to Rankine and Brayton batteries, other types of Carnot Batteries have also been under development; see Table 17 for a summary. Among them, Liquid Air Energy Storage (LAES) has attracted increasing attention. Such technology has gone through lab scale, pilot scale, and commercial demonstration scale since 2006, and is now under commercial deployment. Carnot Battery based on the Stirling engine for discharging is another hot topic with demonstration plants commissioned and the commercialization process underway. Some other Carnot Battery concepts, including combined discharging cycle and thermo-photovoltaic cell, are also summarized in Table 17.

---

[85] Viaintermedia.com. Storage - 1414 Degrees Launches Energy Storage System Powered by Biogas - Renewable Energy Magazine, at the heart of clean energy journalism n.d.

[86] WindTP – Wind Driven Thermal Pumping n.d. https://www.windtp.com/ (accessed July 21, 2022)

[87] Novotny V, Basta V, Smola P, Spale J. Review of Carnot Battery Technology Commercial Development. Energies 2022, Vol 15, Page 647 2022;15:647. https://doi.org/10.3390/EN15020647

Table 16: Demonstration projects of Carnot Batteries based on Brayton cycle for discharging.

Charging cycle	Discharging cycle	Thermal energy storage (TES)	Suggested scale for commercialization	Round trip efficiency (RTE)	Current status of the technology/ project	Company/project and reference
Resistive heating or solar collector	Gas turbine (Brayton cycle)	Silica sand at up to 1000 °C	Turbine: 400 kWe modules, scalable to any capacity claimed TES: 4-20 hours	~30%	Concept Design Commercial turbine Commercial TES	247solar, Heat2Power Turbine[61,62]
Resistive heating or biogas combustion	Gas turbine (Brayton cycle)	Si-based PCM at 1414 °C	10-1000s MWh	N/A	Medium- to large-scale commercial and industrial scale device (commissioned in 2018): 1.2 MW for charging, 200 kW power output or 1 MWh heating supply for discharging, 10 MWh	1414 Degree, TESS-IND[63]
Resistive heating	sCO_2 closed Brayton cycles	Miscibility Gap Alloy (MGA) based Thermal Storage at up to 1400 °C	1MW/8MWh MGA based TES (scalable)	up to 45%	sCO_2 Turbo-compressor testing	Peregrine Turbine Technologies[64,66] [[17–19]]
Heat pump (reverse Brayton cycle/reciprocating devices)	Brayton cycle (using the same reciprocating devices as the discharging)	Two crushed rock packed beds at -150 °C (cold store) and 500 °C (heat store)	2 MW /16 MWh (scalable)	72-80% (concept)	Lab proof of concept (heat pump prototypes) Demonstrator - 150 kW/600 kWh	Isentropic Ltd (before ~2017), Newcastle University (2017-2019) and Durham University (after ~2019)[67,70] [[20–23]]
Heat pump (reverse Brayton cycle)	Brayton cycle	Crushed basalt rock packed bed (cold store at -30 °Cand heat store at 600 °C)	Storage duration: 12-18 hours for smoothing solar PV and 3-7 days for smoothing of wind power	55-60%	First full-scale demonstration is under construction (in Rødby on the Danish Island of Lolland): 4 MW for charging, 2 MW for discharging,10 MWh	Stiesdal, GridScale[71,72] [[24,25]]

Heat pump (reverse Brayton cycle), N_2 or Ar	Brayton cycle, N_2 or Ar	Silica sand packed bed (silica sand, iron-based sand, basalt)	Concept design: ~8 MW/ ~80 MWh	58–66%	High temperature TES (in operation since 2015): 1.5 MWh Concept design (Pilot designing/ constructing)	Enolcon, OPTES[73]
Heat pump (reverse Brayton cycle)	Brayton cycle	Gravel bed at 605 °C(heat store) and -133 °C(cold store)	3–20 MW, up to 100 h	up to 85%	Component demo	WindTP[86]

Notes: 1) RTE – Electricity to electricity round trip efficiency; RTE_{CCHP} – Combined cooling, heating and power efficiency; PCM: phase change material; 2) Concept design, feasibility study projects, as well as projects in planning stage are not included.

Table 17: Demonstration projects of Carnot Batteries based on hybrid or other cycles for discharging.

Charging cycle	Discharging cycle	Thermal energy storage (TES)	Suggested scale for commercialization	Round trip efficiency (RTE)	Current status of the technology/ project	Company/project and reference
Resistive heating	Stirling engine (power and heat generation at 55-65 °C)	Aluminium alloy based PCM at 600 °C	Scalable and cost competitive at 0.1 to 100 MW, with a focus on installations of 0.1 to 20 MW; 13-24 hours power supply	~30%	TES.POD 1.0 unit has been in operation in Sweden: 13kW/165kWh (electricity) + heat supply at 55-65 °C Multiple demonstrators in Morocco and Abu Dhabi, mature supply chain, commercial	Azelio, TES.POD[74,75]
Resistive heating	Stirling engine	Molten silicon based PCM at 1400 °C	A standard unit 5-100 kW/1.2 MWh (scalable)	N/A	Pilot test unit at Sonnex Engineering, South Australia	CCT Energy, Thermal Energy Device (TED)[76,77]
Resistive heating	Stirling engine	Metal hydrides and metal carbonates based TCMs	One standard unit delivers 30 kW and can be sized from 30 minutes to 24 hours (15 kWh – 720 kWh) of storage	40%	Preparation for industrialization (large-scale battery production planning)	TEXEL Energy Storage[78]

Resistive heating	Stirling engine	Si-based PCM at 1414 °C	N/A	31% RTE_{CCHP}= 80%	Demonstrator (commissioning in 2016): 40 kW/500 kWh (charging at 60 kW)	1414 Degree[63]
Resistive heating or waste heat	Stirling engine and ORC (power and heating supply)	Ceramic storage at 1000 °C	N/A	N/A	multiTESS concept has been demonstrated	Solar-Institut Jülich, multiTESS[79,80]
Resistive heating	Combined Brayton and Rankine cycle	Fluidized bed with silica sand at 1200 °C	Conceptual design is scalable for 50-400 MW/0.5-80 GWh	52-55%	Components prototypes (10 kW charging heater, 5 kW fluidized-bed heat exchanger and 100 kW TES)	National Renewable Energy Laboratory (NREL)[88]
Resistive heating	Thermo-photovoltaic cell	Graphite blocks (1500 °C)	0.1-1 MW/ 10 MWh	40%	Proof of concept (lab-scale prototype): 500 kWh	Antora Energy[89 90 91]
Air compression and liquefaction	Vaporization, air turbine	Liquid air; High-grade cold packed bed at ~180 °C; Molten salt / pressurized water / thermal oil at 50-300 °C	N/A	~60%	Pilot plant ran from 2011-2014 connected to SSE's biomass facility near London, currently located in University of Birmingham: 350 kW/2.6 MWh Pre-commercial has been in operation for over two years, located in Bury, Greater Manchester: 5 MW/15 MWh	Highview[81,82]

[88] Ma Z. Economic Long-Duration Electricity Storage Using Low-Cost Thermal Energy Storage and a High-Efficiency Power Cycle (ENDURING). Natl Renew Energy Lab 2021. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://arpa-e.energy.gov/sites/default/files/2021-03/07 Day1-Zhiwen Ma_NREL.pdf (accessed July 1, 2022).
[89] This startup's energy storage tech is 'essentially a… | Canary Media n.d. https://www.canarymedia.com/articles/energy-storage/this-startups-energy-storage-tech-is-essentially-a-giant-toaster?_hsenc=p2ANqtz-8hHJKEudwMsj77z373ReNap2I4fpbN5j3Tlh96V42As_SbsB1Q96IkGyTbLOiOX93atCpagXFbs9TS8kJZgeVonA3q_Q&_hsmi=209898073&utm_campaign=canary&utm_medium=email&utm_source=newsletter (accessed August 19, 2022)
[90] Bill Gates, Chris Sacca invest $50 million in Antora Energy n.d. https://www.cnbc.com/2022/02/16/bill-gates-chris-sacca-invest-50-million-in-antora-energy.html (accessed August 19, 2022)
[91] TECHNOLOGY — Antora Energy n.d. https://antoraenergy.com/technology (accessed August 19, 2022)

					Commercial plants construction: 50 MW/300 MWh, and 200 MW/2.5 GWh etc.	
CO_2 compression & liquefaction	Vaporization, expansion turbine	Liquid CO_2 + other TES	2.5 MW / 4 MWh	RTE=77% (±2%)	Demonstrator: 2.5 MW / 4 MWh Commercial plant construction: 20 MW/200 MWh	Energydome, CO_2 battery[92]

Notes: 1) RTE – Electricity to electricity round trip efficiency; RTE_{CCHP} – Combined cooling, heating and power efficiency; PCM: phase change material; 2) Concept design, feasibility study projects, as well as projects in planning stage are not included.

[92] Meet the world's first CO2 battery for long-duration energy storage n.d. https://electrek.co/2022/06/28/worlds-first-co2-battery/ (accessed July 21, 2022)

2.2.4.2 Barriers and solutions for the development of Carnot Batteries

In order to analyze the future development path and R&D needs for Carnot Batteries, a survey was done by the IEA Task 36 members, who provided their current understanding of the most challenging obstacles and associated solutions. Table 18 - Table 21 summarize the survey results in terms of the challenges and solutions at materials, component, and system levels, as well as the non-technical aspects.

Table 18: Component-level barriers and solutions for the development of Carnot Batteries.

Challenges/barriers/comments	Potential solutions/suggested R&D pathways
Overall problems: • **High temperature and high-pressure condition (non-standard condition) poses challenges to system components, especially compressors;** • **It lacks methods/standards to select components for Carnot Batteries.**	1. Develop components (compressors, heat exchangers, heat store etc.) for high pressure and temperature applications; 2. Investigate the behaviors and performance of the related components for high-temperature/high-pressure applications; 3. Develop intelligent strategies to select the components of Carnot Batteries based on the system capacity; 4. Develop efficient components for different system scales.
Turbomachinery: • **Reliable reversible compressor/expander needs to be investigated.** • **Efficiency of small-scale (low-power) expander and compressor is low, and the price is high.** • **Two-phase flow poses challenges to compressor and turbine system (in Rankine Batteries), e.g., turbine blade erosion.**	1. Develop different types of reversible compressors/expanders, including reciprocating compressor-expander, co-rotating scroll compressor-expander, and counter-rotating axial compressor- turbine etc.[93] [94] [95]; 2. Develop effective turbomachinery for system down-sizing; 3. Involve renowned original equipment manufacturers (OEM) in Carnot Battery projects to help design and commercialize compressors and expanders. 4. Further investigate the two-phase flow characteristics and their effects on compressors and turbines in Rankine Batteries.
Thermal store: • **Thermal stratification of packed beds causes a gradual reduction of the temperature level and also produces a variable power supply to users.** • **Mismatch of thermal profiles of hot/cold storage with working fluids in Rankine batteries considering the phase change process**	1. Conduct experiments (lab experiments and demo) and dynamic simulation with new storage/heat transfer design; 2. Develop advanced control systems to manage the flow of the heat transfer fluids in thermal storage unit in order to match power request and power supply; 3. Optimize all other relevant components (including ducts, fans, advanced insulation materials, heat exchanger etc.) and storage materials (see material level in Table 20); 4. Utilize designs without heavy steel tanks, possibly embedded in existing infrastructure.

[93] Sapin P, Simpson MC, Olympios A V., Mersch M, Markides CN. Cost-benefit analysis of reversible reciprocating-piston engines with adjustable volume ratio in pumped thermal electricity storage. ECOS 2020 - Proc 33rd Int Conf Effic Cost, Optim Simul Environ Impact Energy Syst 2020:1534–45

[94] Marie-noelle S. (12) Patent Application Publication (10) Pub. No.: US 2011/0094212 A1 2011;1

[95] Brayton Energy LLC. Reversing Turbomachine to Enable Laughlin-Brayton Cycle for Thermally-Pumped Electrical Energy Storage. Massachusetts Institute of Technology, Gas Turbine Lab; n.d.

• Compact, light and cost-effective thermal store design is needed.	
Heating components (charging components): • Efficient charging methods, especially high-temperature charging methods, need to be investigated. • Durability of heating resistors with molten salts needs to be considered. • The management of charging step dynamics needs to be developed to avoid over-heating etc.	1. Fund more projects to support the development of efficient chargers (e.g., heat pump, waste heat) for higher temperatures (especially > 400 °C; 2. Evaluate operating costs of resistive elements immersed in molten salt bath by experiments, and build thermal fluid-dynamic modelling to individuate geometries of resistive elements integrated into molten salts tanks; 3. Develop advanced control systems for charging process.
Heat exchange • Effective heat exchanging structure is needed.	1. Develop effective heat exchanger designs for system down-sizing. 2. Develop innovative production technique or use 3-D printing to realize custom-made flow channels.

Table 19: System-level barriers and solutions for the development of Carnot Batteries.

Challenges/barriers/comments	Potential solutions/suggested R&D pathways
System development: • System-level optimization/development with different configurations and under different conditions needs to be conducted/improved. • Experience on the real-size Carnot Battery system is required.	1. Develop a system with new/innovative heat transfer fluids and thermal storage (e.g., sorption reaction, liquid metal); 2. Develop a system to utilize very high temperature heat and/or low temperature heat (<100 °C); 3. Develop a system in different scales; 4. Conduct off-design condition calculations, dynamic simulations, experiment validation and demonstration projects;
System operation: • It lacks understanding of the dynamic behaviors of Carnot Batteries. • Operating strategy/dynamic control of Carnot Batteries needs to be well designed. • The services that Carnot Batteries can provide currently and in the future needs to be identified.	1. Build the dynamic model and conduct experiments to investigate the dynamic behaviors of Carnot Batteries (e.g., response time, start-up/shut-down behaviors etc.); 2. Develop advanced control strategies to provide flexibility in the response; 2. Develop storage management system by using AI, machine learning and big data technologies; 3. Collaborate with large company to conduct an experimental demonstration of innovative management systems/control systems; 4. Understand the requirements and cost of grid ancillary services (e.g., peak load shifting etc.), figure out the capabilities of Carnot Batteries to engage in these services, and demonstrate Carnot Batteries on the actual utility market.

System integration: • Integration of Carnot Batteries with other processes/waste energy/ multi-vector energy grids needs to be developed and assessed.	1. Design, simulate and demonstrate the integration of Carnot Battery with conventional power plants (e.g., coal-fired power plants etc.), replacing the fuel-fired boiler unit; 2. Design, simulate and demonstrate the integration of Carnot Battery with renewables (e.g., wind power and PV etc.); 3. Design, simulate and demonstrate the integration of Carnot Battery with heating and cooling networks to achieve co-generation and/or tri-generation; 4. Design, simulate and demonstrate the integration of Carnot Battery with waste energy (e.g., industrial waste heat); 5. Design, simulate and demonstrate the integration of Carnot Battery with micro grids and smart-grids;
Technical Comparison: • A technical summary (pros and cons) of all kinds of Carnot Batteries (different cycles, different components, different working fluids etc.) for comparison. • Benchmarking analyses between the most mature Carnot Battery concepts and "conventional" electrical storage methods (including overall thermal efficiency, cost, duration, scalability, LCA, etc.).	1. Fund more projects to support data collection, analyses and comparison work; 2. Strengthen collaboration between different research institutes, industries etc., to share experimental data and make it more publicly accessible.

Table 20: Material-level barriers and solutions for the development of Carnot Batteries.

Challenges/barriers/comments	Potential solutions/suggested R&D pathways
Thermal storage materials: • The database for suitable energy storage materials for different temperature levels and different types of Carnot Battery systems needs to be improved, especially for very high and very low temperature levels.	1. Detailed characterization of all fields of thermal storage materials (e.g., thermal conductivity, phase change enthalpy, usable temperature range, chemical stability, availability, corrosion tests, production costs, environmental impact of using a certain storage material, etc.), including sensible, latent, thermochemical etc.; 2. Development of new promising/new/challenging energy storage materials/ compounds /mixtures/ sorbents, such as magnetite, liquid metal and MOFs etc.; 3. Long-term experiments for mechanical as well as thermophysical properties, and finalization of standardized procedures to characterize materials compatibility and stability (lifetime testing); 4. More projects on building and improving long-term thermal storage materials database and making the database more accessible.

Working fluids: • New working fluids needs to be developed and studied to increase Carnot Battery cycle efficiency	1. Screening, characterization and development activities for the working fluids (refrigerants/gases); 2. Using simulation methods to determine the effect of using new working fluids on the cycle performance; 3. Drawing guidelines to select the optimal working fluid depending on the application; 4. Solving working fluid glide match problems by adopting trans-critical cycles and zeotropic mixtures.
Cost of materials: • Cost for the TES materials needs to be reduced	1. Analysis of the compatibility of storage materials with low-cost structural materials; 2. Focus on the abundant and cost-effective storage materials; 3. Screening of global resources of natural (mines) and non-natural origin (waste industry material) for storage materials; 4. Including companies/manufacturers in the consortium and cooperating with industrial fields for mass production; 5. Drawing guidelines to select materials in terms of both technical and cost aspects (as well as environmental aspects etc.).
Environmental impact of materials: • The environment impact of the energy storage materials needs to be considered and researched	1. Focus on the storage materials possibly derived from recycled materials; 2. Investigating material that can be charged with common renewables (e.g. solar) and then supercharged with electricity; 3. Analysis of the environmental impact of using a certain storage material, making it a standard to select thermal storage materials for practical applications.

Table 21: Non-technical-level barriers and solutions for the development of Carnot Batteries.

Challenges/barriers/comments	Potential solutions/suggested R&D pathways
Political acceptance and social acceptance: • The legal and fiscal status of Carnot Batteries is not fully clear. • The acceptance of Carnot Battery technology in politics needs to be raised. • Social acceptance of Carnot Battery technology needs to be raised.	1. Conducting workshops with stakeholders and politics; 2. Analysis of the legal and fiscal status (e.g., subsidy situation) of electrical energy storage in general and Carnot Batteries in particular in different countries; 3. Calculations/simulations on the national economy level to quantify appropriate tax burden, political sanctions and preferential treatment; 4. Involving more non-technical people, e.g., economists and social scientists, to come up with proposals and scenarios; 5. Funding more projects to demonstrate Carnot Battery technology which can be available/beneficial for the neighborhood.

Economic performance and market acceptance: • Accurate cost and LCOS estimation/assessment of different Carnot Batteries is highly needed for direct comparison with other electricity energy storage technologies. • New financing strategies are required to deal with the issues of high investment for infrastructure and low energy cost. • The market assessment of Carnot Batteries is insufficient.	1. More R&D projects on the accurate study of existing Carnot-Battery systems in order to accurately estimate the specific cost of Carnot Batteries, and each Carnot Battery technology should be clearly defined in terms of specific cost; 2. Conducting techno-economic analyses to evaluate the potential of Carnot Batteries; 3. Considering new financial schemes, including multi-ownership, crowd funded storage, securitization vehicles, rental of storage space etc.; 4. Data collection from different markets and evaluating the most promising markets for each Carnot Battery technology.
Environmental impact: • Environmental impact evaluation for different Carnot Battery concepts is highly needed.	1. Conducting LCA studies on different Carnot Battery concepts to clarify when Carnot Batteries are environmentally beneficial over their lifetime; 2. Comparing the environmental impact of different Carnot Battery concepts with other electricity energy storage technologies.
Geographic acceptance: • It is very hard to acquire an extensive area of connected land near cities.	1. Utilizing compact, light (without heavy steel tanks) and cost-effective system design; 2. Embedding system in existing infrastructure; 3. Retrofitting conventional fuel-fired power plants into Carnot Battery plant; 4. Integration of Carnot Batteries with existing industrial processes/renewable plants etc.

2.2.4.3 R&D Needs for Carnot Batteries

Based on the summary of the barriers and solutions in Section 2.2.4.2, the R&D needs are proposed as follows:

(1) R&D efforts are needed in the enhancement of -thermodynamic and economic- performance and technical maturity of components of Carnot Batteries under non-standard conditions, e.g., very high or very low temperatures, very high pressures, small and/or large sizes, under two-phase flow regions.

(2) Reversible heat pumps and power generators are highly promising for reducing the costs and system complexity of the Carnot Batteries, but a significant level of R&D efforts is needed.

(3) Advanced control technology that can resolve or mitigate problems caused by the thermocline of the thermal store during discharging and avoid overheating during the charging process requires some R&D efforts, so to allow the system to work in a more manageable and flexible way. This includes a more fundamental understanding of dynamic behavior and associated process control for Carnot Batteries.

(4) Carnot Batteries have potential applications through integration with industrial processes, renewables, existing traditional fuel-fired power plants and waste heat/cold, which requires more attention.

(5) One of the advantages of Carnot Batteries over other electricity energy storage methods is the potential to provide both cooling and heating on top of the power supply to end-users, decarbonizing the thermal sector. More R&D efforts are needed in these aspects.

(6) The development and manufacture of cost-effective, long-life, and environmentally friendly thermal storage materials for different temperature applications are essential for large scale deployment of Carnot Batteries.

(7) The involvement of economists, social scientists, environmentalists, industrial stakeholders, politicians etc. is essential in the development and assessment of Carnot Batteries projects, which can help increase the political acceptance, social acceptance, and market acceptance of the technology.

(8) The role of the Carnot Batteries in the power grids, micro grids and heating/cooling networks, e.g., ancillary services and combined cooling and heating supply, needs to be defined.

(9) Experimental and demonstration work are essential for the validation of the emerging technologies. This applies to both small scale and large-scale Carnot Batteries under real operational conditions.

2.3 Market Analysis, Energy System, Policy and Regulations

2.3.1 Climate Crisis and Decarbonization Challenges

In May 2021, the International Energy Agency released a flagship report offering the world's first comprehensive study of how to transition to a net-zero global energy system by 2050 (NZE).[96] Noting that the number of countries announcing pledges to achieve net zero emissions over the coming decades continued to grow, the roadmap identified a path to net-zero that ensured stable and affordable energy supplies, provided for universal energy access, and enabled robust economic growth. It set out a cost-effective and economically productive pathway, resulting in a clean, dynamic, and resilient energy economy dominated by renewables, like solar and wind, instead of fossil fuels.

Since then, pledges and actions by governments have fallen well short of the steps required to bring global energy-related carbon dioxide emissions to net zero by 2050.[97] In 2021, emissions rose by a record 1.9 gigatons (Gt) to reach 36.6 Gt.[98] This was driven by rapid post-pandemic economic growth, slow progress in improving energy intensity, and a surge in coal demand even as renewables capacity additions scaled record heights. In February 2022, Russia's unprovoked invasion of Ukraine created broad and rippling impacts on the global energy system, "disrupting supply and demand patterns and fracturing long-standing trading relationships."[99]

Efforts to address climate change have manifested in rapid electrification of our economy, from home heating to industry to transportation.[100] Globally, a dramatic increase in power demand has occurred and is expected to accelerate. To meet this demand without jeopardizing a sustainable path to NZE, as much new power generation as possible must come from renewable sources. Electricity and heat generation are responsible for more than 40% of global CO_2 emissions, with coal plants emitting over 70% of the associated emissions.[101]

The global electricity-generation transformation will impact how power systems are designed and operated. Sunshine and wind are not always available, requiring a range of backup options, smarter and better-connected grids, and a new approach to ensuring energy system flexibility – "the ability of power system to reliably and cost effectively manage the nearly instantaneous, hourly, daily, weekly and seasonal variability of demand and supply."[102]

Emerging clean technologies are critical in this context. Through 2030, most of the global CO_2 emissions reductions will come from technologies readily available today. Reaching net zero by 2050 will require widespread use of technologies that are not on the market yet, like Carnot Batteries.[103] Many of them

---

[96] IEA (2021), Net Zero by 2050, IEA, Paris https://www.iea.org/reports/net-zero-by-2050

[97] IEA (2023), Climate Change: Energy sector is central to efforts to combat climate change, IEA, Paris https://www.iea.org/topics/climate-change

[98] Ibid.

[99] IEA (2022), World Energy Outlook 2022, IEA, Paris https://www.iea.org/topics/world-energy-outlook

[100] IEA (2022), Electricity, IEA, Paris https://www.iea.org/fuels-and-technologies/electricity

[101] IEA (2021), Greenhouse Gas Emissions from Energy Data Explorer, IEA, Paris https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer

[102] IEA (2022), Electricity

[103] IEA (2021), Net Zero by 2050

are still nascent, in the prototype or demonstration phase, and must be quickly deployed and scaled. Major innovation efforts must occur over this decade to bring these new technologies to market in time.

In Carnot Batteries, electric energy is stored as thermal energy, which is later recovered during discharge; the charging can be done with different heating technologies, whereas the discharging can be done with different thermal engine technologies.[104] For additional information about the diversity of Carnot Batteries, please see Section 2.2.1.

Carnot Batteries can accelerate the energy transition while building energy resilience. As an example, Europe's highest priority is decarbonizing sectors that consume the most natural gas: power, industry, and buildings. Accelerated electrification is already straining the electric grid, with rationing schemes proposed throughout the continent. At the same time, the weaponization of natural gas creates new risks to the construction of new natural gas-fired power plants that can meet the increased demand but will then run for decades. Carnot Batteries can convert VRE into on-demand, around-the-clock power, meeting the accelerating need for power without worsening the dependency on fossil energy. Industry uses large amounts of natural gas to create heat. Carnot Batteries can discharge clean heat when charged with VRE. Buildings use fossil energy to keep families warm. Carnot Batteries, during the transformation of Heat to electricity release low-temperature heat. This heat can be integrated into district energy systems partially or fully electrifying the heat supply for buildings. Most areas of the developed world face some combination of these three challenges.

At the same time, Carnot Batteries can improve the resiliency of the grid. Some Carnot Batteries re-generate power using turbomachinery and are like-for-like replacements for thermal power generators, like natural gas, coal, and nuclear power plants. As the penetration of VRE grows, time shifting of VRE will be critical to reliably and cost effectively manage the variability of demand and supply.

Equally important is providing the grid flexibility that conventional generation assets provide today. Global power systems are typically composed of synchronous generators: large, centralized, dispatchable assets. These generation units contribute to the energy system's inertia to ensure stability, resiliency, and reliability. When a plant unexpectedly trips offline, the inertia of the system allows other plants to continue operating and prevents blackouts. VRE and electrochemical batteries are asynchronous generators and instead rely on inverters to convert their DC power to the AC grid. They do not inherently add to the system's inertia and reliability and instead rely on as yet unproven simulated inertia. Areas with increasing VRE and electrochemical battery deployment are today experiencing drops in grid stability, which is of great concern to grid planners and operators. I

In North America, more than 88 GW of generating capacity is confirmed for retirement in the next 10 years.[105] More than 70% of the new generation in development for connecting to the bulk power system is solar, wind, and hybrid (a generating source combined with a battery).[106] The North American Electric Reliability Council recommended in December 2022 that regional transmission and integrated resource planning processes address the loss of necessary sources of system inertia and frequency stabilization, which are essential for a reliable grid, caused by these retirements.[107] In Europe, Spain adopted a new regulation in 2021 that requires developers to ensure no area loss of synchronism when adding new

---

[104] Olivier Dumont, Guido Francesco Frate, Aditya Pillai, Steven Lecompte, Michel De paepe, Vincent Lemort (2022), Carnot battery technology: A state-of-the-art review, Journal of Energy Storage, Volume 32, 101756, ISSN 2352-152X, https://doi.org/10.1016/j.est.2020.101756.

[105] North American Electric Reliability Council (2022), 2022 Long-Term Reliability Assessment, Atlanta, https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2022.pdf

[106] Ibid.

[107] Ibid.

generation.[108] As a result, renewables developers are increasingly seeking to partner with synchronous storage solutions, like Carnot Batteries.

Global policy actions, while still insufficient to meet the NZE timelines, have driven much of the transformation of the energy sector to date: [109]

- Due in large part to the Inflation Reduction Act, annual solar and wind capacity additions in the United States are predicted to grow 250% over today's levels by 2030; electric car sales are predicted to grow by 700%.
- In the European Union (EU), accelerated deployment of renewables and efficiency improvements are expected to reduce natural gas and oil demand by 20% and coal demand by 50% by 2030.
- India is expected to progress towards its domestic renewable capacity target of 500 gigawatts (GW) by 2030, with renewables providing nearly two-thirds of the country's accelerating demand for electricity.

Each of these policy actions relies on and may result in significant shifts in how electricity is generated: from conventional fossil-fueled assets to VRE. Further policy action is necessary to ensure that rapid electrification is matched by equally rapid rollouts of low-carbon sources and that it does not result in less secure energy systems.

2.3.2 Barriers to Deployment

Carnot Batteries are not broadly deployed today outside of concentrated solar power (CSP) plants. In CSP, TES is integrated with the solar-thermal systems to allow the plants to provide power 24 hours per day.[110] Standalone Carnot Batteries, where electricity is stored from integrated generation facilities (e.g., solar PV, wind, etc.) or from the electric grid, can address the intermittency and flexibility challenges of VRE, but face several barriers to deployment.

2.3.2.1 Tech-to-Market Transition Barriers

Some Carnot Batteries are still early in development with significant research and development needs. Funding to advance these technologies to higher technology readiness levels (TRL) is challenging to secure. Mechanical systems have greater capital costs than electrochemical and other energy storage solutions. More developed technologies face similar financial challenges to build pilot plants to demonstrate the technologies in real-world settings.

Several technologies are ready to deploy first-of-a-kind (FOAK) commercial-scale plants. These technologies are considered to have higher technology risk than an alternative flexibility investment, like new natural gas plants or repowering older generation units with natural gas. Expected customers for Carnot Batteries are highly-regulated utilities or others who require near-perfect certainty of operational performance. This is a barrier to technologies without validated performance records and start-up technology developers with limited financial resources to offer performance guarantees and warranties.

---

[108] Luis Rouco (2021), Grid access of non-synchronous generation: Review of the Spanish regulation, Comillas Universidad Pontifica, Almeria, https://www.icrepq.com/icrepq21/pl2.pdf

[109] IEA (2022), World Energy Outlook 2022

[110] SolarPACES (2017), How CSP's thermal energy storage works, IEA, https://www.solarpaces.org/how-csp-thermal-energy-storage-works/

Technology risk can lead to market risk, with potential customers being unwilling to commit to long-term contracts for FOAK projects. Without a long-term contract, securing financing for projects is even more challenging. This has been termed the "Valley of Death" for technology start-ups.[111]

New, clean technologies are also inherently more expensive than their GHG-emitting alternatives. At the apex of their cost-down curves, new technologies must compete with fossil-economy technologies with decades of deployments, refinements, and cost savings measures. Bill Gates terms this the "green premium:" the additional cost of clean technology over a polluting alternative.[112]

2.3.2.2 Commercialization Barriers

For Carnot Battery developers who able to build a FOAK unit to validate a technology's operational and financial viability, market barriers make broader commercialization and widespread deployment challenging. Current energy systems and markets are insufficiently designed to incentivize deployment and appropriately compensate Carnot Battery owners and/or operators for all the services the technology can provide. Many markets have discriminatory policies in place that make bidirectional energy storage uneconomic.

The green premium cannot be overcome with a FOAK unit. Scaling, cost-downs, and efficiencies of scale are required to make non-emitting technologies cost competitive with alternative, emitting resources. Potential customers of Carnot Batteries are generally required to select the most cost-competitive solutions to their needs, which often is a higher priority than meeting climate goals or supporting the development of new, clean technologies.

2.3.3 Policy Recommendations

The drivers for the deployment of Carnot Batteries and energy storage technologies, in general, are akin to the drivers for renewable energy: adoption of policy support packages to traditional market frameworks that were created to accommodate the conventional generation industry. Globally, power market laws, rules, and regulations vary by jurisdiction. There is no one-size-fits-all solution to removing barriers to and fostering support for Carnot Batteries. However, there are a host of mechanisms that could be drawn as inspirations and guidance for how the most suitable support mechanism(s) could operate in specific markets and geographies.

2.3.3.1 Clarity and Fairness

Carnot Batteries is a diverse technology class with solutions at all technology readiness levels. Collectively, all Carnot technologies would benefit from clarity and fairness in policy and regulation. Only through fair competition on a level playing field will transitioning markets organize efficiently and cost effectively.

Definition of energy storage. As bidirectional energy assets, Carnot Batteries operate similarly to short-duration lithium-ion batteries. They are at times a load when storing electricity, and at times a generator, when discharging electricity and/or heat. In global markets without clear definitions of energy storage, this has resulted in complex and often unfavorable regulation. Without such definitions, market rules will not be able to define the services and benefits that Carnot Batteries provide. The Electricity Market Design Directive, part of the EU's Clean Energy for All Europeans legislative package,

---

[111] Saheed A. Gbadegeshin, Anas Al Natsheh, Kawtar Ghafel, Omar Mohammed, Ashten Koskela, Antti Rimpiläinen, Joonas Tikkanen, Antti Kuoppala (2022), Overcoming the Valley of Death: A New Model for High Technology Startups, Sustainable Futures, Volume 4, 100077, ISSN 2666-1888, https://doi.org/10.1016/j.sftr.2022.100077.

[112] Breakthrough Energy (2022), The Green Premium, https://breakthroughenergy.org/our-approach/the-green-premium/

adopted a wide definition of "energy storage," encompassing both reconversion to electricity or conversion into another energy carrier.[113] Energy storage is also recognized as a distinct asset class, separate from generation.[114] In 2022, Germany defined energy storage as an asset where "the final use of electrical energy is postponed to a later point in time than when it was generated." Adopting clear, legal definitions, similar to the EU or German versions, will reduce the complexity of creating markets and market rules and speed up the deployment of Carnot Batteries.

Definition of TES. Carnot Batteries (and other thermal applications) should be fully acknowledged as a form of energy storage, just as other storage technologies (e.g. lithium-ion battery systems). For an overall framework, it is important to see storage solutions as a fourth pillar of the energy system in addition to generation, transmission/ distribution and consumption. Any definition of energy storage that identifies specific technologies must include Carnot Batteries as a subcategory.

Modelling Carnot Batteries. System-wide grid modelling relies on complex tools to determine the optimum deployment of power assets. Carnot Batteries challenge most modern models because of their bidirectional nature. While some models have been adapted to include short-duration energy storage, long-duration technologies continue to flummox grid modelers. Jurisdictional grid models must be updated to include bidirectional grid assets with longer durations. Development of such models should be supported by national and/or subnational governments to ensure adequate financial and technological resources to complete and regularly update modelling.

Non-discriminatory market rules. Non-discriminatory policy design is imperative to provide adequate and optimum signals to incentivize the deployment of storage solutions, like Carnot Batteries. Energy storage resources are already providing energy and ancillary services in some markets. They do so through participation models designed for other technologies or models that limit the full range of services that storage can provide. In the United States, the Federal Energy Regulatory Commission (FERC) found that the existing rules discriminated against energy storage resources and took action to require regional transmission organizations to enable storage resources located on the interstate transmission system, on a distribution system, or behind-the-meter to participate to the full extent of each storage technology's capabilities.[115] Designing electricity markets to ensure Carnot Batteries are compensated in a competitive and non-discriminatory manner for the services they provide will level the playing field and enable rapid deployment of least-cost viable solutions to deliver value to end consumers.

Codes and standards: To quickly deploy Carnot Batteries, national or international codes and standards for the siting, construction, interconnection, operation, and decommissioning of Carnot Batteries must be developed to enable engineering, procurement, and construction companies, investors, and developers to execute projects quickly, safely, and sustainably. The American Society of Mechanical Engineers (ASME) has issued a Draft Standard to establish uniform test methods and procedures for conducting performance tests of mechanical or TES systems.[116] Similar efforts have been completed for Carnot Batteries operating worldwide in CSP plants with thermal storage. The U.S. National Renewable Energy Laboratory, in collaboration with IEA's SolarPACES, the World Bank, the Electric Power Research

[113] Amandine Delsaux, Matthijs van Leeuwen, Christina Korinthios, Arnaud Belisaire (2019), Regulatory progress for energy storage in Europe, Norton Rose Fulbright, https://www.nortonrosefulbright.com/de-de/wissen/publications/8b5285f4/regulatory-progress-for-energy-storage-in-europe#section3

[114] Ibid.

[115] Federal Energy Regulatory Commission (2018), Order 841: Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Operators, 162 FERC 61,127 (18 CFR Part 35), https://www.ferc.gov/sites/default/files/2020-12/Order-No-841.pdf

[116] ASME (2018), Mechanical and Thermal Energy Storage Systems (Draft Standard for Trial Use), https://www.asme.org/codes-standards/find-codes-standards/ptc-53-mechanical-thermal-energy-storage-systems/2018/drm-enabled-pdf

Institute, and SolarDynamic, issued a report identifying best practices for the construction of these plants, including codes and standards.[117] ASME has also analyzed gaps in CSP codes and standards.[118]

2.3.3.2 Financial Policies

Public investment in the development and deployment of Carnot Batteries can help to overcome both tech-to-market barriers and commercialization barriers.

Funding Research and Development: Public funding to support research and development efforts for Carnot Batteries can assist technology developers to advance the TRL of their Carnot Batteries. In Japan, the New Energy and Industrial Technology Development Organization manages the Green Innovation Fund for Business, a ¥2 trillion (18.2 billion EUR) fund to assist ambitious green projects to develop technologies in key areas essential to achieving carbon neutrality by 2050, including electrification and greening of electricity.[119] Many countries included clean technology investments in their Covid-19 recovery efforts. Where public funding is not available for research and development, governments should create programs with Carnot Batteries as eligible technology investments.

Grants. Direct public support for capital expenditures would help to overcome financial gaps and risks due to the high investment costs that Carnot Batteries often still face. Public funding for FOAK installations supports de-risking new technologies and validating their operational and financial viability, transitioning them toward commercialization. In the United Kingdom, the Department for Business, Energy & Industrial Strategy operates the £1.5 billion (1.7 billion EUR) Energy Innovation Program, which targets key net-zero innovation opportunities from a whole energy system perspective to accelerate the commercialization of innovative low-carbon technologies, systems and processes in power, buildings, and industry sectors.[120] Similar to R&D funding, many countries offer financial support to construct FOAK units. Countries that do not offer such aid should consider developing similar programs.

Tax incentives. Indirect public support for capital expenditures can also help to offset costs and attract private investment. In the United States, the Inflation Reduction Act of 2022 created a clean energy tax credit for investments in zero-emission generation or energy storage technologies.[121] Offering up to 50% of the cost of an asset as a credit against taxes, the program will dramatically reduce financial barriers to deployment of new, clean technologies. For some taxpayers, the credit is refundable, where a net-negative tax exposure after claiming the credit would result in a payment to the taxpayer for the difference between taxes owed and credits earned. In Canada, a similar investment tax credit was proposed in the 2022 Fall Economic Statement.[122] Similar policies should be considered by all governments to accelerate the deployment of Carnot Batteries.

Support for Performance Guarantees and Warranties: To fully commercialize, Carnot Battery developers must offer commercial-grade performance guarantees and warranties (PGW). Financiers

[117] Mehos, Mark, Hank Price, Robert Cable, David Kearney, Bruce Kelly, Gregory Kolb, and Frederick Morse. 2020. Concentrating Solar Power Best Practices Study. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-75763. https://www.nrel.gov/docs/fy20osti/75763.pdf

[118] ASME (2012), Concentrated Solar Power (CSP) Codes and Standards Gap Analysis, https://www.asme.org/codes-standards/find-codes-standards/stp-pt-054-concentrated-solar-power-codes-standards-gap-analysis/2012/drm-enabled-pdf

[119] IEA (2021), National Budget 2021 - Green Innovation Fund Business, IEA/IRENA Renewables Policies Database, https://www.iea.org/policies/13128-national-budget-2021-green-innovation-fund-business

[120] UK Department of Business, Energy & Industrial Strategy (2021), Energy Innovation, UK.gov, https://www.gov.uk/guidance/energy-innovation

[121] IEA (2023), Inflation Reduction Act 2022: Sec. 13702 Clean Electricity Investment Credit, IEA/IRENA Renewables Policies Database, https://www.iea.org/policies/16284-inflation-reduction-act-2022-sec-13702-clean-electricity-investment-credit

[122] Government of Canada (2022), Jobs, Growth, and an Economy That Works for Everyone, https://www.budget.canada.ca/fes-eea/2022/report-rapport/chap2-en.html#a16

and expected customers, including highly regulated utilities, require these instruments before making commitments. Early-stage companies without capital reserves lack the ability to offer commercially acceptable PGW themselves, which is a barrier to commercialization. Private insurance is available but is generally too expensive for start-up companies to afford. This creates a vicious cycle: sales require PGW, but PGW require sales. Governments should mobilize capital to support technology developers' efforts to offer PGW to customers. Novel insurance programs offered by national banks or public investment in private, pooled insurance funds would address this barrier.

2.3.3.3 Demanding Supporting Policies

Governments are playing increasingly expansive roles in driving and accelerating clean energy transitions. However, as the IEA stated, "transitions are unlikely to be efficient if they are managed on a top-down basis alone."[123] Governments are expected to be able to provide approximately 30% of the required investments. The balance will need to come from private sources. This will require policies that incentivize private investment in Carnot Batteries. To support commercialization, governmental policies can help to support demand for Carnot Battery deployment.

Procurement Mandates and Targets: Governments can create deployment mandates or targets for the services that Carnot Batteries offer, like long-duration energy storage. This sends a signal to potential customers to invest in innovative technology. In the United States, the California Public Utilities Commission mandated investor-owned utilities to establish energy storage procurement targets (1.3 GW by 2020).[124] This policy drove significant deployment of storage systems.

Regulated asset base. In the regulated asset base (RAB) model, risk is shared between investors and customers. Private companies (infrastructure managers) invest in, own, and operate infrastructure assets. The infrastructure manager receives revenue from users and/or subsidies to fund its operations and recoup investment costs. The infrastructure manager is governed by an economic regulator to provide efficiency incentives and to cap prices, revenue, or rates of return. Efficiency incentives mimic the incentives that would be faced in a competitive market. RABs have been used to finance transportation infrastructure,[125] nuclear power,[126] and other assets,[127] and it is the model used by investor-owned utilities in the United States. Policies and regulations that allow Carnot Batteries to be included in the RAB would allow customers to deploy the technology more easily. Many regulated infrastructure managers are disallowed from acquiring higher-risk or higher-cost innovative technologies. In Colorado, USA, a law was passed allowing the regulator to approve investment in innovative technologies that advance climate and energy transition goals.[128]

Public purchase of services. Governments are often among the largest customers in any country. By leveraging their scale and procurement power, governments can support the development of markets for preferred services. In the United States, President Biden directed his government to purchase

---

[123] IEA (2022), World Energy Outlook 2022

[124] California Public Utilities Commission (2023), Energy Storage Targets - Publicly Owned Utilities - AB 2514, https://www.energy.ca.gov/data-reports/reports/energy-storage-targets-publicly-owned-utilities

[125] Makovšek, Dejan, Veryard, Daniel (2016), The Regulatory Asset Base and Project Finance Models, International Transport Forum, Organization of Economic Co-operation and Development, Paris, https://www.itf-oecd.org/sites/default/files/dp_2016-01_makovsek_and_veryard.pdf

[126] UK Department for Business, Energy & Industrial Strategy (2022), Development costs and the nuclear Regulated Asset Base (RAB) model, https://www.gov.uk/government/publications/development-costs-and-the-nuclear-regulated-asset-base-rab-model

[127] Spence, Cecilia Nancy, Finding Tobin's Q in Neverland. Available at SSRN: https://ssrn.com/abstract=681903 or http://dx.doi.org/10.2139/ssrn.681903

[128] Colorado General Assembly (2021) HB21-1324, Promote Innovative And Clean Energy Technologies, https://leg.colorado.gov/bills/hb21-1324

exclusively carbon pollution-free electricity by 2030, at least half of which must be locally supplied to meet demand 24 hours per day, seven days per week (24/7).[129] Public purchase of 24/7, 100% renewable energy will necessitate the use of long-duration energy storage, benefitting all technologies that provide this service, including Carnot Batteries. Governments can also purchase other services offered by Carnot Batteries, such as discharge heat for district energy services. This will incentivize private investment in enabling technologies.

2.3.3.4 Supply-Supporting Policies

Valuation of the full spectrum of services. Nearly all energy market rules globally were created before energy storage was deployed broadly. Existent market rules value a narrow spectrum of services and are based on the generation/load model. Bidirectional energy assets (BEAs), like Carnot Batteries, are new. Some markets have begun to create rules for BEAs to accommodate short-duration storage assets, like electrochemical energy storage, but none have identified the full spectrum of services that Carnot Batteries and other long-duration energy storage technologies offer (e.g., synchronous inertia, short-circuit current, demand response, etc.).[130] As a result, potential revenue that would incent private investment is not available. Carnot Batteries under current market rules must rely on the sale of electricity and potentially discharge heat and other market-specific services (e.g., a capacity reserve where available) to attract investment and operate economically. When compared to alternative investments (e.g., natural gas generation), Carnot Batteries are less economical. Governments should work with research bodies to identify the full spectrum of services that Carnot Batteries and other BEAs offer to the grid and customers. These values should be recognized in market rules to allow appropriate remuneration, incent private investment, and accelerate deployment.

Feed-in tariffs: Feed-in tariffs (FITs) are a policy tool designed to promote investment in renewable energy. FITs have been used to guarantee solar and wind projects an above-market price for their production. Contract terms vary (e.g., 5 to 25 years). Designed to promote investment in renewable energy, feed-in tariffs were first implemented in the United States in 1978[131] and have been adopted in other countries (e.g., Japan,[132] Germany,[133] and China[134]). Approximately three-fourths of global solar energy is estimated to be linked to FITs.[135] FITs for Carnot Batteries would ensure the financial viability of projects, attracting private capital to support development, construction, and operation costs.

Contract for difference: A CFD is a long-term contractual agreement between an electricity generator and a customer designed to provide the generator with price certainty over the lifetime of the contract. As used in the United Kingdom, the CFD is a contract between a generator and a government-owned

---

[129] The White House (2021), FACT SHEET: President Biden Signs Executive Order Catalyzing America's Clean Energy Economy Through Federal Sustainability, Washington, https://www.whitehouse.gov/briefing-room/statements-releases/2021/12/08/Factsheet-president-biden-signs-executive-order-catalyzing-americas-clean-energy-economy-through-federal-sustainability/

[130] Denholm, Paul, Wesley Cole, A. Will Frazier, Kara Podkaminer, and Nate Blair. 2021. *The Challenge of Defining Long- Duration Energy Storage*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-80583. https://www.nrel.gov/docs/fy22osti/80583.pdf

[131] Chernyakhovskiy , Ilya, Tian, Tian, McLaren, Joyce, Miller, Mackay, and Geller, Nina (2016), U.S. Laws and Regulations for Renewable Energy Grid Interconnections. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-66724. https://www.nrel.gov/docs/fy16osti/66724.pdf

[132] IEA (2020), Feed-in Tariff for renewable electricity and solar PV auction, IEA, https://www.iea.org/policies/5173-feed-in-tariff-for-renewable-electricity-and-solar-pv-auction

[133] IEA (2023), Germany's Renewable Energy Act, IEA, https://www.iea.org/policies/12392-germanys-renewables-energy-act

[134] IEA (2021), Feed-in tariff for CSP, IEA, https://www.iea.org/policies/6278-feed-in-tariff-for-csp

[135] Polonsky, Pete (2019), The case for state solar feed-in-tariffs (FiTs) in the USA, Duke University Nicholas School of the Environment, https://blogs.nicholas.duke.edu/env212/the-case-for-state-solar-feed-in-tariffs-fits-in-the-usa/

company under which the generator's income per unit of electricity is fixed.[136] This is done by both parties committing to pay or be paid a difference payment, which is calculated by comparing a reference price (i.e., the market price for electricity) with the generator's strike price (i.e., a price set usually by auction at the commencement of the contract). If the reference price is below the strike price, the government owned corporation pays the generator the difference. When the strike price is below the reference price, the generator pays the government the difference. By providing long-term price certainty, CFDs can help to attract private investment in the development of projects. Governments should consider offering CFDs for Carnot Batteries.

Cap and floor: Like CFD policies, cap and floor mechanisms are contracts that subject project revenues to minimum and maximum levels. Below the "floor," customers would top-up revenues. Earnings above the "cap" would be returned in whole or in part by the generator to customers. A cap and floor regime would reduce risks for investors by clarifying annual maximum and minimum revenues over a long-term period. It also encourages operators of Carnot Batteries to respond to system needs, helping grid regulators to maintain the security of supply.

Sector coupling incentives: As stated above, some Carnot Batteries can also generate clean heat, which can be used for sector coupling, similar to combined heat and power plants. These services offer the opportunity to address the three leading uses of natural gas: electricity generation, industrial heat production, and residential heating. Carnot Batteries can decarbonize electricity production by firming VRE and enabling its broader deployment. Their clean heat production can help to decarbonize industrial heat, depending on the Carnot Battery. It can also be used for district energy services, to heat homes in the winter and, using chillers, to cool them in the summer. In some jurisdictions (e.g., Germany), Carnot Batteries are not eligible for sector coupling regulations (e.g., combined heat and power) and do not benefit from existent market rules (e.g., fixed feed-in tariffs). In order to tap this large potential for decarbonization via electrification, barriers between different sectors must be removed. Carnot Batteries able to provide both electricity and heat should be made eligible for existent and proposed sector coupling policies. This would create predictable revenue for projects, incentivize private investment, and speed deployment.

Capacity Markets. The capacity market (CM) is essentially an insurance policy to ensure that the security and reliability of the electricity supply a constantly maintained. It is designed to incentivize new and existing generation capacities by providing stable, minimum payments to projects to encourage investments in new capacity. Long-term contracts are often available, with a notable example shown in the United Kingdom of 15 years.[137] The design of CMs could be further refined to include emission limits to further restrict the participation of inefficient conventional generators and incentivize low carbon generation to enter the system. Carnot Batteries could be included as eligible assets for CMs, which would incent private investment in their deployment.

Curtailment compensation: Partly seen in markets, curtailment payments currently further hinder the deployment and integration of Carnot Batteries and other (large) storage solutions into the energy markets. Rather than curtailing renewable energies, other solutions must be found: The German government has for example included a paragraph into the German CHP-act, allowing the payment of a so-called Power-to-Heat-Bonus for flexible CHP-plants that add flexibility to the energy system in times of energy surplus. "Nutzen statt Abregeln" is defined in yet another paragraph, allowing the use of

---

[136] Low Carbon Contracts Company (2022), Briefing – An introduction to the CfD and its role in the energy bill crisis, https://www.lowcarboncontracts.uk/sites/default/files/2022-09/LCCC-briefing-on-%20the-CfD-scheme-5-September-2022.pdf

[137] A. Barillas, R. Cohen and N. Sukthaworn, "Lessons from the first capacity market auction in Great Britain," *2015 12th International Conference on the European Energy Market (EEM)*, Lisbon, Portugal, 2015, pp. 1-6, doi: 10.1109/EEM.2015.7216748 https://ieeexplore.ieee.org/document/7216748

renewable energy that would otherwise have to be curtailed. Hereby, investment costs of power-to-heat applications that add flexibility to the grid are refunded by the grid operator – costs for such applications as part of a Carnot Battery could thus also be refunded.

3 Appendices

3.1 Appendix 1: Key Performance Indicator at Component and Material Level

3.1.1 Component Level

Volume (TES)	m^3
Thermal Capacity (TES)	MWh/m^3
Maximum Charging Power (TES)	MW
Maximum Discharging Power (TES)	MW
Capacity (HPs)	MW
Efficiency (converters, TES)	adm. (e.g. COP for HPs)
Operational Temperature	°C (range)
Lifetime (TES, converters)	cycles before fail
TRL	1-9
Maintenance cost	€/year; €/cycle
Heat Losses (self-discharge)	kJ/h or%/day or kJ/m^2 or kW/m^2

3.1.2 Material Level

DEFINITION	UNIT
Volumetric Energy Density	MWh/m^3
Gravimetric Energy Density	kJ/kg, MJ/ton, MWh/ton
Thermal Conductivity	W/m K
Heat Capacity	kJ/kg K
Density	kg/m^3
Operating Temperature	°C (range)
Degradation	%/1000 x cycles
Safety and environmental aspects	see chemical categories (toxic, flammable…)
Recyclability	CO_2 footprint
Availability	GOOD/POOR, natural/synthetized
Type	feature: sensible, Latent, sorption, TC
Latent Heat	(LHTES) kJ/kg
Reaction Enthalpy	(TCTES) kJ/kg
Operation Pressure	bars
Cost	€/kg, €/MWh

3.2 Appendix 2: State of the Art of Carnot Battery Technologies

State of the Art of Carnot Battery Technologies

White paper of the IEA ES Task 36 Carnot Batteries, Deliverable ST0-3

Vaclav Novotny[1], Ales Basta[1], Vit Basta[1], Jan Spale[1]

[1]Czech Technical University in Prague (Czechia)

Introduction

A Carnot Battery (CB), as defined below, is a relatively new concept for a flexible, geographically independent and cost-effective electricity storage based on thermal energy storage and conversion systems between power and heat. Currently, there are various methods and technologies competing both at the market and in academia as the need for large-scale flexible cost-effective electricity storage increases with the increasing amounts of volatile renewable energy sources connected to the grid and fluctuating electricity costs at the markets. Despite CB showing a lower efficiency compared to other electrical storage systems, e.g. pumped storage hydropower plants or electrochemical batteries, its low-cost thermal storage systems, flexibility, and the possibility to use existing technologies for power to heat and heat to power conversion makes it currently a very interesting technology for pilot-scale and early-market solutions. This paper therefore tracks the active development in both academic research as well as in commercial development and describes the current state of the art of these systems.

Scientific definition: "A **Carnot battery is a system primarily used to store electric energy**. In a Carnot battery, the electric energy (input) is used to establish a temperature difference between two environments, namely the low temperature (LT) and high temperature (HT) reservoirs. In this way, the storage is charged, and the **electric energy is stored as thermal exergy**. As the heat flows against the thermal gradient, work is spent to charge the storage. In the discharge phase, the thermal exergy is discharged by allowing the heat flowing from the HT to the LT reservoir. The heat flow powers a heat engine (HE) which converts it into work and discharges the residual heat into the LT reservoir. In this way, a fraction of the electric input is recovered." [1]

There are various ways to categorize concepts, principles, and technologies related to Carnot Batteries (CB), which all follow the underlying principle of power to heat to power conversion as illustrated in Figure 42. This involves surplus electricity to power a power-to-heat (P2H) system, which generates a temperature gradient (converts electricity to thermal exergy). When the battery is discharged, the thermal energy is converted back into electricity using a heat-to-power (H2P) system, which acts as a heat engine. Classification of these systems can include factors such as the charging and discharging methods, thermal energy storage technology, and the type of conversion system used. In this white paper, the classification system used focuses on the discharging system, specifically Rankine cycle systems, Brayton cycle systems, and other hybrid systems, in accordance with the categories established by the IEA Task 36 on Carnot Batteries. Within each of these groups, a further distinction is made between systems that have direct Power-to-Heat (P2H) conversion and those that use the Pumped Thermal Energy Storage (PTES) systems, which employ a heat engine (heat pump) principle for charging.

The difference between the 2 main charging methods is illustrated in Figure 43, (a) and (b), standing for direct heating and utilizing a thermodynamic cycle. The cycle can create thermal exergy with temperature above ambient, below, or both (Figure 43 (c), (d) and (b)). There is furthermore a possibility of thermal integration, either external heat source during charging, as illustrated in Figure 43 (c) and (d), or separate thermal output from the storage or discharging system.

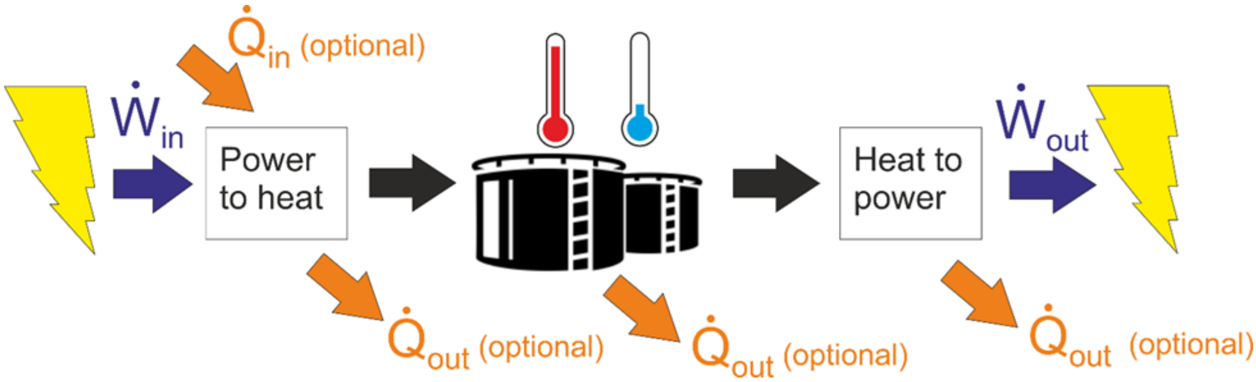


Figure 42: General principle of Carnot Battery systems [3].

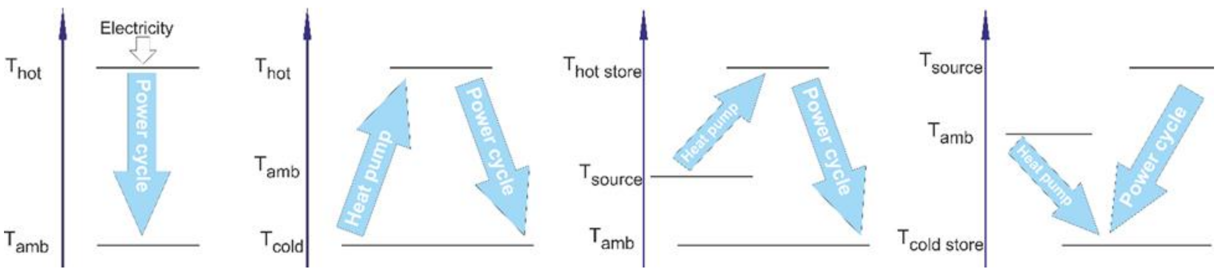


Figure 43: CB concept for thermal integration of heat sources and conversion systems [3].

Bibliometric Study and Theoretical Analyses

In recent years the term Carnot Battery, along with other terms considering the same group of technologies, is increasingly getting attention as is documented in Figure 44 by a bibliometric study tracking the number of publications containing (exactly) these specific terms. Within these publications are also a number of review works. Primary references for interested readers pursuing more information are review work [1] providing a general overview of CB principles. Prospects of PTES system is then provided in [2]. A comprehensive overview of the commercial development has been reported in [3]. An additional summary of state of the art, providing mainly a quantitative review of many research articles is provided in [4]. Carnot Batteries are commonly evaluated along with other thermo-mechanical storage technologies as compressed air energy storage [5,6] This white paper takes as the main source of information works [3] and [4], with especially commercial development being continuously updated.

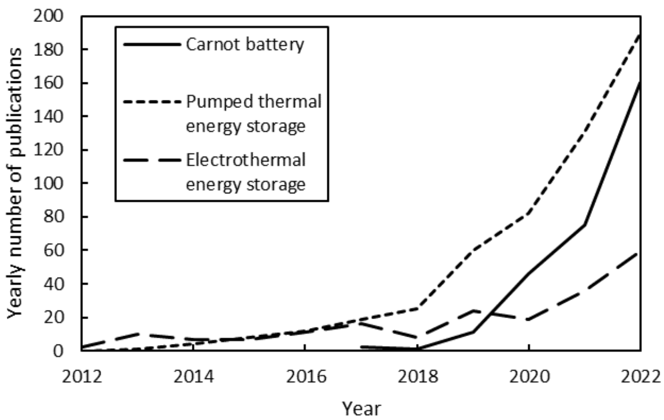


Figure 44: Yearly number of scientific publications with main CB keywords.

When theoretical analyses of PTES CB systems are performed, it is important to note that the roundtrip electrical efficiency is highly dependent on assumptions of the system components. In the ideal case, both charging and discharging are performed by an identical thermodynamic cycle with ideal components, zero pressure drop or temperature difference in heat exchangers, only running in reverse direction. In such a case the roundtrip efficiency is unity.

Analysis of impact of real component efficiency show for example effect of the compressor efficiency on the overall efficiency is in the quadratic form [7], thus the actual components highly impact the roundtrip efficiency. Together with temperature difference and pressure losses during heat exchange, typical realistic roundtrip efficiency values are between 40% and 65% (excluding external heat sources). From a certain point it can become more beneficial to convert power to high temperature heat by direct heating, store it (no need for storage of multiple temperature levels as in many PTES) and in times of need convert back to power by systems not much dissimilar to current thermal power plants.

State of the Art in Experimental and Commercial Development

The beginnings of the Carnot Batteries, including experimental works and commercialization trials, can be traced to to work of Ericsson in 1833 [1] or thermal energy storage patents by Fritz Marguerre in 1924 [8]. This work is however mapping a much more recent development, driven mainly by the increasing volatility of renewable electricity production and the rising need for large scale economically feasible electricity storage. The commercial development is summarized in an attempt to be an exhaustive list, providing a comprehensive overview of the market situation. The tables below summarize developed systems based on with Rankine cycle in Table 22, Brayton cycle systems in Table 23 and finally CB system using other principles in Table 24. In the tables, the systems are sorted first by the power to heat conversion method, first resistance heated, and then reverse thermodynamic cycles. For Rankine cycle, it is followed by the working fluid, i.e. water, organic fluids, air and CO_2.

Note that most of the reported RC systems are conducting experimental, demonstration or even pilot operations of their systems. For BC systems the extent of the projects is smaller, possibly attributed to the requirement of very high efficiency of compressors and expanders to which the systems are highly sensitive. This is contrary to the extent of academic research. Eight out of ten reported system is doing or has performed at least some experimental work, so real-life feasibility might be known in the near future. Many of the systems use other working principles, there are 5 systems in the experimental phase and one already in commercial operation.

Additionally, there is growing number of standalone TES systems enabling CB. These are not include here, but a specific list of them and more details can be found in [3] or in a separate white paper [9].

Table 22: List of commercial development projects in CB using Rankine cycle discharging.

Company, system	Charging method	TES	Discharging method	Power output	Storage capacity / duration	Roundtrip efficiency	State	ref.
Siemens Gamesa, ETES	Resistance heaters to air	Volcanic rock bed ~ 600°C	steam Rankine cycle	units to 100s MW	24 h	25% to >40%	Demo	[10–12]
RWE, Store2Power	Resistance heaters	molten salt	steam Rankine cycle	100s MW	hours	~ 40%	n.a.	[13]
LEAG	Resistance heaters / flue gas from (H_2) gas turbine	Undecided	steam Rankine cycle	100s MW	hours	~ 40%	Intent for Jänschwalde & Boxberg plants	[14]
Enel+ Brenmiller	Resistance heaters / flue gas from gas turbine	Brenmiller TES (gravel packed bed)	steam Rankine cycle	several MW	24 MWh	n.a.	Tests on NGCC	[15]
E2S Power	Resistance heaters	Graphite-aluminium alloy at 700°C	steam Rankine cycle	1-100s MW	hours	25-40%	lab proof of concept	[16]
Hyme, Boreholm	Resistance heaters	Molten hydroxide salt	steam Rankine cycle, CHP	1 MWe (potencial 100s MW)	hours	n.a.	demo/pilot & CHP plant conversion ongoing	[17]
Spilling	Steam compression & liquefaction	Saturated water (steam accumulators)	Steam expander (steam engine)	up to MW	hours	n.a.	n.a.	[18,19]
GE, AMSESS	CO_2 Brayton + el. heating	Molten salt, water tank	Steam cycle with extraction	20-100 MW	8 hours	42 – 62%	Concept	[20]
Consortium CHESTER	Heat pump (organic fluid)	PCM and water	ORC	MW scale (8 kW exper.)	hours to days	RTE $_{CCHP}$= >100%	lab proof of concept	[21]
Climeon	Heat pump (organic fluid)	water (e.g. district heating system)	ORC	80 kW to MW	hours	25-60%	concept with existing ORC	[22]
TC Mach	Heat pump (organic fluid)	Stone dust TES	ORC	kW	hours	n.a.	construction of proof of concept	[23]
Future Bay	Heat pump (organic fluid)	water (hot) and PCM (cold)	ORC	10s kW	hours	n.a.	Demo	[24]
TORC	Heat pump (organic fluid)	PCM (hot & cold) 30/130°C	ORC	~ dozens kW	12+ hours	n.a.	concept/design	[25]
Highview	Air liquifaction	Liquid air + other TES	Vaporization, expansion turbine	50-350 MW	about 6	60-70%	Pilot, full scale construction	[26–28]
MAN/ABB, ETES	CO_2 heat pump	120°C water + cold (ice) storage	CO_2 Rankine cycle	several MWe	~ 5 h	~45%	lab demo	[29–32]
Echogen, ETES	CO_2 heat pump, fluidized bed heat exchange	Sand (hot 400°C) and ice (cold)	CO_2 Rankine cycle	25MW	250 MWh	~60%	demo w/ exp. Valves, 200 kWh, MoU for large scale	[33–37]
Energydome, CO_2 battery	CO_2 compression & liquefaction	Liquid CO_2 + other TES	Vaporization, expansion turbine	10-80 MW modules	20-200 MWh	77%	Pilot 2 MWe operational	[38,39]
Gasevo, LiNES	Air separation, nitrogen liquification	Liquid nitrogen	Vaporization, expansion turbine (cryogenic RC)	10 MW	hours	13%	Discontinued concept	[40]

Table 23: List of commercial development projects in CB using Brayton cycle discharging.

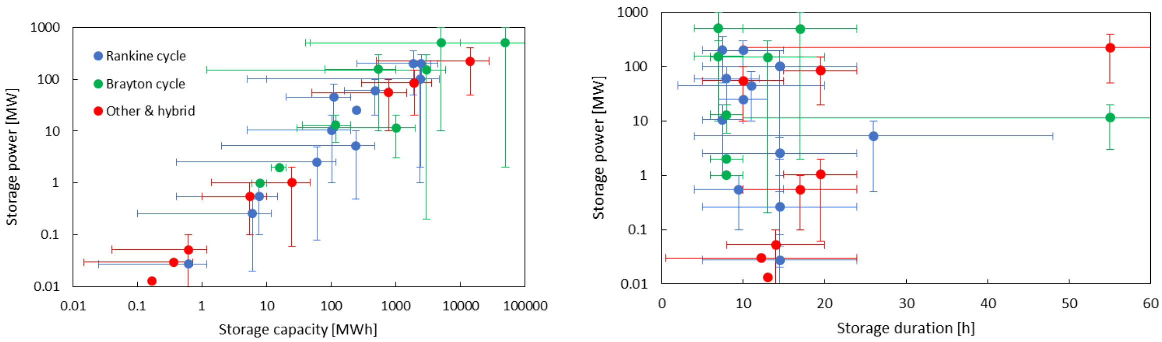
Company, system	Charging method	TES	Discharging method	Power output	Storage capacity / duration	Roundtrip efficiency	State	ref.
247Solar, Heat2Power Turbine	Electric resistance heaters	Silica sand	Gas turbine (Brayton cycle)	200 kWe – 100s MW	6 – 20 hours	30%	Concept, design	[41]
1414Degrees, TESS	Electric resistance heaters	Silicon based alloy, melting temperature 1414°C	Gas turbine (also steam turbine, Stirling engine, direct heat)	10MW-GW		n.a.	Demos (done) Planning grid scale pilot	[42,43]
Peregrine Turbine Technologies	Electric resistance heaters	Graphite-aluminium alloy (MGA), 800°C	CO_2 Brayton cycle	1 MW	8 MWh	45%.	CO_2 turbine / compressor tests	[44]
Isoentropic	Heat pump (Brayton cycle - reciprocating devices)	Crushed rock packed bed	Brayton cycle (reciprocating devices)	2 MW (exper. 150 kW)	16 MWh	72%	Demo (bankruptcy)	[45]
Malta, Pumped Heat Energy Storage	Heat pump (reverse Brayton cycle)	Molten salt + hydrocarbon antifreeze	Recuperated Brayton cycle	10-100 MW	80 MWh - 1 GWh	~60%	Demo, design of full/pilot scale	[46,47]
Stiesdal, GridScale	Heat pump (reverse Brayton cycle)	Crushed basalt rock packed bed	Brayton cycle	2 MW -1 GW	100,000 MWh	35 – 60%	MW scale pilot built; suspended indefinitely	[48]
Toshiba & Marubeni	Heat pump (reverse Brayton cycle)	packed bed	Brayton cycle	MW scale	n.a.	n.a.	100 kWh demo	[49]
STOLECT	Heat pump (reverse Brayton cycle)	packed bed	Brayton cycle	1-20 MW	5-100 MWh	70% (potencial)	Concept	[50]
Enolcon, OPTES	Heat pump (reverse Brayton cycle), N_2 or Ar	Silica sand packed bed (silica sand, iron based sand, basalt)	Brayton cycle, N_2 (or Ar)	~ 8 MW	~80 MWh	58-66%	Concept, design (demo construction)	[51]
WindTP	Heat pump (reverse Brayton cycle)	Gravel bed, indirect heat transfer	Brayton cycle	3-20 MW	up to 100 hours	up to 85%	component demo	[52]

Table 24: List of commercial development projects in CB in the other and hybrid discharging cycle category.

Company, system	Charging method	TES	Discharging method	Power output	Storage capacity / duration	Roundtrip efficiency	State	ref.
Azelio	Electric resistance heaters	Aluminium based PCM (600 °C)	Stirling engine	13kW	13 h	~30-40%	Multiple pilots, production line, commercial	[53]
CCT Energy Storage	Electric resistance heaters	Silicon based PCM (1400 °C)	Stirling engine	5 kW-100 kW	up to 1.2 MWh per module	n.a.	Pilot	[54,55]
TEXEL Energy Storage	Electric resistance heaters	Metal hydrides (MH)/metal carbonates	Stirling engine	30 kW	15 – 720 kWh	40%	commercial installation effort	[56]
Kraftlagenn München, multiTESS	Electric resistance heaters / waste heat	Ceramic system (1000 °C)	Stirling engine and ORC	60 kW (demo)	1.4 MWh_{th} (demo)	n.a.	Demo commissioned	[57,58]
NREL ENDURING LDES (GE, PEI, Allied)	Electric resistance heaters	Fluidized packed bed with solid materials (1100 °C)	Combined Brayton and Rankine cycle	50 – 400 MW	10 – 100 hours	50 –55%	Components prototypes, demo preparation	[59]
Pintail Power, Liquid Salt Combined Cycle	Electric resistance heaters	molten salt	Combustion combined cycle integration	from dozens MW	24 hours	82-96% (+ fuel)*	Patented concepts	[60]
Pintail Power, Liquid Air Combined Cycle	Compressor for air liquefaction	liquid air	Combustion combined cycle integration	from dozens MW	24 hours	118% (+ fuel)*	Patented concepts	[61]
Airthium Energy Storage	Stirling engine (reversible, heat pump mode)	Molten salt (sodium and potassium nitrate salts) or sand	Stirling engine	> 100 kW	1MW+ and 14 MWh+	70%	1kW (prototype), 100kW (demonstrator)	[62]
Antora Energy	Electric resistance heaters	Graphite blocks (1500 °C)	Thermophotovoltaic cell	0.1 – 1 MW	10 MWh_e	40%	Proof of concept	[63]
NaCompEx	Compresed heat followed by desorption	NaOH-H_2O solutions via concentration difference	Expansion followed by absorption	10-100 MW	60 kWh/m^3 storage	80%	Concept, design	[64,65]

**The reported RTE is based on electrical and burned fossil fuel as energy inputs, and this is the reason for RTE > 100%*

Nearly 40 CB systems and their technologies and states are documented. These encompass a wide variety of concepts, including direct power-to-heat (P2H) Joule (resistance) heating conversion, heat pump-based conversion, thermodynamic cycles such as the Rankine cycle (using steam, organic, or CO_2 fluid), Brayton cycle, their combinations, Stirling cycle, and direct heat-to-power (H2P) conversion with systems like thermophotovoltaics. The spectrum of power output and storage capacity (or storage duration in hours) derived from all gathered systems is depicted in Figure 45. In the absence of precise data, engineering approximations were employed. The figure indicates that CB systems span from kW to GW. The smallest systems are based on ORC and Stirling engines, while the largest generally rely on contemporary thermal power plant technologies. The storage duration validates an application range of approximately 4 to 24 hours, corresponding to the time range of medium-duration energy storage systems. As these systems mature and the demand for increased storage duration grows, it may become viable to augment storage capacity at a relatively low cost.



(a) (b)

Figure 45: Storage power output and capacity (a) and discharge duration (b) for the commercially developed CB systems.

The collected data can be displayed in terms of round-trip efficiency, as shown in Figure 46. A broad range of values from approximately 25% to 80% is evident, with co-firing systems being an exception, as they attain values above 100%. However, this is solely due to the definition accounting only for input electricity (a fuel-burning plant would consequently have infinite efficiency). Round-trip efficiency is often reported for conceptual systems, which resemble theoretical outcomes with rather optimistic system assumption estimates. As a result, prudence is advised, particularly for systems that exist solely in a conceptual or preliminary design phase and lack experimental data support. Even in cases where demonstration and pilot plants are in place, the values are typically still projected for full-scale and have not been validated.

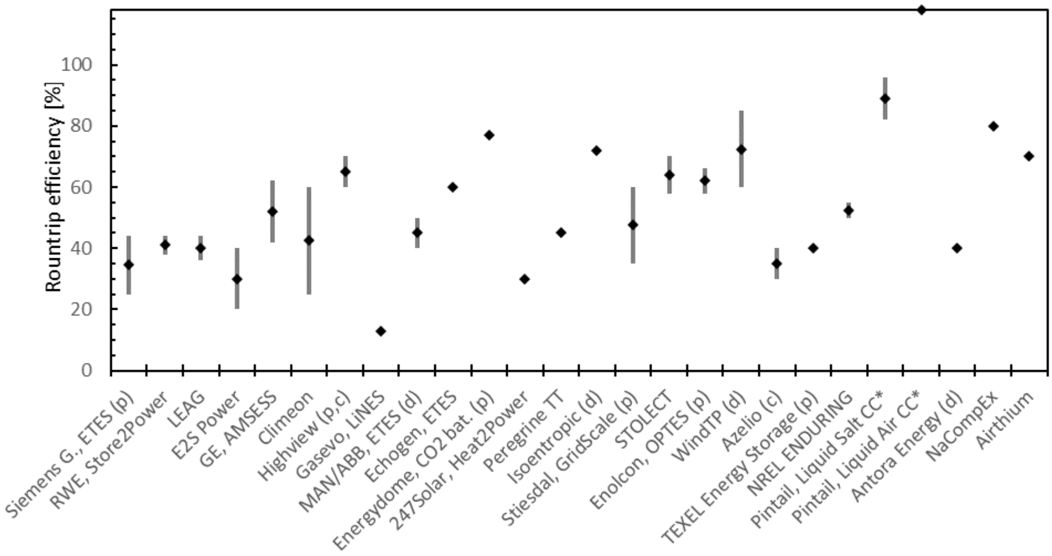


Figure 46: Overview of round-trip efficiency in the commercially CB systems (mostly declared as experimental values are limited). In notation (d) stands for demo, (p) pilot, (c) commercial units (built or under construction), * for systems with additional fuel firing.

Figure 47 presents efficiency values from academic articles. Within these, it can be observed that some values align with optimistic estimates stemming from commercial development. Nonetheless, there is minimal work involving direct resistance heating for these systems, with the majority concentrating on reverse heat engines.

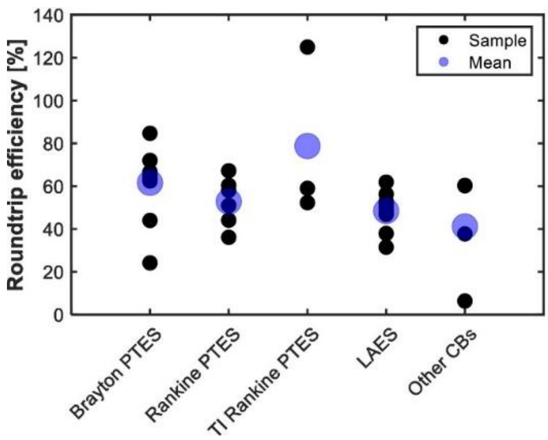
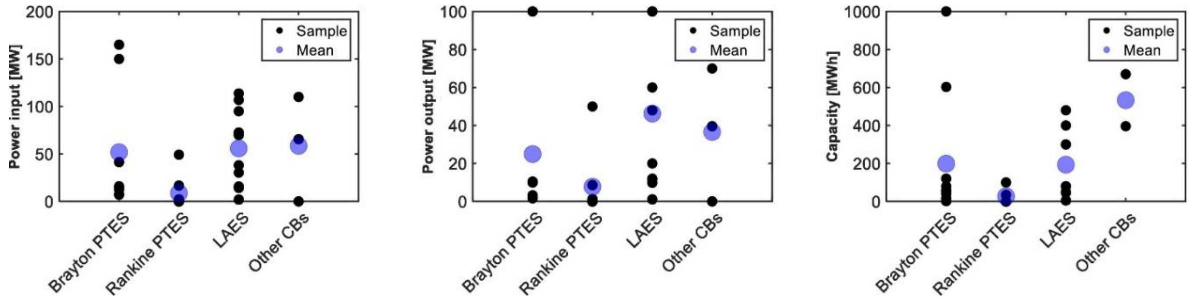


Figure 47: Overview of CB efficiency in published scientific papers [4].

Similar to Figure 45, the performance of the systems explored in scientific studies is shown in Figure 48. Note the relatively low power levels compared to the projections of the industry, especially in the Rankine cycle field. The reason can be found in the fact, that most of the Rankine cycle systems here are based on lower power ORC. The the number of works focusing on LAES is very high in contrast with only a single industrial company seriously developing this concept.



(a) (b) (c)

Figure 48: Storage systems performance from scientific studies regarding (a) power input, (b) power output and (c) system capacity [4].

PTES were generally more favored in scientific literature due to their higher efficiency potential, but commercial development lacked behind, with many systems remaining in the conceptual stage or with unrealized designs, but this is changing. The largest CB commissioned thus far is Highview's 5 MW liquid air energy storage (LAES) pilot system. The company is also constructing a full-scale 50 MW unit with 5 hours of operation. As contracts are being prepared for additional LAES units, the first-of-a-kind challenge is being addressed, putting the technology on a clear path towards commercial applications. Following MW scale PTES systems are Energy Dome and Stiesdal, both commissioned in 2022. MAN explores a unique approach to commercialization, where the transcritical Rankine CO_2 heat pump used for charging can operate separately and the first 50 MWth scale system is nearing its completion on site.

Siemens Gamesa ETES uses direct power to heat conversion, storage of heat in rock packed bed and using steam cycle for power to heat conversion with size of 1.2 MWe and 29 MWhe was the first pilot system of this size for resistance heating with steam cycle. However, the only existing commercial installations are smaller-scale Azelio units with a 13 kWe output provided by Stirling engines. Charging is also performed via direct conversion, and thermal storage consists of aluminium alloy phase change material. Several other systems using direct electricity-to-heat conversion are at least in the experimental demonstration phase.

However, the bankruptcy of Isentropic, a company developing reversible Brayton cycle CB, emphasizes the need for real CB systems to have low unit costs, simple and robust designs, and the expectation that their feasibility will improve with future renewable-based grids.

Summary

Carnot Battery technology is currently in its early stage of development, though it undercomes rapid growth and fast evolution. Several companies using different experimental, demonstration, pilot and (pre)commercial units using different methods for power to heat, thermal energy storage and heat to power conversion **are nowadays competing for the emerging and growing market with flexible large scale cost-effective electricity storage** which can provide ancillary grid services. There is a great demand for such systems, which motivates fast development and large investments. This demand is further expected to grow with the future installation of renewable energy sources.

Current state of the art commercial CB systems can be roughly distinguished into three groups **Rankine cycle based** Carnot Batteries, **Brayton cycle based** Carnot Batteries **and hybrid** (Stirling, combination of previous, thermophotovoltaics). Though **each commercially developed system aims at different business cases, storage capacities and installed power input/output** it is difficult to compare them side by side by the means of a single value, from the collected reported data, one can derive that the roundtrip efficiency of the mature full-scale technology may achieve around 50% - 60% but hardly more, unless external heat source is used. **Caution with respect to the reported RTE is necessary**, particularly for systems that exist only in the conceptual or early design stage without experimental data support. Although demonstration and pilot plants exist, the **values are typically still projected for full scale and have yet to be verified.**

Acknowledgements

The authors acknowledge the Grant Agency of the Czech Technical University in Prague, especially grant No. SGS23/055/OHK2/1T/12 for partially providing funds to prepare this white paper and participation in the Task 36 of IEA TCP Energy storage.

Literature

[1] Dumont O, Frate GF, Pillai A, Lecompte S, De paepe M, Lemort V. Carnot Battery technology: A state-of-the-art review. J Energy Storage 2020;32:101756. https://doi.org/10.1016/j.est.2020.101756.

[2] Frate GF, Ferrari L, Desideri U. Energy storage for grid-scale applications: Technology review and economic feasibility analysis. Renew Energy 2021;163:1754–72. https://doi.org/10.1016/J.RENENE.2020.10.070.

[3] Novotny V, Basta V, Smola P, Spale J. Review of Carnot Battery Technology Commercial Development. Energies 2022, Vol 15, Page 647 2022;15:647. https://doi.org/10.3390/EN15020647.

[4] Vecchi A, Knobloch K, Liang T, Kildahl H, Sciacovelli A, Engelbrecht K, et al. Carnot Battery development: A review on system performance, applications and commercial state-of-the-art. J Energy Storage 2022;55:105782. https://doi.org/10.1016/J.EST.2022.105782.

[5] Olympios A V., McTigue JD, Farres-Antunez P, Tafone A, Romagnoli A, Li Y, et al. Progress and prospects of thermo-mechanical energy storage—a critical review. Prog Energy 2021;3:022001. https://doi.org/10.1088/2516-1083/ABDBBA.

[6] Moore J, Smith NR, Brett G, Kerth J, Kurz R, Freund S, et al. Heat engine-based storage systems. Therm Mech Hybrid Chem Energy Storage Syst 2021:293–450. https://doi.org/10.1016/B978-0-12-819892-6.00006-X.

[7] Held T. Pumped Thermal Energy Storage (PTES) Low-cost, safe and environmentally-responsible electrical energy storage anywhere. Int. Work. Carnot Batter., Stuttgart, Germany: 2022.

[8] Marguerre F. Thermodynamic energy storage. US2065974A, 1936.

[9] Rohringer C, Riegler T, Vasta S. Thermal energy storage methods for Carnot Batteries. 2022.

[10] ETES-Electric Thermal Energy Storage-Technology and Commercial Proposition. Siemens Gamesa Renew Energy GmbH Co KG n.d. https://www.siemensgamesa.com/en-int/-/media/siemensgamesa/downloads/en/products-and-services/hybrid-power-and-storage/etes/siemens-gamesa-etes-general-introduction-3d.pdf (accessed October 11, 2021).

[11] Barmeier T. Electric Thermal Energy Storage (ETES) Transition of energy supply. 26. Wind. Warn., Warnemünde, Germany: 2017.

[12] Electric Thermal Energy Storage (ETES) ETES:SWITCH 2021. https://www.siemensgamesa.com/en-int/products-and-services/hybrid-and-storage/thermal-energy-storage-with-etes-switch (accessed November 4, 2021).

[13] Witold A. StoreToPower Pilot plant for the development of a heat storage power plant. 2nd Int. Work. Carnot Batter., Stuttgart, Germany: DLR; 2020.

[14] Hörtinger T. LEAG's Carnot Battery. 3rd Int. Work. carnot Batter., Stuttgart, Germany: 2022.

[15] World's first utility-scale, rock-based storage facility goes online in Italy – pv magazine International n.d. https://www.pv-magazine.com/2022/11/11/worlds-first-utility-scale-rock-based-storage-facility-goes-

online-in-italy/?fbclid=IwAR1lZDJjFpR3PtS0_jMh1fGO9guXxaiL1BuGuTcjzr7xY5gyoVfUjQlNaTc (accessed December 5, 2022).

[16] E2S Power | 2020. http://e2s-power.com/ (accessed November 4, 2021).

[17] 2LiPP — Hyme n.d. https://www.hyme.energy/project/2lipp (accessed December 5, 2022).

[18] Schäfer T. Thermo-MechanischerSpeicher (CARNOT-Batterie). Zittau, Germany: 2020.

[19] Spilling Technologies: About Spilling 2021. https://www.spilling.de/about-spilling/about-spilling.html (accessed October 21, 2021).

[20] Aga V, Conte E, Carroni R, Burcker B, Ramond M. Supercritical CO2-Based Heat Pump Cycle for Electrical Energy Storage for Utility Scale Dispatchable Renewable Energy Power Plants. 5th Int. Symp. - Supercrit. CO2 Power Cycles , San Antonio, Texas: 2016.

[21] CHESTER Project | COMPRESSED HEAT ENERGY STORAGE FOR ENERGY FROM RENEWABLE SOURCES n.d. https://www.chester-project.eu/ (accessed October 21, 2021).

[22] Karthäuser J. The Low Tempeature (80-120 °C) Carnot Battery and its Potential for the Integrated Energy System. 2nd Int. Work. Carnot Batter., Stuttgart, Germany: DLR; 2020.

[23] Novotny V, Mach S, Rathan M, Basta V, Spale J. Modelling and experimental development of a waste heat upgrade integrated ORC Carnot Battery with stone dust thermal storage. 6th Int. Semin. ORC power Syst., Munich, Germany: 2021.

[24] FutureBay - Energy Storage, Hvac 2021. https://futurebay.uk.com/ (accessed October 22, 2021).

[25] TORC – Pure Energy, Zero Emissions 2021. https://www.torccleanenergy.com.au/ (accessed October 11, 2022).

[26] Plants | Highview Power 2021. https://highviewpower.com/plants/ (accessed October 2, 2021).

[27] Morgan R, Nelmes S, Gibson E, Brett G. Liquid air energy storage - Analysis and first results from a pilot scale demonstration plant. Appl Energy 2015;137:845–53. https://doi.org/10.1016/j.apenergy.2014.07.109.

[28] Ross K. Highview hires MAN Energy for UK cryogenic energy storage project. Power Eng Int 2021. https://www.powerengineeringint.com/smart-grid-td/energy-storage/highview-hires-man-energy-for-uk-cryogenic-energy-storage-project/ (accessed November 24, 2021).

[29] Sanz Garcia L, Jacquemoud E, Jenny P. THERMO-ECONOMIC HEAT EXCHANGER OPTIMIZATION FOR ELECTRO-THERMAL ENERGY STORAGE BASED ON TRANSCRITICAL CO2 CYCLES. 3rd Eur. Conf. Supercrit. CO2 Power Syst., Paris, France: 2019, p. 2019-sCO2.eu-151. https://doi.org/10.17185/duepublico/48917.

[30] Morandin M, Mercangöz M, Hemrle J, Maréchal F, Favrat D. Thermoeconomic design optimization of a thermo-electric energy storage system based on transcritical CO2 cycles. Energy 2013;58:571–87. https://doi.org/10.1016/J.ENERGY.2013.05.038.

[31] Mercangöz M, Hemrle J, Kaufmann L, Z'Graggen A, Ohler C. Electrothermal energy storage with transcritical CO2 cycles. Energy 2012;45:407–15. https://doi.org/10.1016/J.ENERGY.2012.03.013.

[32] Jacquemoud E. Electro-Thermal Energy Storage System (ETES) Based on CO2 Cycles. Ref Modul Earth Syst Environ Sci 2021. https://doi.org/10.1016/B978-0-12-819723-3.00055-X.

[33] ETES System Overview | Echogen Power Systems 2021. https://www.echogen.com/energy-storage/etes-system-overview (accessed November 3, 2021).

[34] Echogen Energy Storage. Supercritical CO 2-Based Long-Duration Electrical Energy Storage Technical Overview. 2019.

[35] Held T. Systems and Methods for Generating Electricity Via a Pumped Thermal Energy Storage System. US20200003081A1, 2020.

[36] Held T. Systems and methods for generating electricity via a pumped thermal energy storage system. US10883388B2, 2021.

[37] Held T. Low-cost, long-duration electrical energy storage using a CO2 -based Electro Thermal Energy Storage (ETES) system. Arpa-E DAYS Annu. Meet., 2021.

[38] Energy Dome | Groundbreaking Long Duration Energy Storage 2021. https://energydome.com/ (accessed November 2, 2021).

[39] Astolfi M, Rizzi D, Macchi E, Spadacini C. A Novel Energy Storage System Based on Carbon Dioxide Unique Thermodynamic Properties. Proc ASME Turbo Expo 2021;4. https://doi.org/10.1115/GT2021-59487.

[40] Zotter G, Hermeling W, Sanz W. Thermodynamic Analysis of a Novel Cryogenic Rankine Cycle for Wind Energy Storage. Proc ASME Turbo Expo 2013;3:41–50. https://doi.org/10.1115/GT2012-68180.

[41] Anderson BN. Modular Solar Systems for 24/7 Scalable, Flexible, Affordable Electricity. ASME 2017 Power Conf. Jt. With ICOPE-17 collocated with ASME 2017 11th Int. Conf. Energy Sustain. ASME 2017 15th Int. Conf. Fuel Cell Sci. Eng. Technol. ASME 2017 Nucl. Fo, vol. 2, Charlotte, North Carolina, USA: American Society of Mechanical Engineers Digital Collection; 2017, p. V002T09A002. https://doi.org/10.1115/POWER-ICOPE2017-3155.

[42] Moriarty K. Prospectus 1414 DEGREES 2018. http://1414degrees.com.au/wp-content/uploads/2018/12/1414Degrees-Limited-Replacement-Prospectus-14D.pdf (accessed November 7, 2021).

[43] Parham J, Vrettos P, Levinson N. Commercialisation of ultra-high temperature energy storage applications: the 1414 Degrees approach. Ultra-High Temp Therm Energy Storage, Transf Convers 2021:331–46. https://doi.org/10.1016/B978-0-12-819955-8.00013-2.

[44] Dewis D. PTT's Thermal Energy Storage (TES) Application Utilizes the Power Block Comprising Proprietary Turbo-machinery and PCHE Technology . 2021.

[45] Howes J. Concept and development of a pumped heat electricity storage device. Proc IEEE 2012;100:493–503. https://doi.org/10.1109/JPROC.2011.2174529.

[46] Laughlin RB. Pumped thermal grid storage with heat exchange. J Renew Sustain Energy 2017;9:044103. https://doi.org/10.1063/1.4994054.

[47] SwRI demonstrates small-scale pumped heat energy storage system | Southwest Research Institute n.d. https://www.swri.org/press-release/swri-demonstrates-small-scale-pumped-heat-energy-storage-system?utm_source=LinkedIn&utm_medium=SM&utm_campaign=Energy-Storage-PR (accessed October 11, 2022).

[48] The GridScale technology explained | Stiesdal n.d. https://www.stiesdal.com/storage/the-gridscale-technology-explained/ (accessed October 31, 2021).

[49] Toshiba, Marubeni launch rock-based thermal energy storage tech pilot – pv magazine International n.d. https://www.pv-magazine.com/2022/11/23/toshiba-marubeni-develop-rock-based-energy-storage-tech-pilot/?fbclid=IwAR0_yfM44bhO9QirLgIRLxfNaPp1pPTkF5YI96TicHjvUaMxyNUkJfZurR0 (accessed December 5, 2022).

[50] STOLECT - Clean Electricity Storage n.d. https://www.stolect.com/en/ (accessed December 5, 2022).

[51] Schneider G, Maier H, Häcker J, Siegele S. Electricity Storage With a Solid Bed High Temperature Thermal Energy Storage System (HTTES) - A Methodical Approach to Improve the Pumped Thermal Grid Storage Concept. Proc 14th Int Renew Energy Storage Conf 2020 (IRES 2020) 2021;6. https://doi.org/10.2991/AHE.K.210202.005.

[52] WindTP – Wind Driven Thermal Pumping 2021. https://www.wind-tp.com/ (accessed December 6, 2021).

[53] Azelio - Clean power when & where you need it 2021. https://www.azelio.com/ (accessed November 15, 2021).

[54] CCT Energy | Thermal Energy Storage Specialists n.d. https://www.cctenergystorage.com/ (accessed October 18, 2021).

[55] Blain L. "World's first working thermal battery" promises cheap, eco-friendly, grid-scalable energy storage.

New Atlas 2019. https://newatlas.com/cct-silicon-energy-battery-thermal-energy-storage/59098/ (accessed September 30, 2021).

[56] TECHNOLOGY - TEXEL. Texel Energy Storage n.d. https://www.texeles.com/technology/ (accessed October 7, 2021).

[57] Herrmann U. Projects Energy Storage: FH Aachen. Solar-Institut Jülich n.d. https://www.fh-aachen.de/en/research/solar-institute-juelich/focus-areas/projects-energy-storage (accessed September 5, 2021).

[58] multiTESS Plant in Jülich | FH Aachen n.d. https://www.fh-aachen.de/en/research/institutes/sij/research-projects/multitess-plant-in-juelich (accessed March 16, 2023).

[59] Ma Z, Hofer D, Tallman J, Zhang R, Lambert MM. Economic Long-Duration Electricity Storage Using Low-Cost Thermal Energy Storage and a High-Efficiency Power Cycle (ENDURING) . Arpa-E DAYS Annu. Meet., Advanced Research Projects Agency - Energy; 2021.

[60] Liquid Salt Combined Cycle. Pint Power 2019. https://www.pintailpower.com/technology/liquid-salt-combined-cycle/ (accessed December 7, 2021).

[61] Liquid Air Combined Cycle. Pint Power 2019. https://www.pintailpower.com/technology/liquid-air-combined-cycle/ (accessed December 7, 2021).

[62] Airthium n.d. https://airthium.com/ (accessed October 11, 2022).

[63] Briggs J. Antora Energy: Solid State Thermal Battery. Arpa-E DAYS Annu. Meet., Advanced Research Projects Agency - Energy; 2021.

[64] NACOMPEX. NACOMPEX 2021. https://feredox.de/ (accessed October 11, 2021).

[65] NACOMPEX thermal heating power plant 2019. http://nacompex.com/ (accessed May 30, 2020).

3.3 Appendix 3: Thermal energy storage methods for Carnot Batteries

Thermal energy Storage Methods for Carnot Batteries

White paper of the IEA ES Task 36 Carnot Batteries, Deliverable ST0.4

DI Christoph Rohringer[1], Thomas Riegler M.Sc.[1], Dr. Salvatore Vasta[2]

[1]AEE INTEC (Austria); [2]CNR- ITAE (Italy)

Introduction

The increase in renewable energy requires flexible, cost-effective and efficient electrical storage to compensate for the imbalance between energy supply and demand. The **Carnot Battery** technology is able to **store electrical energy as thermal energy** (heat or cold) when electricity production is higher than demand. When electricity demand is higher than production, the Carnot Battery generates electricity from the stored thermal energy.

> Scientific definition: "A **Carnot battery is a system primarily used to store electric energy**. In a Carnot battery, the electric energy (input) is used to establish a temperature difference between two environments, namely the low temperature (LT) and high temperature (HT) reservoirs. In this way, the storage is charged, and the **electric energy is stored as thermal exergy**. As the heat flows against the thermal gradient, work is spent to charge the storage. In the discharge phase, the thermal exergy is discharged by allowing the heat flowing from the HT to the LT reservoir. The heat flow powers a heat engine (HE) which converts it into work and discharges the residual heat into the LT reservoir. In this way, a fraction of the electric input is recovered.", [1]

In the recent past, Carnot Battery technology has experienced rapid development and international attention through the **IEA ES Task 36 Carnot Batteries**. This technology for the storage of electrical energy shows a lower efficiency compared to other electrical storage systems, e.g. pumped storage power plants and electrochemical batteries, but due to the low-cost thermal storage units and the scalability up to **GWh storage capacity**, it has the potential to be an economically attractive option. Developments range from kWh to several hundred MWh Carnot Batteries, with the degree of development extending from concepts to experiments and pilot plants to commercial plants [1],[2]. The basic working principle is depicted in Figure 49 and highlights the importance of thermal storage as the heart of every Carnot Battery.

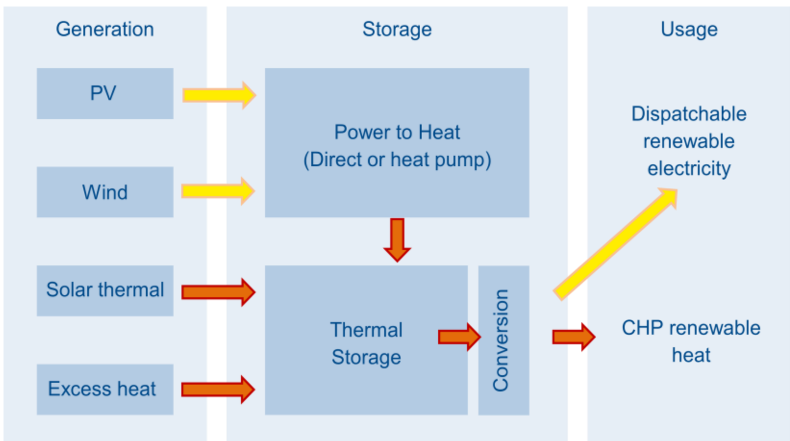


Figure 49: Basic working principle of a Carnot Battery, divided into the three sections Generation, Storage and Usage. Yellow arrows indicate electrical energy, red arrows thermal energy (heat or cold). Source: AEE INTEC.

Thermal Storage Principles and Materials

In practice, the process described above can be realized with different storage and energy conversion technologies. The thermal storage units (HT and LT) could be physical tanks filled with gas, liquid, solids or phase-change materials. Alternatively, one of the two storages could be absent, and its role could be taken over by the environment. The absorbed specific work increases with the temperature difference between the HT and LT storages for a fixed amount of charged thermal exergy. Similarly, the recovered specific work decreases as the temperature difference between the storages is reduced. However, additional heat sources and heat sinks can be used to reduce or increase the operating temperature differences during charging or discharging (i.e., they act as additional sources of thermal exergy) [1].

The **thermal energy storage (TES) is a key component** of every Carnot Battery system. It is located between the power-to-heat and heat-to-power systems, so its discharging and charging operations must be adapted to these systems for optimal operation. In the following sections, various TES technologies are discussed in the context of Carnot Batteries [3], [4]. A detailed description of the main types of thermal storage technologies can be found in [5], [6], whereas they can be divided into three groups based on their physical working principle:

Sensible heat storage uses a **change in material temperature** to store thermal energy. The material temperature changes inevitably during charging and discharging, resulting in higher losses at higher temperature differences to the ambient.

Latent heat storage utilizes the **melting or evaporation heat** of certain materials to store thermal energy. During phase change, the material temperature changes negligibly, resulting in lower overall temperatures compared to sensible storage at the same energy intake. (see Figure 50) Additionally, by properly selecting the material to phase change at the desired mean operation temperature, the material temperature does not change and provides a constant level during charge and discharge.

Thermochemical heat storage stores heat as a **thermochemical potential** between two components. The major upside to this storage principle is that virtually no storage losses occur as soon as the two reactants are separated. If combined again (e.g. during ab- or adsorption) the thermal energy can be released at the desired time.

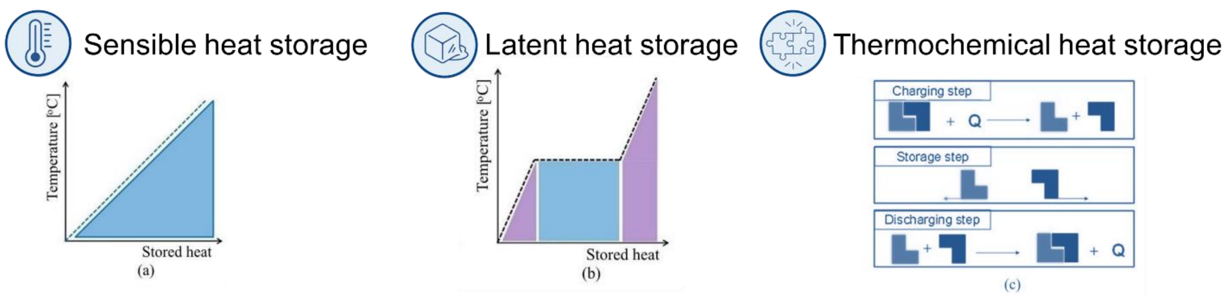


Figure 50: Methods of thermal energy storage: (a) sensible heat; (b) latent heat; (c) thermo-chemical, based on [4].

To be able to compare different thermal storage types and materials, they are characterised by a set of parameters that can also be used to give an average indication for the three storage principals, see Table 25.

Table 25: Typical parameters of TES systems, based on [5].

TES System	Capacity (kWh/t)	Power (MW)	Efficiency (%)	Storage Period	Cost (€/kWh)
Sensible (hot water)	10–50	0.001 – 10.0	50–90	days/months	0.1–10
Phase-change material (PCM)	50–150	0.001 – 1.0	75–90	hours/months	10–50
Chemical reactions	120–250	0.01 – 1.0	75–100	hours/days	8–100

Capacity defines the energy stored in the system and depends on the storage process, the medium, and the size of the system;

Power defines how fast the energy stored in the system can be discharged (and charged);

Efficiency is the ratio of the energy provided, to the energy needed to charge the storage system. It accounts for the energy loss during the storage period and the charging/discharging cycle;

Storage period defines how long the energy is stored and lasts hours to months (i.e., hours, days, weeks, and months for seasonal storage);

(Dis)charge time defines how much time is needed to charge/discharge the system;

Cost refers to either capacity (€/kWh) or power (€/kW) of the storage system and depends on the capital and operation costs of the storage equipment and its lifetime (i.e., the number of cycles).

The following section will look at the three storage principles in detail, discussing what benefits and drawbacks they have and what materials are suitable for the deployment of Carnot Batteries as highlighted by selected examples from the IEA ES Task 36.

Storage Materials for Carnot Batteries

Sensible

In sensible TES (STES) systems, heat is stored or dissipated by raising or lowering the temperature. STES systems use the heat capacity of the storage material to store energy, and the material is always in a single phase. This is usually either the solid or liquid phase due to much higher volumetric energy densities than gases. The most common example of STES with a liquid medium is water, while with a solid medium, it could be rock. Both have the advantage of being **cheap, abundantly available and non-toxic storage materials**. The specific heat capacity of water is about four times that of rock material. However, water requires high pressure to reach temperatures above 100 °C, while rock material can easily reach temperatures of 700 °C, limited only by the strain the material can withstand without being damaged by changing its phase. A detailed list of the different materials can be found in several papers published on this topic, e.g. in [4].

The efficiency of STES highly depends on the insulation quality and thermal bridges caused by the construction, as an increase in stored energy always results in increasing storage temperature (or decreasing if cold is stored instead of heat) and therefore **increased heat losses**. However, investigations on the dynamic behaviour (details e.g. in [7]) of the fixed bed showed that the energy density and the overall Carnot Battery efficiency are less dependent on thermal losses than on the performance of the compressor and expander. [8] Due to the **comparatively low storage capacity of STES**, the volume sizes are large and thus require a large space. However, the low cost of STES is an attractive advantage (see Table 25)[1]. For sensible heat storage, the **cyclic thermal stress** on the materials is a major challenge which can lead to high pressure losses and embrittlement.

In order to minimize exergetic losses during energy conversion from electricity to heat and vice versa, the temperature profiles of the deployed conversion technologies and thermal storage need to match during charge and discharge. Since sensible storage changes its temperature when taking in thermal energy, **conversion technologies with similarly changing temperature profiles** are desired. The most common process with such a profile is the so-called **Joule-Brayton cycle**, with the classic gas turbine or CO_2 heat pumps as one example. In [2], detailed descriptions of storage materials for Carnot Batteries with Brayton cycles are available.

Sensible storage technologies that have been developed separately, but whose use is proposed for Carnot Batteries can be found in [2]. In addition to water and the materials listed in [4], also aluminium pebbles or aluminium metal foam, thermal oil and other hydrocarbons as well as molten salt are used as sensible storage materials in literature and also in real applications.

Table 26: Further storage technologies for Carnot battery applications [2]

Company, System	TES Type (Temperature Limit)	Thermal Capacity	State
EnergyNest	High temperature concrete modules (up to 380 °C)	Scalable to hundreds of MWh	Pilot plant, preparing commercial project
Storworks power, BolderBloc	High temperature concrete modules (up to 600 °C)	from 30 MWh	200 kWh demo, construction of 10 MWh
Kraftblock	High temperature concrete granules (up to 1300 °C)	Scalable	Pilot industrial applications
Magaldi Green Energy	Silica sand fluidized bed (up to 1000 °C)	5 to 100 MWh	full size demonstrator
Dürr & Kraftanlagen	Ceramic blocks with gas heat exchange	MWh to GWh	Demonstrator as CB
Carboclean	Ceramic blocks with direct heating (above 1000 °C)	up to 1 GWh	Laboratory proof of concept
Joule Hive (Electrified Thermal Solutions)	Ceramic firebricks (up to 1700 °C)	n.a.	n.a.
BrenmillerEnergy	Rock bed	6–750 MWh	Pilot applications
Lumenion	Steel rods (up to 650 °C)	up to 500 MWh	Pilot applications

One real scale example for sensible based Carnot Batteries is the **ETES:Base System** deployed by **Siemens Gamesa** in Germany. It is a sensible rock storage charged with high temperature air flow (direct resistance heating, matching temperature profile for the sensible storage, up to 750 °C storage temperature). The system contains around **1.000 t of volcanic rocks** and can store about **130 MWh thermal energy** for about a week depending on ambient conditions. The conversion back to electricity is carried out by an off-the-self steam turbine which can dispatch up to **30 MWh electrical energy** using the full storage capacity. The storage capacity did not significantly change with time and an increasing number of charging and discharging cycles, showcasing the durability of the chosen storage material over several cycles.

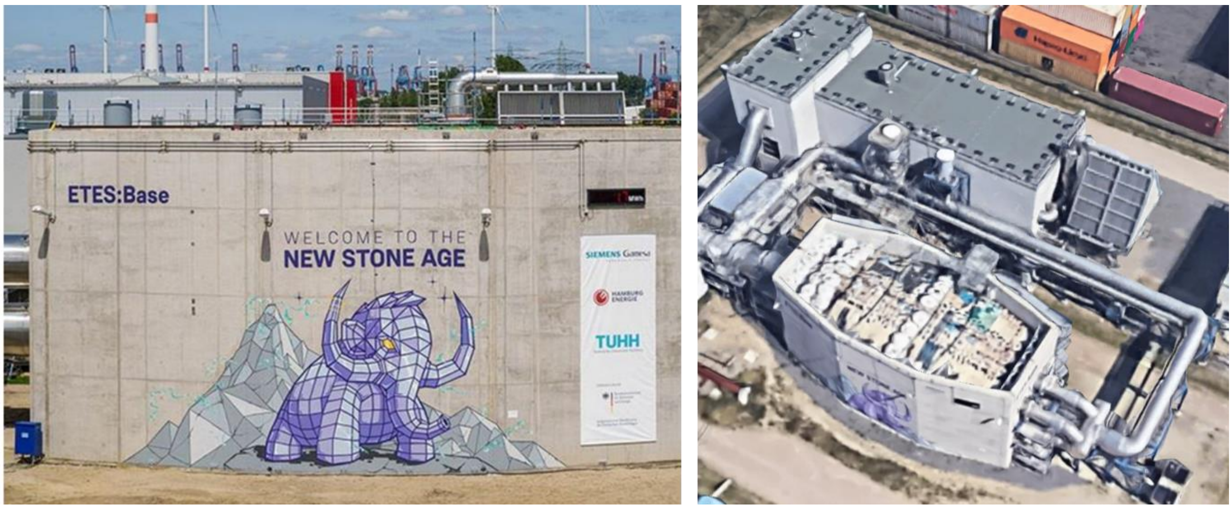


Figure 51: ETES: Base System built by Siemens Games in cooperation with TU Hamburg and Hamburg Energie in 2019, source: IEA ES Task 36 Fact-sheets (left) and Google Maps (right).

Latent

Latent TES (LTES) uses the phase change respectively the melting or evaporation energy of materials for storage charging and discharging, usually with an added portion of sensible thermal energy storage (PCM – Phase change material). For most applications, the solid-liquid phase change is utilized in order to avoid the large volume change associated with evaporation or damage to the PCM. The energy released or taken in during the phase change is called latent heat. The phase transitions take place at **approximately constant temperatures**. This has an advantageous effect on temperature stabilization and thus heat transfer. LTES is advantageous in specific heat capacity compared to STES but requires a much higher cost (see Table 25). Prototypes that provide LTES in Carnot Batteries can be found for example in [9], melting ice and [10], molten salt, however, there are a **variety of phase change materials** available covering a wide range of phase change temperatures to be deployed for different uses.

Figure 52 showcases the distribution of different phase change materials over temperature levels and material classes (with Eutectic materials being mixtures between two components that do not separate during phase change) as well as their specific advantages and disadvantages.

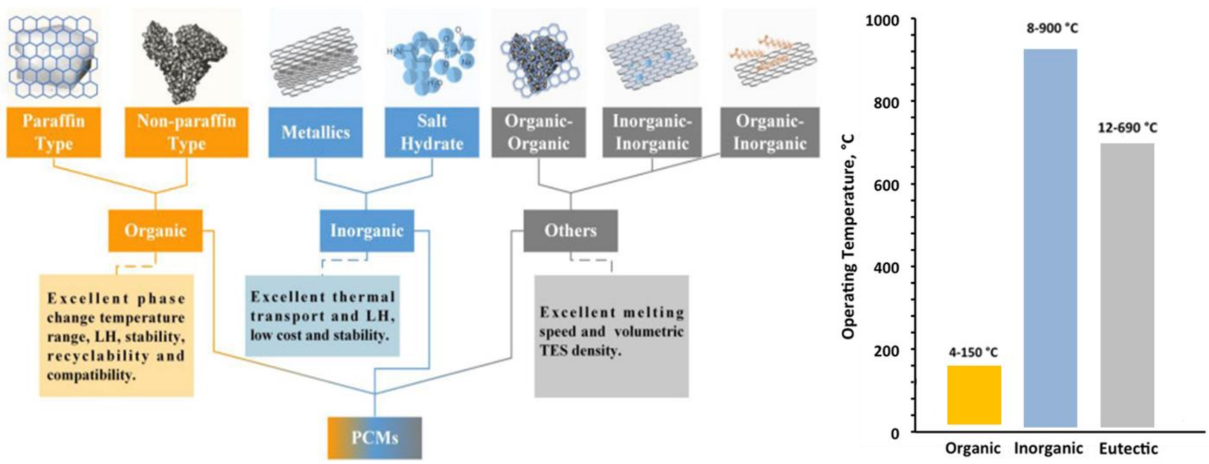


Figure 52: Different classes of phase change material and their advantages and disadvantages for thermal energy storage, as well as the respective temperature ranges for operation, based on [1], [11], [12].

In order to minimize exergetic losses, again matching temperature profiles for charging and discharging should be targeted. Therefore, especially **Rankine cycles** are well matching to phase change materials, providing **constant temperatures throughout heat transfer**, one simple example of those being a steam turbine.

MAN Energy Solutions is currently developing and marketing a Carnot Battery system called MAN ETES, containing not only sensible storage (pressurized hot water for heat storage at 150 °C max) but also a latent storage system based on ice (cold storage) as well as a trans critical CO2 heat pump. The ice storage allows for very space-efficient storage of the cold generated during charge by the heat pump and utilized during discharge for the expansion. MAN is planning also to use heat and cold not only for electricity storage and conversion but also for combined heat/cold and power applications, using the assets to their maximum and increasing the efficiency of the overall system instead of focusing only on electrical storage efficiency. The system is therefore not only an electrical battery but also an efficient tool for sector coupling. The proposed system should be able to store about 150 MWh of heat and 110 MWh of cold.

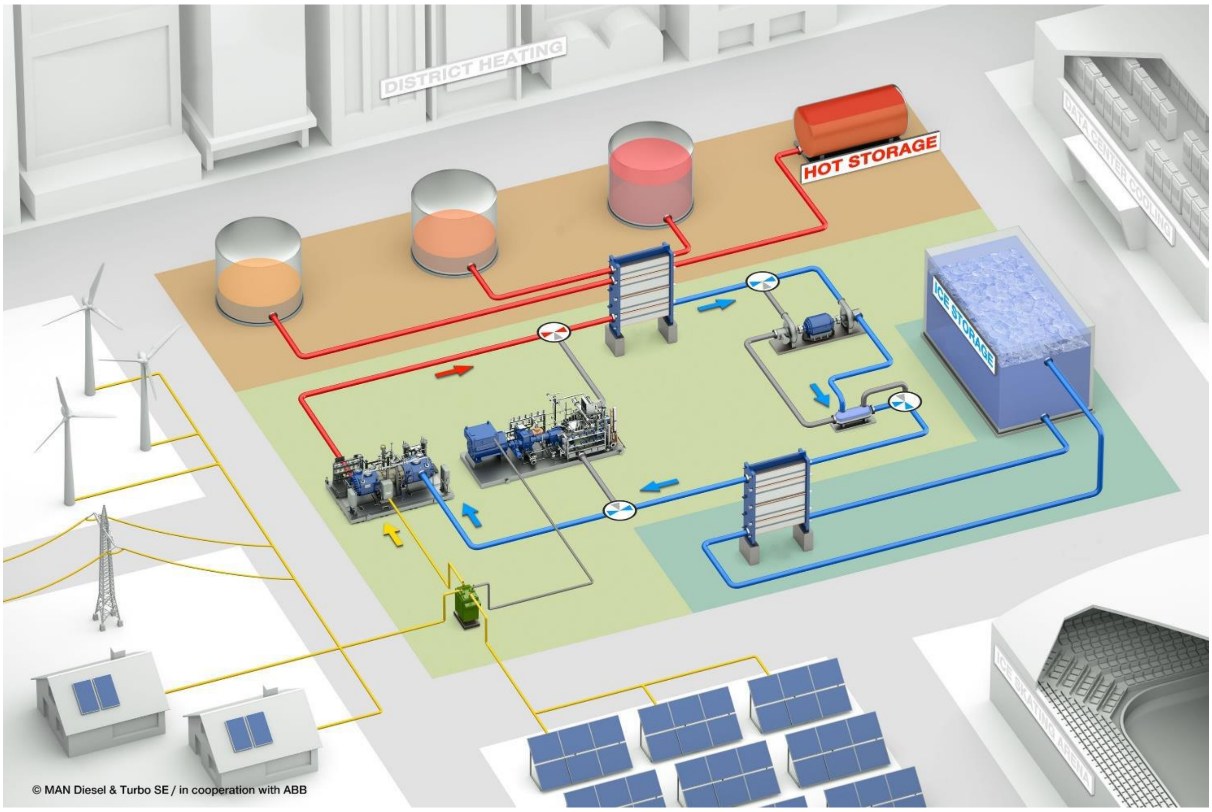


Figure 53: Schematic of the MAN ETES System by MAN Energy Solutions, based on [13].

Thermochemical

Thermochemical TES (TCES) use a **thermochemical potential** to store heat. Usually, that means the chemical or physical potential **between two components (reactants)** that are able to interact with each other. In most cases, these reactions (chemical reaction, absorption, adsorption) are exothermic and provide thermal energy, resulting in a controlled discharge of the storage. In order to charge the storage after use, thermal energy is used to separate the two reactants and store them individually, preventing a reaction until the desired time of discharge. The main benefit of this type of heat storage is, that virtually **no storage losses** occur during the storage period since the majority of the heat is provided by the reaction. Additionally, since exothermic reactions can provide a significant amount of energy per unit of volume or mass, these storage systems have **higher volumetric or gravimetric energy densities** than sensible storage systems. However, most of the reactants are usually more costly than simple sensible or latent storage materials, resulting in CTES systems being the most **expensive** of the three thermal storage principles on average. Depending on reactants and their thermal stability as well as the ideal reaction temperature, CTES can be realised for a range of temperature levels. Sorption based systems (absorption, adsorption) are more suited for low-grade heat while non-sorption-based reactants are utilized for higher temperature applications. An overview of common thermochemical reactant pairs and their associated temperature levels is provided in Figure 54.

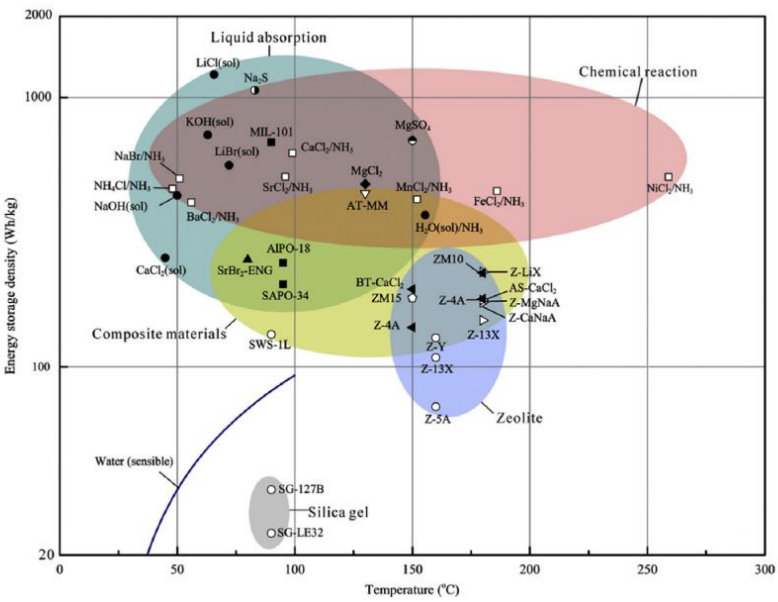


Figure 54: Overview of common thermochemical reactant pairs, their associated temperature levels and energy storage densities. Based on [14].

Similarly, to latent thermal energy storage, the reactions are usually controlled to take place at **approximately constant temperatures**, favouring Rankine cycles for charging and discharging as described above. During the Task 36 duration, no TCES based Carnot Batteries were identified within the industry sector and only individual ones at the prototype stage in the research sector. However, the mitigation of storage losses and high volumetric and gravimetric energy densities coupled with a broad range of temperature levels suggest a high implementation potential for TCES systems in future Carnot Battery concepts. This is highlighted by recent research projects developing TCES material for Carnot Battery applications specifically. [15]

Control Strategies and System Integration

In order to harness the desired qualities of the three different thermal energy storage principles described above, not only the proper selection of the storage material is essential. A final system that satisfies technical, economical and ecologic goals needs to combine suitable materials **with fitting control strategies and an optimized system integration**.

The fit between storage material and conversion technologies has been discussed in the previous chapters, highlighting the importance of **reducing exergetic losses** during charge and discharge by selecting matching temperature profiles of storage and conversion technologies. Additionally, the heat transfer in and out of the storage is critical to system performance as well, raising technical and economic questions for **heat exchanger design** and storage segmentation. An important aspect to consider for heat exchanger design is if the storage should be geared more towards **energy storage** (total amount of stored energy should be maximised) or **power storage** (charge and discharge power should be maximised). Some thermal storage options are able to start up with only marginal auxiliary energy, enabling Carnot Batteries to have **black-start capabilities**. In the wake of increasing electrification and more volatile renewables in the grid, this property can provide crucial services to energy systems, extending the use cases for Carnot Batteries.

The electricity-to-electricity efficiency of classic Carnot Batteries (called "roundtrip" efficiency) is always lower than 1. However, if generated heat and cold can be used in addition to electricity, those can be taken into account for calculating an **overall efficiency**, which can exceed the purely electrical roundtrip efficiency significantly. From a technical perspective, such a system can be realized by utilizing **combined heat/cold and power processes** at charge or discharge with a connection to heat and cold customers (district heating and cooling, industry etc.). Additionally, Carnot Batteries don't need to rely on electrical charging only but can also be **charged with thermal energy directly**, increasing their roundtrip efficiency.

Summary

Carnot Batteries provide a **GWh scale solution for electricity storage** that will be needed to stabilize future renewable based energy systems and electricity grids. They can store volatile renewable electricity at peak production times as thermal energy and convert it back to dispatchable electricity at a later time, matching production and demand.

In differentiation to e.g. Li-Ion batteries, the concept of storing thermal energy instead of electrical energy allows for the usage of **cheaper, abundantly available** and most importantly **easily scalable thermal storage materials** and concepts. Carnot Batteries can draw from the three main principles of thermal energy storage, sensible, latent and thermochemical and the associated materials with their respective benefits and drawbacks. In the individual chapters, a short overview is given of these three principles combined with examples of materials and systems from Task 36.

Selecting the **optimal material for the task** and combining it with proper control strategies, suitable conversion technologies and smart system integration will remain one of the major challenges for the development of Carnot Batteries. However, the multitude of thermal storage options will provide **sufficient design possibilities** to develop optimal thermal storage for a variety of Carnot Battery applications.

Acknowledgements

The Austrian authors thank the Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie for providing the funds to participate in the Task 36 Carnot Batteries under grant agreement Nr. BW000020015. Besides preparing this white paper, the task participation will allow to transfer knowledge to the Austrian research and industry sector while positioning Austria as attractive research and business location internationally.

Literature

[1] O. Dumont, G. F. Frate, A. Pillai, S. Lecompte, M. De paepe, and V. Lemort, 'Carnot Battery technology: A state-of-the-art review', *Journal of Energy Storage*, vol. 32, p. 101756, Dec. 2020, doi: 10.1016/j.est.2020.101756.

[2] V. Novotny, V. Basta, P. Smola, and J. Spale, 'Review of Carnot Battery Technology Commercial Development', *Energies*, vol. 15, no. 2, p. 647, Jan. 2022, doi: 10.3390/en15020647.

[3] S. M. Hasnain, 'Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques', *Energy Conversion and Management*, vol. 39, no. 11, pp. 1127–1138, Aug. 1998, doi: 10.1016/S0196-8904(98)00025-9.

[4] I. Sarbu and C. Sebarchievici, 'A Comprehensive Review of Thermal Energy Storage', *Sustainability*, vol. 10, no. 1, p. 191, Jan. 2018, doi: 10.3390/su10010191.

[5] A. Hauer, 'Storage Technology Issues and Opportunities, International Low-Carbon Energy Technology Platform. In Proceedings of the Strategic and Cross-Cutting Workshop "Energy Storage—Issues and Opportunities", Paris, France, 15 February'. 2011.

[6] G. Alva, L. Liu, X. Huang, and G. Fang, 'Thermal energy storage materials and systems for solar energy applications', *Renewable and Sustainable Energy Reviews*, vol. 68, pp. 693–706, Feb. 2017, doi: 10.1016/j.rser.2016.10.021.

[7] F. Ni and HS. Caram, 'Analysis of pumped heat electricity storage process using ex ponential matrix solutions, Appl. Therm. Eng. 84 (2015) 34–44'. 2015. [Online]. Available: https://doi.org/10. 1016/j.applthermaleng.2015.02.046.

[8] J. D. McTigue and A. J. White, 'Parametric studies and optimisation of pumped thermal electricity storage, Appl. Energy 137 800–811'. 2015. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0306261914008423?via%3Dihub

[9] 'Active Energy systems'. https://www.activeenergysystems.com/ (accessed Mar. 11, 2022).

[10] 'Malta'. https://x.company/projects/malta/ (accessed Mar. 11, 2022).

[11] L. Qiu, Y. Ouyang, Y. Feng, and X. Zhang, 'Review on micro/nano phase change materials for solar thermal applications', *Renewable Energy*, vol. 140, pp. 513–538, Sep. 2019, doi: 10.1016/j.renene.2019.03.088.

[12] T. Maha, 'Recent frontiers in solar energy storage via nanoparticles enhanced phase change materials: Succinct review on basics, applications, and their environmental aspects'. 2021.

[13] R. Decorvet, 'Sector coupling the essential key to decarbonisation, 2nd International Workshop on Carnot Batteries'. Sep. 2020.

[14] D. Aydin, S. P. Casey, and S. Riffat, 'The latest advancements on thermochemical heat storage systems', *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 356–367, Jan. 2015, doi: 10.1016/j.rser.2014.08.054.

[15] M. Zamengo, K. Yoshida, and J. Morikawa, 'Numerical evaluation of a Carnot Battery system comprising a chemical heat storage/pump and a Brayton cycle', *Journal of Energy Storage*, vol. 41, p. 102955, Sep. 2021, doi: 10.1016/j.est.2021.102955.

3.4 Appendix 4: Fact-Sheets on Systems and Components

Version: 05.03.2021

Factsheet - BATRENEW

BATRENEW is a Carnot battery develop in the thermodynamics laboratory of the university of Liège in Belgium. It was founded by the "Proof Of Concept" found and by the lab. The Carnot battery prototype consists in a reversible heat pump/organic Rankine cycle (same machine for heat and electricity production). Thermal integration is considered (waste heat around 75°C) in order to achieve a roundtrip efficiency of 100% with a heat pump coefficient of performance of 14. The technical feasibility has been proven but more tests and optimization are still going on. A detailed description of the first tests can be found here: http://hdl.handle.net/2268/250924

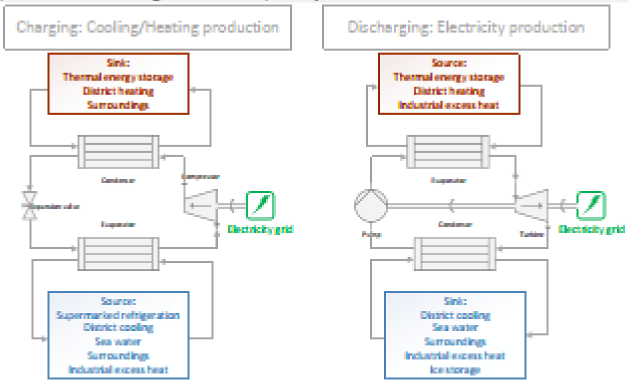
System Type	Reversible organic Rankine cycle / heat pump cycle
Maturity / TRL	Pilot laboratory / technical feasibility proven
Institution / Contact person	Uliège / olivier.dumont@ulg.ac.be
Where	Thermodynamics laboratory / Uliège / Belgium
Power to Heat Unit	
Type	Vapor compression cycle heat pump
Working fluid	R1233ZD(E)
P_{nom} [MW]	0.001-0.002
Temperature level [°C]	75°/95°
Pressure level [bars]	1.2/8.2
Thermal Energy Storage System	
Type	Sensible
Medium of storage	Water
Storage Capacity [MWh]	0.01
Temperature level [°C]	95°C
Cycle frequency [N°/day]; [N°/week]; ...	1 per day
Heat Powered Cycle	
Type	Reversible organic Rankine cycle
Working fluid	R1233ZD(E)
P_{nom} [MW]	0.001-0.002
Temperature level [°C]	95°C / 15°C
Pressure level [bars]	1.2/8.2
Other characteristics	
Efficiency [%]	Actual 75% / expected after optimization 100%
Storage capacity costs (SCC) [€/Kwh]	300
Storage power costs (SPC) [€/kW]	1500-3000
Dimensions (LxW; LxD; V) [m²] or [m³]	4X2X2
Thermal integration	Waste heat is recovered at the evaporator of the heat pump
Year	Running since 2019
Scientific papers	DOI: 10.1016/j.est.2020.101756 https://orbi.uliege.be/handle/2268/251552

Technology Collaboration Programme
by iea

FactSheet - Component/System/Concept ‚X'	
The first proof-of-concept rock bed thermal energy storage at the Technical University of Denmark (DTU) is based on a horizontal air flow. The system can store heat at up to 600 °C and has been tested with different rock sizes and internal configurations. The main purpose of the system was to gain experience in the area and test the efficiency of a horizontal flow rock bed. System described in https://doi.org/10.1016/j.apenergy.2019.113345	
Performance and dimensions	
'Battery' Type	High temperature thermal energy storage
Storage type	Rock bed, unpressurized based on diabase
Dimensions (LxW; LxD; V) [m²] or [m³]	1.5 m³
Temperature range [°C]	Ambient up to 600 °C
Cycle frequency [N°/day]; [N°/week];…	1 / day
Storage capacity [MWh]	0.45 MWh
P_{nom} [MW]	0.03 thermal
TRL ?	4
Storage Density	300 kWh/ m³
Type of Applications	Power-to-Power, Heat-to-Heat
Efficiency	65-80
Indication of Costs:	
Storage capacity costs (SCC) [€/Kwh]	Proof of concept
Storage power costs (SPC) [€/kW]	N/A
…	
Auxiliary Components:	
Electric Heaters (x2)	Leister LE 10 000 HT (15 kW)
Fans (x1)	Becker SV 300/1 (upto 200 m³/h)
Data Acquisition System	NI 9203 DAQ with K-type thermocouples

FactSheet - Component/System/Concept ‚X'	
At the Technical University of Denmark (DTU), we have built a pilot scale rock bed thermal energy storage that is able to store heat at up to 650 °C. The system represents a 1:14 scale of a full size rock bed storage that has been envisioned for grid level applications in Denmark. The main purpose was to prove the concept and verify models and larger scale design concepts.	
Performance and dimensions	
'Battery' Type	High temperature thermal energy storage
Storage type	Rock bed, unpressurized based on diabase
Dimensions (LxW; LxD; V) [m²] or [m³]	3.2 m³
Temperature range [°C]	Ambient up to 650 °C
Cycle frequency [N°/day]; [N°/week];...	1 / day
Storage capacity [MWh]	1 MWh
P_{nom} [MW]	0.05 thermal
TRL ?	5
Storage Density	312 kWh/ m³
Type of Applications	Power-to-Power, Heat-to-Heat
Efficiency	85-95 ?
Indication of Costs:	
Storage capacity costs (SCC) [€/Kwh]	Proof of concept
Storage power costs (SPC) [€/kW]	N/A
...	
Auxiliary Components:	
Electric Heaters (x3)	Leister LE 10 000 HT (15 kW)
Fans (x2)	Becker SV 300/1 (upto 325 m³/h)
Data Acquisition System	NI 9203 DAQ with 38 K-type thermocouples

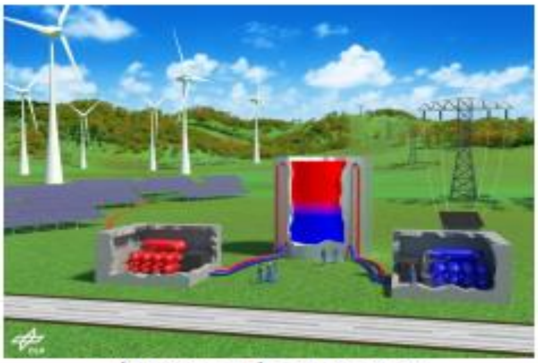
FactSheet – CO_2 carnot battery with water storage
The system is based on a Rankine cycle using CO_2 as the working medium and water as storage medium. It operates as follows: **CHARGING** the storage is done by converting electricity into thermal energy using a heat pump (Reverse Rankine cycle). **STORING** the thermal energy is done in the district heating network using existing pit storages. **DISCHARGING** the storage is done by converting thermal energy to electricity using an ORC (Rankine cycle). **ROUND TRIP EFFICIENCY OF 40-60 %**. The efficiency from electricity to heat and back electricity. Dependent on design and complexity.



System Type	Rankine Cycle Carnot Battery
Power to Heat Unit	
P_{nom} [MW]	**1 MW (200kW – 10 MW)**
Dimensions (LxW; LxD; V) [m²] or [m³]	**N/A**
Temperature level [°C]	-4 to 135 C
Pressure levels	31-190 bar
Working fluid	CO_2
Thermal Energy Storage System	
Type	**Vessel or pit**
Medium of storage	**Water**
Storage Capacity [MWh]	50-500 MWh thermal storage
Temperature level [°C]	20 to 130 C
Cycle frequency [N°/day]; [N°/week];...	1 pr day (Flexible)
Heat Powered Cycle	
P_{nom} [MW]	0.5 MW
Temperature level [°C]	4 to 135 C
Working fluid	CO_2
Other characteristics ...	
TRL	3
Efficiency [%]	50
Storage capacity costs (SCC) [€/Kwh]	N/A
Storage power costs (SPC) [€/kW]	N/A

FactSheet – CHESTER system in the management of electricity and heat

An innovative energy management and storage system based on power-to-heat-to-power concept to utilise the excess renewable generation, avoid curtailment of renewables and increase flexibility of the
power grid, taking advantage of the synergies between electric and thermal networks. The technology is based on the principle of a Pumped Thermal Energy Storage applying the Rankine cycles in charging cycle (High Temperature Heat Pump) and discharging cycle (Organic Rankine Cycle turbine). These are activated with electricity using latent and sensible heat storage systems, defined as Compressed Heat Energy Storage (CHEST).



https://www.chester-project.eu

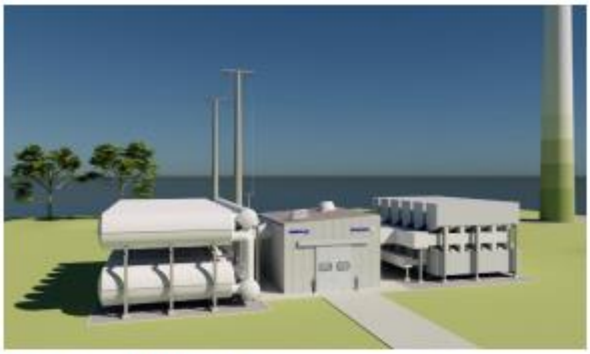
Existing electricity markets	
Spot electricity market, selling according to price 'arbitrage'	Suitable only with sufficient price fluctuation and wide price range
Regulation markets (secondary, tertiary reserve	Improve the business case only when treated an addition to the spot market
Alternative to hydrogen storage	Competitive performance despite lower investment costs of hydrogen storage (electrolyser-pressurised storage-fuel cells)
'Island' mode for self-sufficiency	More financial y viable than battery solution, however, requires an excessive storage volume
Heating markets	
Low temperature heat networks	Selling excessive heat to DH
RES support / integration	Heat storage and maximalising heat production form RES (solar, wind)
Future energy markets	
Frequency regulation	Potentially achievable for the improved technology
System restoration (i.e. black start)	Limited by the technology regulation speed
Aggregated services in 'minigrid'	Balancing and distributing DH heat and electricity among multiple network actors (energy community)
Alternative to large pump-hydro	Mobile alternative to high capacity (5-100 MW) electricity storages
Investment deferral to transmission / distribution lines integrated with wind farms	Avoiding curtailment of RES production, investment in new power line and transmission losses
Alternative to battery storage (acid-lead)	Successful only in the highly electrified DH system (electric heat pumps and electric boilers, EV)
Aggregated services in industrial with focus on heat exchange	Successful economy for the energy storage replaced by different heat level suppliers and consumers
Initial / Future investment and O&M cost	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 764042

Technology Collaboration Programme
by iea

Roundtrip efficiency [%]	40-60
Heat pump (HP) capacity costs [€/kW$_{th}$]	350 / 250
ORC (ORC) capacity cost [€/kW$_{el}$]	1000 / 850
Storage (HT-TES) energy costs [€/kWh]	100 / 50
O&M of HP, ORC , HT-TES [€/MWh$_{el}$]	5 , 10 , 5 / 5 , 10 , 5
Lifetime	
Heat pump (HP)	25
ORC (ORC)	25
Storage (HT-TES)	40

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 764042

FactSheet – enolcon OPTES Battery	
The enolcon Optimized Pumped Thermal Energy Storage (OPTES) Battery is a Carnot Battery based on the Brayton cycle. It uses standard turbomachinery with Nitrogen or Argon as a working fluid to store electricity as thermal energy in a hot and a cold storage. The stored thermal energy can then be used in a reversed process to generate electricity again.	
System Type	Brayton Cycle Carnot Battery
Power to Heat Unit and Heat to Power Unit	
Type	Turbomachinery, Compander
P_{nom} [MW_e]	7,6 (Power to Heat) 3,7 (Heat to Power), alternatively 7,4
Temperature Level [°C]	-50 up to 510 (approx.)
Pressure Level [bar(a)]	1,47 up to 4,66 (with Nitrogen)
Working fluid	Nitrogen (or Argon)
Thermal Energy Storage System	
Type	STORASOL HTTES (hot side) and CTES (cold side)
Medium of storage	packed bed, e.g. silica sand or iron silica sand
Storage Capacity [MWh_{th}]	~150 ("Hot" Storage) ~100 ("Cold" Storage)
Temperature level [°C]	67 up to 507 ("Hot" Storage) -45 up to 267 ("Cold" Storage)
Cycle frequency [N°/day]	1 per day (8 hours charging time, 8 hours discharging time)
Overall System	
TRL	4 (Overall System) 9 (Power to Heat and Heat to Power Units) 8 (Thermal Energy Storage)
Efficiency	up to 43 - 46% (Power to Power, status March 2020)
Storage Capacity [MWh_e]	80 - 120 (Can be increased by increasing the thermal storage capacity. Power and Capacity are decoupled.)
Storage capacity costs (SCC) [€/kWh_e]	~160 - 220
Storage power costs (SPC) [€/kW_e]	~ 2100 - 2600
Dimensions (LxWxH) [m]	~ 55 x 38 x 10 (whole plant, incl. Power Cycles and TES)

FactSheet – STORASOL High Temperature Thermal Energy Storage	
The STORASOL High Temperature Thermal Energy Storage (HTTES) System is a scalable packed bed thermal energy storage unit. The storage material (e.g. sand) is arranged in multiple layers, allowing for a compact design, high thermal outputs and very low pressure losses. A reference storage unit in the MW-level was built within the ORCTES project in 2015 (see picture) and is used to constantly produce electricity from an intermittent energy source via an ORC.	
System Type	Packed bed high temperature energy storage
Performance and dimensions	
P_{nom} [MW_{th}]	customizable 1,8 in ORCTES
Storage capacity [MWh_{th}]	customizable 1,6 in ORCTES (ambient to 600 °C)
Efficiency [%]	>90 (Heat-to-Heat)
Pressure loss [mbar]	<10
Heat Loss during storage	~ 1 K/h when fully charged, depending on applied insulation thickness
Dimensions (LxWxH) [m]	depends on capacity 4,4 x 1,6 x 1,6 + piping on top (per unit, ORCTES)
Temperature level [°C]	ambient to 600 °C (ORCTES) successful tests for temperatures of >1000 °C
Cycle frequency	adaptable from 1/h to 1/d
TRL	9 for Heat-to-Heat application
Storage Density	Depending on the storage material, different options available For silica sand (used in ORCTES): ~200 kWh/m³ at ΔT=500K
Possible Applications	Power-to-Power, e.g. in enolcon OPTES Battery, Power-to-Heat, Heat-to-Heat
Indication of Costs	
Storage capacity costs (SCC) [€/kWh]	< 10, at ΔT=500K, per 8 – 12 MWh-unit
Storage power costs (SPC) [€/kW]	~ 10

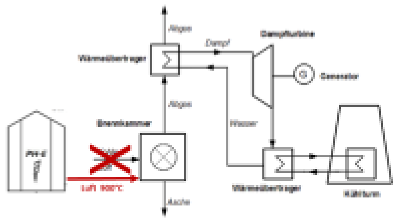
FactSheet – enolcon OPTES-GT Battery	
The enolcon **OPTES-GT Battery** is a Carnot Battery based on the open Brayton-cycle with HTTES-Storage as heat recovery of the heat leaving the turbine during discharging. The concept includes two high temperature heat storages: the pressurized very high temperature heat storage (P-VHTTES) and the HTTES. For charging the heat of the HTTES will be used for air preheating and then the very high air temperatures of more than 1050°C will be achieved by an electrical heater under ambient pressure. Green H_2 is possible as option and back-up.	
System Type	Open Brayton-Cycle Carnot Battery
Power to Heat Unit and Heat to Power Unit	
Type	Charging: electrical air heater Discharging: Turbomachinery, Gas turbine
P_{nom} [MW_e]	2.35 (Power to Heat) 1.15 (Heat to Power)
Temperature Level [°C]	Ambient up to 1050 (approx.)
Pressure Level [bar(a)]	Ambient up to 3.33
Working fluid	Ambient air
Thermal Energy Storage System	
Type	STORASOL P-VHTTES (pressurized) and HTTES (heat recovery)
Medium of storage	Packed bed, e.g. silica sand
Storage Capacity [MWh_{th}]	~40 ("Hot" Storage) ~30 ("Cold" Storage)
Temperature level [°C]	150 up to 1050 ("pressurized" Storage) 20 up to 770 ("heat recovery" Storage)
Cycle frequency [N°/day]	1 per day (5.5 hours charging time, 5.5 hours discharging time)
Overall System	
TRL	6 (Overall System) 9 (Power to Heat and Heat to Power Units) 8 (Thermal Energy Storage)
Efficiency	up to 47-49 % (Power to Power, status March 2023)
Storage Capacity [MWh_e]	12.9 (Increasing possible by increasing thermal storage capacity.)
Storage capacity costs (SCC) [€/KWh_e]	~75 – 87
Storage power costs (SPC) [€/kW_e]	~ 480 - 560
Dimensions (L x W x H) [m]	~ 23 x 20 x 6 (whole plant, incl. Power Cycles and TES)

Technology Collaboration Programme
by iea

FactSheet - **HiTES**	
High Temperature Energy Storage (or shortly HiTES) is a power-to-heat-to-power technology based on three technologies that are state-of-the-art: • Pebble-Heater technology • Radial Gas Turbine • Electric Resistive Heating. It could be used for secondary load control, shaving the disturbances due to intermittent renewable generation, overcoming longer periods without wind and solar generation, or for island operation.	
System Type	Brayton Cycle
Power to Heat Unit	
P_{nom} [MW]	Between 5 MW (10 h) and 25 MW (2 h)
Dimensions (LxW; LxD; V) [m²] or [m³]	150 m³
Temperature level [°C]	1100 °C
Pressure (abs)	1 - 7
Heat transport fluid	Air
Thermal Energy Storage System	
Type	Sensible heat
Medium of storage	Alumina pebbles
Storage Capacity [MWh]	50 MWh (may be doubled /100MWh or tripled /150 MWh)
Temperature level [°C]	1100 °C
Cycle frequency [N°/day]; [N°/week]	2/day till several/week
Heat Powered Cycle	
P_{nom} [MW]	2 MW_{el}
Temperature level [°C]	980 °C
Pressure (abs)	7,3
Circulation gas	Air/Humid air
Other characteristics	
TRL	TRL 5 (System) TRL 8 (Components)
Efficiency [%]	40 % (TRL 5) 55 % (TRL 3)
Storage capacity costs (SCC) [€/Kwh]	250 €/kWh_{el}
Storage power costs (SPC) [€/kW]	4000 €/kW_{el}

FactSheet – **HiTES-Steam**

The **Steam** version of **High Temperature Energy Storage** (or shortly HiTES) is a power-to-heat-to-power technology with drastically reduced investment cost, due to the usage of decommissioned coal power plants with steam turbine.
In order to further reduce costs, the storage temperature is limited to 950 °C, which enables the usage of considerably cheaper storage material.
It could be used for tertiary load control / tertiary reserve, with power plants in the range 10 MW_{el} up to 400 $MW_{e}l$. Here are data for 17 MW_{el}, as an example.

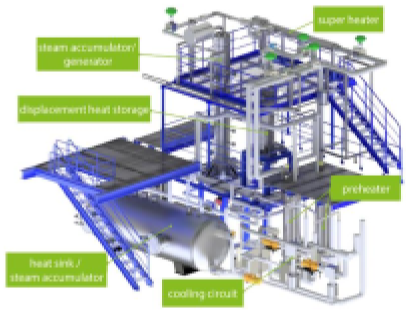


System Type	Clausius-Rankine-Cycle
Power to Heat Unit	
P_{nom} [MW]	Between 3 MW and 15 MW
Dimensions (LxW; LxD; V) [m²] or [m³]	4 x (Ø4 m x 8 m) → 400 m³
Temperature level [°C]	950 °C
Pressure (abs)	1
Heat transport fluid	Air
Thermal Energy Storage System	
Type	Sensible heat
Medium of storage	Natural volcanic stones
Storage Capacity [MWh]	50 MWh (in 4 vessels)
Temperature level [°C]	950 °C
Cycle frequency [N°/day]; [N°/week];	2/day till several/week
Heat Powered Cycle	
P_{nom} [MW]	17 MW_{el}
Temperature level [°C]	900 °C (Steam boiler entry)
Pressure (abs)	1
Circulation gas	Air
Other characteristics	
TRL	TRL 5 (System) TRL 8 (Components)
Efficiency [%]	34 %
Storage capacity costs (SCC) [€/KWh]	50 €/kWh_{el}
Storage power costs (SPC) [€/kW]	50 €/kW_{el}

FactSheet – THERSA Thermal Energy Storage Test Facility

THERESA is a Thermal Energy Storage Test Facility located at HSZG. It represents thermal power plant processes and is feasible for experimental investigations where steam or saturated water under high pressure and temperature conditions is required. THERESA supports research on several topics:

- components of CARNOT-Batteries (Rankine cycle)
- integration of thermal energy storages in existing power plant systems
- experimental investigation under realistic parameters and workloads
- analysis of dynamic operating behaviour
- dynamic simulations and experimental validation
- development of automation concepts for flexible operating of combined heat and power systems with thermal storages
- safety related investigations of plant components for industries
- intelligent gateways (digital twin)



System Type	Thermal Energy Storage Test Facility
Features	
media	water-steam-loop
max. temperature	350 °C
max. pressure	160 bar
max. steady flow rates	0.1 kg/s steam [0.5 kg/s feed-water]
saturated water cycle	up to 275 °C and 60 bar
steam cycle	up to 350 °C and 60 bar
universal interface	• freely selectable steam parameters (wet / saturated / superheated steam) • for analysis of integration of thermal energy storages in thermal processes with different nominal power • for analysis and tests of specific components (heat engines or heat pumps)
Power Plant Sub-Systems	
preheater 1	160 bar, 175 °C, 370 kW_{th}, steam operated
preheater 2	60 bar, 265 °C, 255 kW_{th}, steam operated
steam generator	160 bar, 350 °C, 200 kW_{el}, electrically operated
super heater	60 bar, 350 °C, 60 kW_{el}, electrically operated
heat sink	pressureless, 95 °C, 17 m³
cooling circuit	16 bar, 105 °C, 780 kW_{th}
Heat Storage	
displacement steam storage with mixing preheater	power 240 kW_{th}, capacity 60 kWh_{th}, 60 bar, 275 °C, 0,6 m³
steam accumulator / generator	power 180 kW_{th}, capacity 100 kWh_{th}, 160 bar, 350 °C, 1 m³

Technology Collaboration Programme
by iea

FactSheet – TMS-Battery	
The TMS-Battery developed at HSZG together with Spilling Technologies, is a Carnot-Battery based on the Rankine cycle. The TMS-Battery works with low- and high-pressure steam storages driven by the TMS Dual-Mode Steam Piston Engine. The engine is able to work either in compressor or expander mode. The TMS-Battery is characterized by a carbon-free core process operating with steam and combinable with a couple of heat storages. The TMS-Battery provides Power-to-Heat / Heat-to-Power / Power-to-Power and Heat-to-Heat operation modes. This enables extremely flexible energy storage for sector coupling of Power, Heat and Mobility.	
System Type	Rankine Cycle Carnot Battery
Combined Power-to-Heat and Heat-to-Power Unit	
Type	three-cylinder dual-mode piston engine
P_{nom} [MW]	up to 2.5
Dimensions (LxW; LxD; V) [m²] or [m³]	~10 m³
Temperature Level [°C]	~110…280
Pressure Level [bar(a)]	~2…55
Thermal Energy Storage System	
Type	steam storages
Medium of storage	Steam
Storage Capacity [MWh]	scalable (kWh…MWh)
Storage Density [kWh/m³]	50…200
Temperature Level [°C]	100…280
Cycle frequency [N°/day]; [N°/week]	1…100/day; flexible short-term Storage (Minutes-Hours-Days)
Other characteristics …	
TRL	3
Efficiency (electrical) [%]	~35%-60% (power-to-heat-to-power)
Efficiency (total) [%]	~90% (combined heat and power, sector coupling)
Storage capacity costs (SCC) [€/Kwh]	~100
Storage power costs (SPC) [€/kW]	~800
Life time	very high life time: >>20 Years (up to 50 Years)
Cycles per Life time	>20.000
Coupleable Sectors	Power, Heat, Mobility
raw materials: resources / availability	very high / very good (water and steel)
environmental sustainability	very good, no interaction, materially closed cycle
Disposal	completely recyclable

Technology Collaboration Programme
by iea

FactSheet – CHESTER system	
The CHESTER system is a Carnot Battery based on Rankine cycles. A lab scale prototype is being developed, built and experimentally tested at DLR in the frame-work of the EU H2020 project CHESTER. In charging mode, surplus electricity is transformed to high temperature heat by a heat pump. The heat is stored in a high temperature thermal energy storage system, which is a cascade of latent heat storage and a sensible heat storage. In times of demand, the stored thermal energy can be converted back into electrical energy by an organic Rankine cycle and fed into the grid. The CHESTER system is designed to be coupled with a renewable district heating supply to act as a bidirectional energy hub between the district heating and the electrical grid.	
System Type	Rankine Cycle Carnot Battery
Maturity	Laboratory pilot system
Who / where	EU-H2020 consortium / at DLR Stuttgart (DE)
Power to Heat Unit	
Type	Vapor compression cycle heat pump
Working fluid	R1233zd(E)
P_{nom} [MW_e]	0,01 MW_e heat pump with piston compressor
Temperature level [°C] (cond. / evap.)	≈ 138 / 80
Pressure level [bar] (cond. / evap.)	≈ 22 / 7
Thermal Energy Storage System	
Type	Cascade of a latent heat storage (LHTES) and two tank sensible heat storage system with a hot and a cold tank (SHTES).
Medium of storage (LHTES / SHTES)	Eutectic of KNO_3 – $LiNO_3$ / Water (Melting temperature 133 °C)
Storage Capacity [MWh] (LHTES / SHTES)	≈ 0,16 / 0,22
Temperature level [°C] (LHTES / SHTES)	≈ 128…138 / 40…135
Cycle frequency [N°/day]; [N°/week];	1 per day
Heat Powered Cycle	
Type	Organic Rankine Cycle
Working fluid	DR-12
P_{nom} [MWe]	0,01
Temperature level [°C] (evap. / cond.)	≈ 128 / 40
Pressure level [bar] (evap. / cond.)	≈ 24 / 3
Other characteristics …	
Efficiency [%]	n.a.
Storage capacity costs (SCC) [€/Kwh]	n.a.
Storage power costs (SPC) [€/kW]	n.a.
Dimensions (LXWxH) [m]	≈ 10 x 5 x 4 (whole test rig, incl. infrastructure)

Technology Collaboration Programme
by iea

Version: 05.03.2021

Factsheet - ETES

The Electric Thermal Energy Storage (ETES) uses a packed bed of crushed rocks as the storage material. The packed bed stores the heat, which will be provided by an electrical resistance heater. In total, the heat can be stored for a week with no significant losses and subsequently discharged in times of demand. The technology can be used as a stand-alone solution (ETES:Base), to give existing power plants a new purpose by converting them into an emission-free energy storage system (ETES:Switch) or to provide additional flexibility to power plants or industrial processes (ETES:Add). As part of the publicly funded (BMWi) project *Future Energy Solutions (FES)*, a demonstrator with a capacity of 130 MWh was inaugurated in Hamburg in 2019 as proof of system.

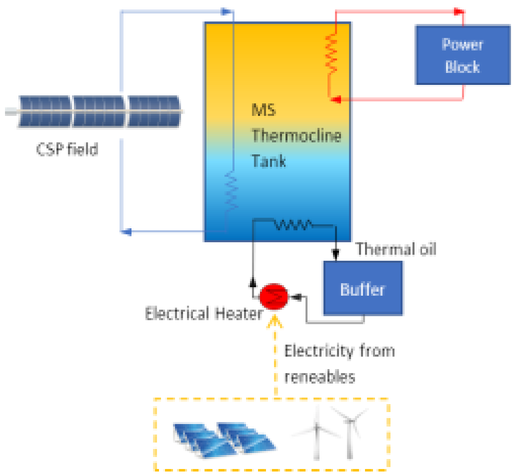
System Type	Rankine Cycle Carnot Battery
Maturity / TRL	Pilot Plant Operation / TRL 6
Institution / Contact person	Siemens Gamesa Renewable Energy
Where	Anywhere [Hamburg]
Power to Heat Unit	
Type	**Electrical Resistance Heater**
Working fluid	**Air**
P_{nom} [MW]	5 – 1000 [up to 5.4]
Temperature level [°C]	Up to 750
Pressure level	+/- 200 mbarg
Thermal Energy Storage System	
Type	**Sensible heat storage using packed bed**
Medium of storage	**Volcanic rock**
Storage Capacity [MWh]	50 – 5000 [130]
Temperature level [°C]	Up to 1000 [750]
Cycle frequency	Daily - Weekly
Heat Powered Cycle	
Type	Rankine cycle
Working fluid	Water/steam
P_{nom} [MWel]	2 - 500 [1.5]
Temperature level [°C]	Up to 600 [480]
Pressure level [bar] (evap. / cond.)	Up to 270 / 0 [65 / 0.12]
Other characteristics ...	
Efficiency	Up to 45% [up to 22.9%]
Storage capacity costs (SCC) [€/Kwh]	highly dependent on power to capacity ratio
Storage power costs (SPC) [€/kW]	highly dependent on power to capacity ratio
Dimensions (LxW; LxD; V) [m²] or [m³]	[35m x 45m]

Technology Collaboration Programme
by iea

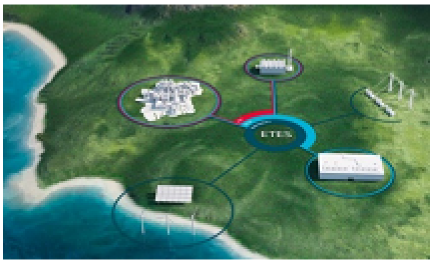
Version: 21.06.2021

Factsheet - ENEA Hybrid TES

The Hybridized Storage CSP/PV system is a thermocline tank heated and powered both by CSP and PV plant. The demo plant, funded by the Italian Electric System Research Programme (2022-2024 Implementation Plan), is being realized at the ENEA Casaccia Research Center. The system is aimed at storing solar energy in a cost-effective solution to produce renewable electricity/heat on demand. The energy storage consists of a thermocline molten salt system, which can be charged flexibly both with electricity from PV or other renewable energy sources, and with thermal energy from a CSP plant, coupled to a power block.



System Type	Hybrid system CSP/PV
Maturity / TRL	Prototype/TRL5
Institution / Contact person	ENEA /V. Russo (ENEA)
Where	C.R. ENEA Casaccia
Thermal Energy Storage System	
Type	Molten salt thermocline system
Storage medium	Molten salt ternary mixture ($NaNO_3/KNO_3/Ca(NO_3)_2$)
Heat transfer fluid	Oil
Temperature level(s)/range [°C]	200-380°C
Cycle frequency [N°/day]; [N°/week];	1 per day
Storage Capacity [MWh]	0.2 MWh
P_{nom} [MW]	-
Storage density [kWh/m³K]	0.87
Efficiency [%]	-
Heat Powered Cycle	
Type	Organic Rankine Cycle (theoretical matching)
Working fluid	Oil
P_{nom} [MWe]	-
Temperature level [°C] (evap. / cond.)	250/50
Pressure level [bar] (evap. / cond.)	22
Other characteristics ...	
Storage capacity costs (SCC) [€/Kwh]	-
Storage power costs (SPC) [€/kW]	-
Dimensions (LxW; LxD; V) [m²] or [m³]	2X1.28 (2.58 m³)
Type of Applications	Solar Heat for Industrial Processes/Power generation

MAN ETES Full System		
Electro-thermal energy storage (ETES) systems couple sectors by connecting the electrical and thermal energy domains. MAN's tri-generation energy system provides heating, cooling and electricity on demand to a variety of industries. This scalable and carbon-neutral solution provides energy and power balancing by absorbing large amounts of surplus or off-peak electricity and/or thermal energy. This is then fed back as needed.		
System Type	ORC Carnot Battery	
Maturity / TRL of system	5 (Power-to-Power) to 7 (Heat-to-Power)	
Institution / Contact person	MAN Energy Solutions / Martin Adams	
Where	Zurich, Switzerland	
Power to Heat Unit		
Type	MAN ETES Heat Pump Unit (HPU / ETES Light)	
Working fluid	CO_2	
P_{nom} [MW_e]	15-50+	
Temperature level [°C]	-5 to 180	
TRL	≥ 8	
Thermal Energy Storage System		
Type	Hot - sensible	Cold - latent
Medium of storage	H_20	H_20
Storage Capacity [MWh_{th}]	200-1000+	130-670+
Temperature level [°C]	20-160	0
Cycle frequency [N°/day]	Up to 2	
TRL	≥ 7	
Heat Powered Cycle		
Type	Rankine Cycle	
Working fluid	CO_2	
P_{nom} [MW_e]	5-25 * *Smaller if thermal service is integrated	
Temperature level [°C]	+5 to 180	
TRL	5-6	
Other characteristics ...		
Efficiency [%]	>45% (Power-to-Power)	
Storage capacity costs (SCC) [€/Kwh]	<110 for commercial application /plant	
Storage power costs (SPC) [€/kW]	<700 for commercial application / plant	
Dimensions (LxWxH) [m]	60 x 50 x 15 for mid-size reference plant	
Design cold temperature level [°C]	0°C nominal (min -20°C to max +20°C)	

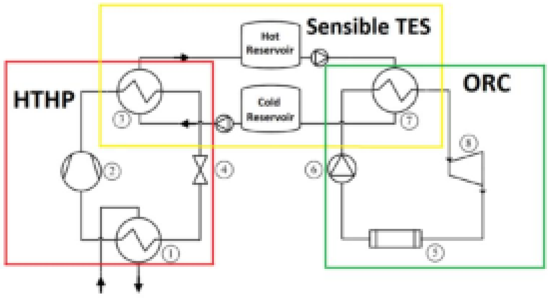
Version: 05.03.2021

Factsheet – Isentropic - System

This demonstrator was designed and built by Isentropic Ltd, UK. The system has been tested at under-design conditions by using nitrogen as working fluid with the pressure ratio of 1:4.

System Type	Brayton cycle carnot battery
Maturity / TRL	First grid scale demonstrator
Institution / Contact person	Durham University, Prof. Tony Roskilly
Where	UK
Power to Heat Unit	
Type	Vapor compression cycle heat pump
Working fluid	Argon, Nitrogen
P_{nom} [MW]	0.15
Temperature level [°C]	500 °C heat storage, −160 °C cold storage
Thermal Energy Storage System	
Type	Sensible heat packed bed storage with layer control, two storage tanks (hot and cold)
Medium of storage	Magnetite
Storage Capacity [MWh]	0.6
Temperature level [°C]	500 °C heat storage, −160 °C cold storage
Cycle frequency [N°/day]; [N°/week]; ...	1 cycle per 8 hours
Heat Powered Cycle	
Type	Brayton cycle
Working fluid	Argon, Nitrogen
P_{nom} [MW]	0.15
Temperature level [°C]	500 °C heat storage, −160 °C cold storage
Other characteristics ...	
Efficiency [%]	42~72%
Storage capacity costs (SCC) [€/Kwh]	0.08-0.15
Storage power costs (SPC) [€/kW]	
Dimensions (LxW; LxD; V) [m²] or [m³]	Hot store 11 m², cold store 18 m²

V1
31.08.2021

Factsheet – Sensible Thermal Energy Storage	
Sensible Thermal Energy storage, heat is stored or released by increasing or decreasing the temperature of the TES material (solid or liquid phase)[1–5]	
System Type	Sensible storage + Brayton cycle/ Steam turbine
Maturity / TRL	STES at demonstration-commercial stage; STES in Carnott Battery prototype stage
Institution / Contact person	Isentropic Ltd; Malta Inc; Siemens Gamesa (1.5 MW/30 MWh);
Where	Prototype in NewCastle University (150kW/600kWh), Siemens Gamesa pilot plant (130 MWh)
Thermal Energy Storage System	
Type	Sensible Thermal Energy Storage System
Storage medium	Solid states/Molten salt, Glycol-water mixture
Heat transfer fluid	Air or inert gas
Temperature level(s)/range [°C]	-160 to 1300 °C (solid state); packed bed system from -160-500 °C [2]; 265-565 °C (molten salts); glycol/water-molten salt system -60-565 °C [2]
Cycle frequency [N°/day]; [N°/week]; …	day-months (solid state)/ hours - days (molten salts)
Storage Capacity [MWh]	10kWh - GWh (solid state)/ MWh - 5GWh (molten salt)
P_{nom} [MW]	10kWh – GWh (solid state)/ MWh - 5GWh(molten salt)
Storage density [kWh/m³]	0.4-0.9 kWh/ m³·K (solid state)/ 70-200 kWh/m³ (molten salt)
Efficiency [%]	50-98%
…	
Other characteristics …	
Storage capacity costs (SCC) [€/Kwh]	0.1-10 $/kWh
Storage power costs (SPC) [€/kW]	3400-4500 $/kW
Dimensions (LxW; LxD; V) [m²] or [m³]	
Type of Applications	Electricity generation, thermal storage services, peak shifting
…	

References
[1] J. Cho, H. Shin, J. Cho, B. Choi, C. Roh, B. Lee, G. Lee, H.-S. Ra, Y.-J. Baik, Electric-Thermal Energy Storage for Large-Scale Renewables and a Supercritical Carbon Dioxide Power Cycle, (n.d.). https://doi.org/10.1063/5.0029014.
[2] J. Mctigue, "Carnot Batteries" for electricity storage, Yale Bluepr. Webinars. (2019).
[3] IRENA, Innovation Outlook: Thermal Energy Storage, 2020. https://www.irena.org/publications/2020/Nov/Innovation-outlook-Thermal-energy-storage.

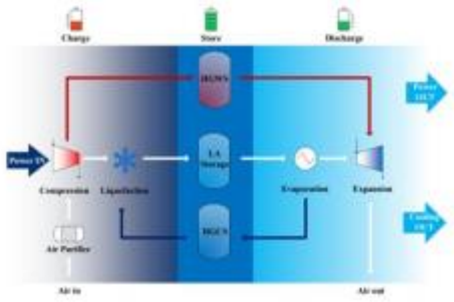
Technology Collaboration Programme
by iea

DLR | Federal Ministry for Economic Affairs and Energy | energy storage | TASK 36 CARNOT BATTERIES

V1
31.08.2021

Factsheet – Liquid air energy storage

LAES is a promising and novel long-term energy storage technology, suitable for mid- to large-scale applications. The system operates in three phases: charging, storage and discharging. During the charging phase, (excess electricity at off-peak hours), electrical work is used to clean, compress and liquefy the air. Then, the liquid air is stored at a low pressure in insulated tanks. During the discharging phase, when needed, expanding the liquid air into a gas which generates electricity[1–5].

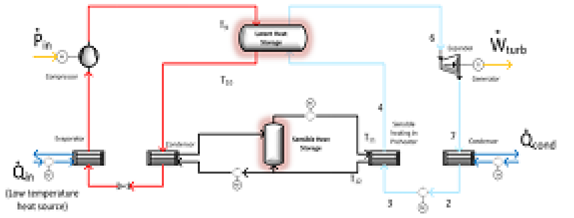


System Type	Air-based Brayton cycle
Maturity / TRL	Demonstrator/Commercial
Institution / Contact person	HighviewPower
Where	University of Birmingham pilot plant (350kW); Pilsworth Grid Scale demonstrator (5MW); Northern Vermont (50MW); Carrington UK (50 MW)
Thermal Energy Storage System	
Type	LAES with two tanks or packed bed
Storage medium	Liquid air or liquid nitrogen/packed bed (rocks) or two tanks (methane and propane[6])
Heat transfer fluid	Liquid air or liquid nitrogen
Temperature level(s)/range [°C]	-196 °C to ambient
Cycle frequency [N°/day]; [N°/week]; ...	Storage from 4 -8 hours to 4 weeks
Storage Capacity [MWh]	up to GWh
P_{nom} [MW]	up to GW[7]
Storage density [kWh/m³]	60-120 [8]
Efficiency [%]	50-70[9]
Life span	30-40 years
Other characteristics ...	
Storage capacity costs (SCC) [£/Kwh]	£200-500/kWh
Storage power costs (SPC) [£/kW]	£850-2500/kW[10] [2]
Dimensions (LxW; LxD; V) [m²] or [m³]	20MW/120MWh: 0.5 acres 200MW/1.2 GWh: 4 acres
Type of Applications	Grid-scale storage applications; frequency regulation services in SpinGen mode (~30 seconds response time), Black start

References
[1] Home | Highview Power, (n.d.). https://highviewpower.com/ (accessed July 23, 2021).
[2] IRENA, Innovation Outlook: Thermal Energy Storage, 2020. https://www.irena.org/publications/2020/Nov/Innovation-outlook-Thermal-energy-storage.
[3] A. V Olympios, J.D. McTigue, P. Farres-Antunez, A. Tafone, A. Romagnoli, Y. Li, Y. Ding, W.-D. Steinmann, L. Wang, H. Chen, C.N. Markides, Progress and prospects of thermo-mechanical energy storage—a critical review, Prog. Energy. 3 (2021) 022001. https://doi.org/10.1088/2516-1083/abdbba.
[4] O. Dumont, G.F. Frate, A. Pillai, S. Lecompte, M. De paepe, V. Lemort, Carnot battery technology: A state-of-the-art review, J. Energy Storage. 32 (2020). https://doi.org/10.1016/j.est.2020.101756.
[5] Highview Power launches world's first grid-scale liquid air energy storage plant, (2018).
[6] E. Borri, A. Tafone, A. Romagnoli, G. Comodi, A review on liquid air energy storage: History, state of the art and recent developments, Renew. Sustain. Energy Rev. (2021). https://doi.org/10.1016/j.rser.2020.110572.

Technology Collaboration Programme
by iea

V1
31.08.2021

Factsheet –Latent Heat Thermal Energy Storage	
Latent Heat Thermal Energy storage, heat is stored during the phase change of the TES material, normally solid-liquid transition. The material is named as PCM (phase change material) [1–5]	
System Type	Latent Heat storage + Brayton cycle/Rankine cycle
Maturity / TRL	LHTES at demonstration-commercial stage; LHTES in Carnot Battery at prototype stage
Institution / Contact person	Malta Inc; Siemens
Where	
Thermal Energy Storage System	
Type	Latent Heat Thermal Energy Storage System
Storage medium	Molten salt [6], Metallic PCM [7], ice [8], Composite PCMs [3]
Heat transfer fluid	Air or inert gas, glycol/water
Temperature level(s)/range [°C]	Typical max PCM working temperature Ice 0 °C Molten salt 564 °C Metallic 500 °C Composite PCMs 500-800 °C [3]
Cycle frequency [N°/day]; [N°/week]; ...	hours-months hours - days (molten salts)
Storage Capacity [MWh]	MWh-GWh
P_{nom} [MW]	MWh
Storage density [kWh/m³]	50-150 W_{th}h/kg, 30-85 kWh/m³ [3]
Efficiency [%]	50-98%
...	
Other characteristics ...	
Storage capacity costs (SCC) [€/Kwh]	10-50 $/kWh
Storage power costs (SPC) [€/kW]	6000-15000 $/kW
Dimensions (LxW; LxD; V) [m²] or [m³]	
Type of Applications	Electricity generation, time shifting, thermal storage services
...	

References

[1] J. Cho, H. Shin, J. Cho, B. Choi, C. Roh, B. Lee, G. Lee, H.-S. Ra, Y.-J. Baik, Electric-Thermal Energy Storage for Large-Scale Renewables and a Supercritical Carbon Dioxide Power Cycle, (n.d.). https://doi.org/10.1063/5.0029014.

[2] J. Mctigue, "Carnot Batteries" for electricity storage, Yale Bluepr. Webinars. (2019).

[3] IRENA, Innovation Outlook: Thermal Energy Storage, 2020. https://www.irena.org/publications/2020/Nov/Innovation-outlook-Thermal-energy-storage.

[4] A. V Olympios, J.D. McTigue, P. Farres-Antunez, A. Tafone, A. Romagnoli, Y. Li, Y. Ding, W.-D. Steinmann, L. Wang, H. Chen, C.N. Markides, Progress and prospects of thermo-mechanical energy storage—a critical review, Prog. Energy. 3 (2021) 022001. https://doi.org/10.1088/2516-1083/abdbba.

[5] O. Dumont, G.F. Frate, A. Pillai, S. Lecompte, M. De paepe, V. Lemort, Carnot battery technology: A state-of-the-art review, J. Energy Storage. 32 (2020). https://doi.org/10.1016/j.est.2020.101756.

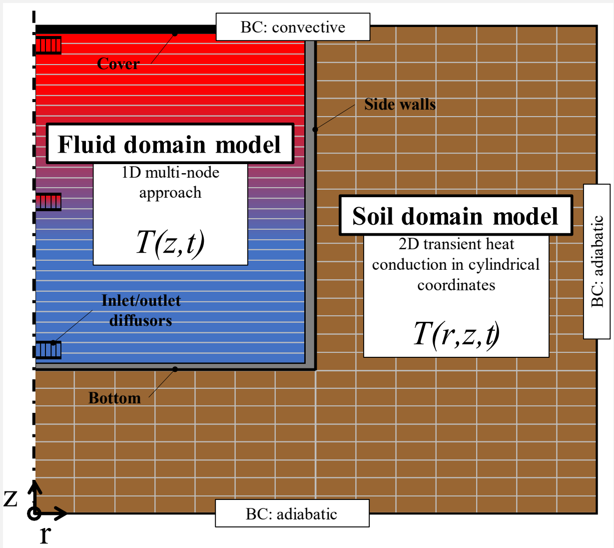
[6] News — Malta Inc., (n.d.). https://www.maltainc.com/news (accessed September 2, 2021).

Technology Collaboration Programme
by iea

3.5 Appendix 5: Factsheets on Modelling and Simulation

IEA Task 36: Model Factsheet

Modelica large-scale underground hot-water pit and tank thermal energy storage model



Details of the model

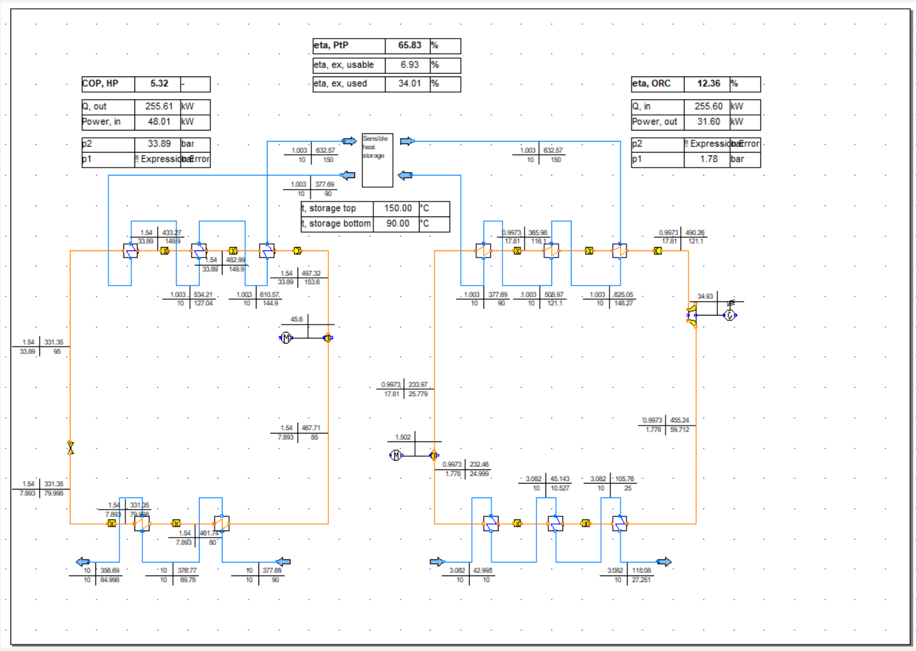
What is the model used for?	(multi-)annual system simulations of local and district energy systems together with other system components; parameter studies; pre-design studies for large-scale TES
Model level (component, system or grid)	component/system
Model scale (scaling, 1D, 2D 3D, multiscale)	2D
(Major) inputs and outputs	**inputs:** inlet mass/volume flow rates, inlet temperatures, ambient temperatures **outputs:** fluid and soil temperatures at different locations, charged/discharged energies, thermal losses (divided into top, side and bottom losses)
Is it static or dynamic?	dynamic
Is it design only or off-design?	
Is the model validated? How?	Yes. The model was validated in a validation case study against real measurement data of a Danish pit storage (Dronninglund; storage volume: 60,000 m³).

Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	No. The model is not tied to a specific system and can be used flexibly in almost any system (e.g., district heating system, P2H applications, Carnot Battery concepts).
Could the model be coupled to a specific system?	Yes (see above).
Does the model use or provide data from/to other models you are using?	Yes. Various heat producers (e.g., solar thermal, heat pumps) and heat consumers (e.g., district heating grids).
Model limitations/simplifications	• Axisymmetric model: o fluid domain: 1-dimensional discretization in axial direction o soil domain: 2-dimensional discretization in axial and radial direction with cylindrical coordinates • For the soil, no moisture transport or groundwater flow is considered • Constant thermophysical properties for fluid and soil are applied
Approximate run time on a stationary PC	For the validation case study (see above and reference Reisenbichler et al., 2021) and for 2 simulation years (pre-heating and validation phase): 2.6 to 5.2 hours. Strongly depending on the number of fluid nodes and the level of detail. For parameter studies and with lower accuracies much lower run times are possible. **Used PC hardware:** virtual machine: Windows Server 2012 R2 (Hyper-V); Intel(R) Xeon(R) CPU E5-2420 v2 @ 2.20GHz (5 logical cores); 32 GB RAM; 300GB HDD; Microsoft Windows 10 Pro (64-bit)
Publications connected to the model	Reisenbichler, Michael, Keith O'Donovan, Carles Ribas Tugores, Wim Van Helden, and Franz Wotawa. "Towards More Efficient Modeling and Simulation of Large-Scale Thermal Energy Storages in Future Local and District Energy Systems [in Press]." In *Proceedings of Building Simulation 2021: 17th Conference of IBPSA*. Bruges, BE: International Building Performance Simulation Association,

	2021. Ochs, Fabian, Abdulrahman Dahash, Alice Tosatto, Michael Reisenbichler, Keith O'Donovan, Geoffroy Gauthier, Christian Kok Skov, and Thomas Schmidt. "Comprehensive Comparison of Different Models for Large-Scale Thermal Energy Storage [in Press]." In *Proceedings of the 14th International Renewable Energy Storage Conference 2021 (IRES 2021)*. Düsseldorf, DE: Atlantis Press, 2021.
Details of the software	
Simulation environment	**Modeling/programming language:** Modelica (Version 3.4) **Simulation environment:** Dymola (Version 2020 (64-bit))
Software license required?	Yes. (only for Dymola)
Used databases or model libraries? Commercial?	Modelica Standard Library (Version 3.2.3), Modelica Buildings Library (Version 6.0.0); (both open-source)
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Yes. Python interfaces, fmi-support for co-simulation, etc.
Why did you choose this software?	High flexibility in modeling process; faster modeling than in other modeling tools (e.g. TRNSYS); very large no. of available (open-source) libraries from different domains (multi-domain modeling)
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	Yes.
To what extent is the model available to IEA partners (use, modify, etc.)?	Has to be defined (open at the moment).
What are the terms for model users (co-authorship, papers to cite, etc.)?	Has to be defined (open at the moment).
Contact person (name and e-mail)	Michael Reisenbichler, m.reisenbichler@aee.at

IEA Task 36: Model Factsheet

Carnot Battery model in the commercial IPSEpro 8.0 simulation environment. The model is used for static heat pump / ORC system simulations. Different cycle configurations can simply be derived by drag-and-drop of components and parameter setting. IPSEpro enables the simulation of other Carnot Battery types and development of tailored component models by means of the integrated Model Development Kit (MDK).



Details of the model

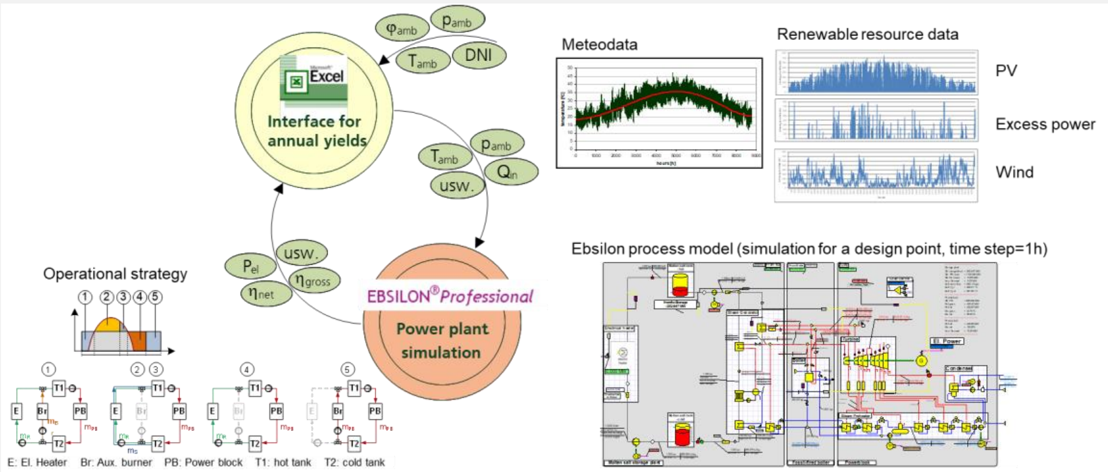
What is the model used for?	Static simulation / parameter variation of different configurations based on heat pump and ORC cycles
Model level (component, system or grid)	Component / system
Model scale (scaling, 1D, 2D 3D, multiscale)	1D
(Major) inputs and outputs	Input and output parameters (such as temperatures and mass flows of heat source/sink and working fluid, transferred heat, power input/output, component specific setting) can easily be adapted depending on the required variations
Is it static or dynamic?	Static (dynamic simulation is possible with the PSDynamics module and will be tested soon)
Is it design only or off-design?	Both possible

Is the model validated? How?	About to be validated with experimental data
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	No, waste heat assumed to be available for the heat pump evaporator
Could the model be coupled to a specific system?	Yes, IPSE offers numerous component models and also allows the programming of tailored components for auxiliary systems
Does the model use or provide data from/to other models you are using?	No
Model limitations/simplifications	Different levels of simplification available for most component models. Assumed set parameters not adapted to pilot plant yet (not validated yet)
Approximate run time on a stationary PC	Approx. 1 s
Publications connected to the model	Weitzer et al.: Organic flash cycles in Rankine-based Carnot Batteries with large storage temperature spreads. In: Energy Conversion and Management, Vol. 255, 115323, 01.03.2022. DOI: https://doi.org/10.1016/j.enconman.2022.11532 Weitzer et al.: Advanced Organic Rankine Cycles for thermally integrated Carnot Batteries. In: Proceedings of the 6th International Seminar on ORC Power Systems, 2021. DOI: https://doi.org/10.14459/2021mp1633100
Details of the software	
Simulation environment	SimTech IPSEpro 8.0
Software license required?	Yes
Used databases or model libraries? Commercial?	Tailored model library (programmed component models) based on commercial model library "Low Temperature Library" by SimTech
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Yes, IPSE can communicate via Excel macros which enables external calling, running, writing and reading by other programs
Why did you choose this software?	Availability of detailed component models, straightforward drag-and-drop creation of thermodynamic cycles, Programming interface to access/adapt code of the models and create tailored component models.
IEA partnership	

Can the provided details be published in the final Task 36 report or in a review article?	Yes
To what extent is the model available to IEA partners (use, modify, etc.)?	Model can be shared among IEA partners on request. Note that an IPSEpro license is required to open and run the model.
What are the terms for model users (co-authorship, papers to cite, etc.)?	Can be defined on request.
Contact person (name and e-mail)	Maximilian Weitzer Maximilian.weitzer@fau.de

IEA Task 36: Model Factsheet

DLR-SF Ebsilon-Excel-Tool for system design, process modeling, performance and annual yield calculation and techno-economic analysis of different types of power plants (thermal storage power plants / Carnot Batteries, solar thermal and coal/gas-fired power plants)



Details of the model

What is the model used for?	Process and system simulation, annual yield calculation and techno-economic analysis of different systems, mainly power plants
Model level (component, system or grid)	System modelling
Model scale (scaling, 1D, 2D 3D, multiscale)	1D
(Major) inputs and outputs	Inputs: technical and economic specifications of components and BOP, meteo data of the site, available load curve of renewable energies, operational strategy, load curve for output Outputs: system annual energy yields, CAPEX, OPEX, LCOE/LCOH, environmental parameters (reduction of CO_2-emissions, CO_2 cost reduction…)

Is it static or dynamic?	Quasi-dynamic (calculations are performed according to the time step selected and terms as start-up energy are included in the model)
Is it design only or off-design?	Both
Is the model validated? How?	Ebsilon is a commercial software and is validated. The described tool here was developed initially for CSP plants and therefore it was validated to real plant data from several projects. The model is validated with the overall power balance of the system and with the design point of the existing plant.
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	With this tool different systems can be coupled
Could the model be coupled to a specific system?	Yes
Does the model use or provide data from/to other models you are using?	This tool consists of an integration of a detailed system model and an evaluation of the obtained values for the development of a techno-economic analysis
Model limitations/simplifications	Specific dynamic effects for start-up and shut-down are simplified.
Approximate run time on a stationary PC	Depending on the profile defined for the operating strategy, the run time can oscillate between 2 minutes and 3 hours for annual simulation. A single load point needs less than 1 sec.
Publications connected to the model	There are several publications with this tool in the field of solar thermal power plant. First publications with the analysis of thermal storage power plants are under development.
Details of the software	
Simulation environment	Ebsilon & Excel/VBA
Software license required?	Ebsilon Professional, Microsoft Excel
Used databases or model libraries? Commercial?	- Database for meto data - Several additional libraries available for Ebsilon as solar library, Ebs Open, …
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	DLR-SF Tool links Ebsilon simulations to an Excel-sheet.

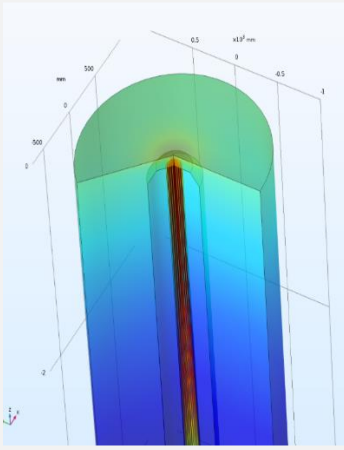
	Tool-coupling is generally possible with Ebsilon. However, so far, we did not use this for this tool.
Why did you choose this software?	Ebsilon offers flexibility to build models with different systems and can be linked with Excel. Additionally, several partners from industry and academia use it and so specific component models etc. can be shared.
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	Yes
To what extent is the model available to IEA partners (use, modify, etc.)?	So far, the tool is exclusively developed and used by DLR-SF (Institute of Solar Research) and cannot be shared.
What are the terms for model users (co-authorship, papers to cite, etc.)?	N/A
Contact person (name and e-mail)	For IEA Task 36: Maria Isabel Roldan Serrano Maria.RoldanSerrano@dlr.de Responsible for this tool in general: Stefano Giuliano stefano.giuliano@dlr.de

IEA Task 36: Model Factsheet	
Steady-state off-design and techno-economic model of Carnot Batteries with thermal integration in different application scenarios.	
Details of the model	
What is the model used for?	Uncertainty Quantification (UQ) and Robust Design Optimization (RDO) of Carnot Batteries, with techno-economic approach (efficiencies and LCOS as metrics)
Model level (component, system or grid)	Component and system for application and scenario based analyses
Model scale (scaling, 1D, 2D 3D, multiscale)	Scaling
(Major) inputs and outputs	Input: design and operational parameters (including economic) Output: exergy efficiencies and LCOS
Is it static or dynamic?	Static
Is it design only or off-design?	Both
Is the model validated? How?	Not yet but should be thanks to experimental results from prototype
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	Possibility to couple it to wide range of heat sources (industrial waste heat, district heating, solar collector, geothermal sources, …) and RES (wind, solar, …)
Could the model be coupled to a specific system?	Yes
Does the model use or provide data from/to other models you are using?	No
Model limitations/simplifications	*Still under development*
Approximate run time on a stationary PC	*Still under development*
Publications connected to the model	*Still under development*
Details of the software	
Simulation environment	Python
Software license required?	No
Used databases or model libraries? Commercial?	CoolProp for thermodynamic properties
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Yes

Why did you choose this software?	Open Source + coupling with RDO frame
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	Yes
To what extent is the model available to IEA partners (use, modify, etc.)?	*Model still under development*
What are the terms for model users (co-authorship, papers to cite, etc.)?	*Model still under development*
Contact person (name and e-mail)	Antoine Laterre (UCLouvain) antoine.laterre@uclouvain.be

IEA Task 36: Model Factsheet

Finite Element Method Model for the transient analysis of charging and discharging phases for TES components and sub-systems. Particularly the Thermal Energy Storage is a thermocline system with molten salt as heat storage medium. The charging phase has been analyzed considering two heat sources: electric heaters and heat exchanger.

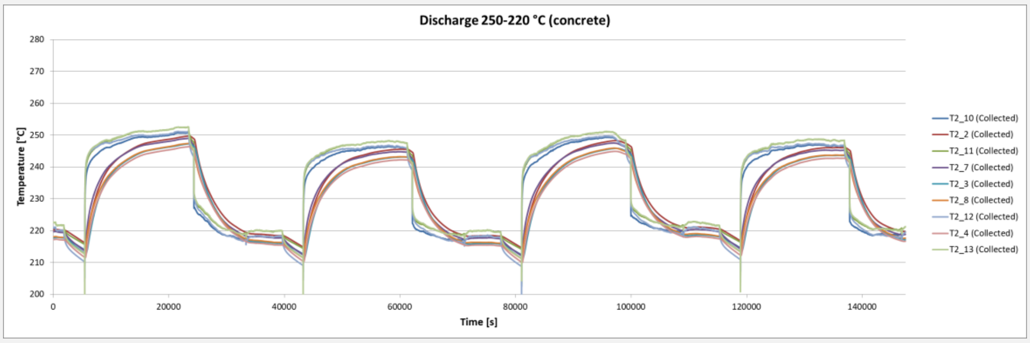


Details of the model	
What is the model used for?	Natural and/or forced convective heat transfer in Molten Salts thermocline storage systems.
Model level (component, system or grid)	Component
Model scale (scaling, 1D, 2D 3D, multiscale)	2D/ Axisymmetric
(Major) inputs and outputs	Input: geometry, thermal load and boundary and initial conditions. Output: pressure, velocity and temperature distribution fields.
Is it static or dynamic?	Dynamic
Is it design only or off-design?	It is a model suitable for both design and off-design
Is the model validated? How?	The simulation results have been compared with experimental data
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	Thermal Energy Storage has been coupled with concentrated solar power plant and/or photovoltaic plant.

Could the model be coupled to a specific system?	It is a generic model and can be coupled with several thermal energy users.
Does the model use or provide data from/to other models you are using?	No
Model limitations/simplifications	Geometric simplifications
Approximate run time on a stationary PC	It depends on the PC and the component discretization. It can take a few hours or several hours.
Publications connected to the model	
Details of the software	
Simulation environment	Comsol Multiphysics
Software license required?	Yes
Used databases or model libraries? Commercial?	Internal and user databases and model libraries were used. Yes.
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Yes, it is possible. But generally, these simulations are separately considered from the rest of the analysis.
Why did you choose this software?	Comsol allows to study these phenomena using internal validated libraries and showed a good capability to model complex phenomena through very efficient mathematical solvers.
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	Yes.
To what extent is the model available to IEA partners (use, modify, etc.)?	The model can be used by other licensed users of the software. The model can be modified
What are the terms for model users (co-authorship, papers to cite, etc.)?	In the papers the use of code and acknowledgments for model developers must be reported
Contact person (name and e-mail)	Giuseppe Canneto, giuseppe.canneto@enea.it

IEA Task 36: Model Factsheet

Model for assessing KPI (Key Performance Indicators) on sensible and latent storage prototypes

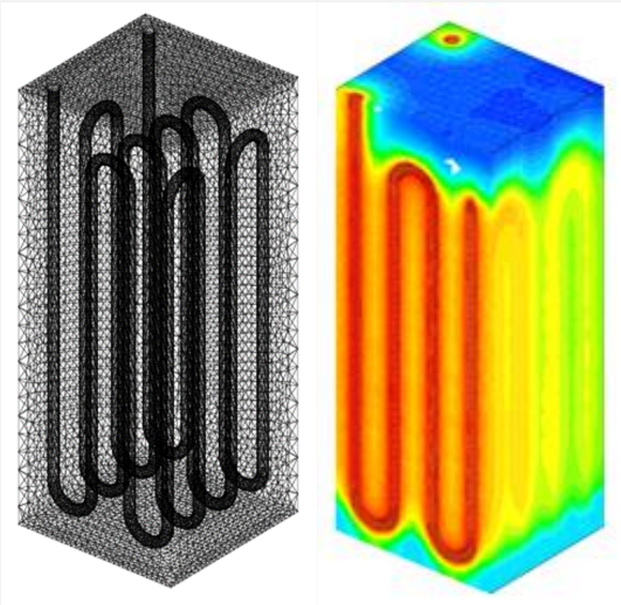


Details of the model	
What is the model used for?	KPI assessment: nominal storage, storage capacity, charging and discharging time, utilization rate, energy efficiency, exergy efficiency, thermal losses.
Model level (component, system or grid)	component
Model scale (scaling, 1D, 2D 3D, multiscale)	1D
(Major) inputs and outputs	Input: physical properties of materials and experimental data collected on a sensible and latent storage prototype. Output: KPIs.
Is it static or dynamic?	static
Is it design only or off-design?	Off-design
Is the model validated? How?	Work in progress
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	NA
Could the model be coupled to a specific system?	NA
Does the model use or provide data from/to other models you are using?	The model can accept/provide data from/to whatever program connectable to Excel
Model limitations/simplifications	Only for sensible and latent heat storage
Approximate run time on a stationary PC	1 second

Publications connected to the model	Not yet
Details of the software	
Simulation environment	Microsoft Excel
Software license required?	Yes, for MS Excel
Used databases or model libraries? Commercial?	No
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Yes
Why did you choose this software?	Easiness
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	In a review article when published
To what extent is the model available to IEA partners (use, modify, etc.)?	NA, at present it is an output of Sfera3 –WP6 task6.3 (task leader: Pierre Garcia – CEA)
What are the terms for model users (co-authorship, papers to cite, etc.)?	NA
Contact person (name and e-mail)	raffaele.liberatore@enea.it for ENEA data

IEA Task 36: Model Factsheet

Finite Element Method Model for the transient analysis of thermal behavior of components and sub-systems of thermal energy storage including conductive and convective heat transfer, heat transfer fluid thermal advection and material phase change.



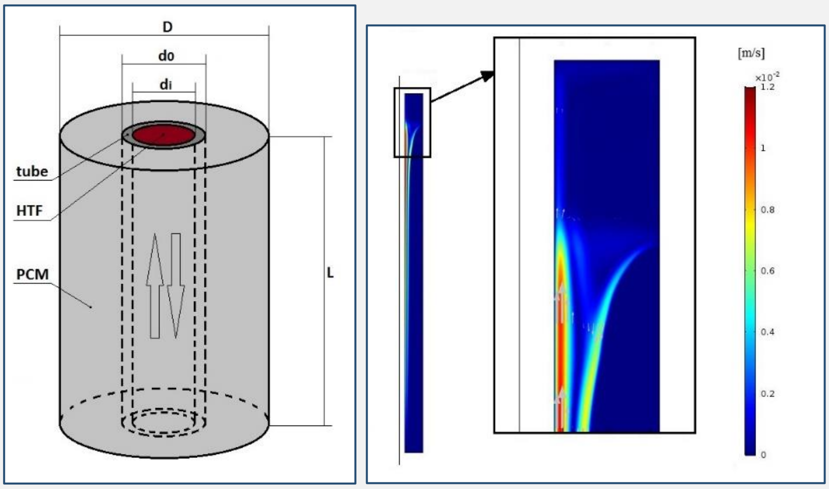
Details of the model

What is the model used for?	Conductive heat transfer in thermal energy storage based on sensible and/or latent heat
Model level (component, system or grid)	Components
Model scale (scaling, 1D, 2D 3D, multiscale)	2D/3D
(Major) inputs and outputs	Input: thermal flux and boundary conditions. Outlet: temperature distribution.
Is it static or dynamic?	Static and dynamic
Is it design only or off-design?	Off-design
Is the model validated? How?	Yes, by comparison with experimental and literature data.
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	Thermal energy storage has been coupled with Concentrated Solar Power plants/District heating/Industrial heat recovery/Waste heat recovery but can be integrated with several thermal energy users

Could the model be coupled to a specific system?	
Does the model use or provide data from/to other models you are using?	No
Model limitations/simplifications	No fluid dynamics considered for fluid
Approximate run time on a stationary PC	It depends on the component discretization: and can range from some minutes to days.
Publications connected to the model	Deliverables of National funded Projects
Details of the software	
Simulation environment	Cast3M – Finite Element Method Code
Software license required?	No (Free Licence)
Used databases or model libraries? Commercial?	
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Yes
Why did you choose this software?	It is free and ENEA has a long experience on it
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	Yes
To what extent is the model available to IEA partners (use, modify, etc.)?	The model cab be shared for use. Furthermore sources code can be modified by collaborating with CEA Saclay (Paris), See code web-site.
What are the terms for model users (co-authorship, papers to cite, etc.)?	Papers citing the use of code and acknowledgments for model developers
Contact person (name and e-mail)	Adio Miliozzi, adio.miliozzi@enea.it

IEA Task 36: Model Factsheet

Numerical model (CFD) for the thermal performance evaluation of a tube&shell LHTES



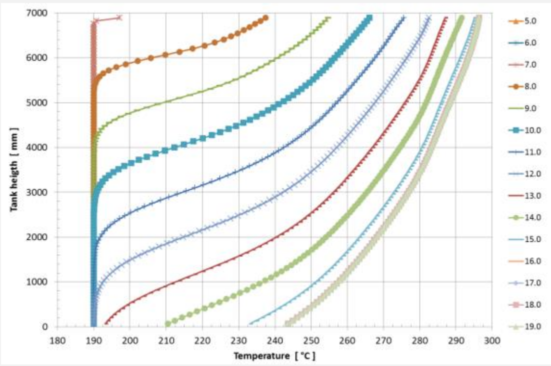
Details of the model

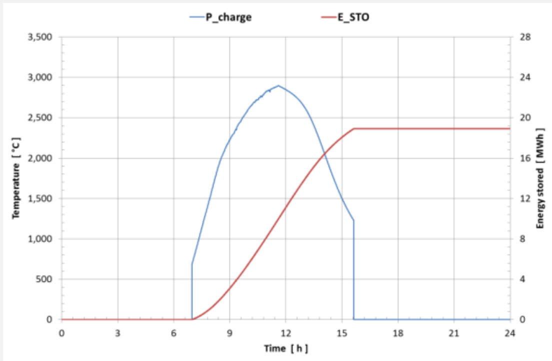
What is the model used for?	Heat exchange in thermal energy storage with latent heat
Model level (component, system or grid)	Component
Model scale (scaling, 1D, 2D 3D, multiscale)	2D, 2D Axisymmetric
(Major) inputs and outputs	Input: Heat flow on boundary condition Output: Temperature distribution
Is it static or dynamic?	Dynamic
Is it design only or off-design?	Off-design
Is the model validated? How?	In part, since it has been validate against experimental and literature data
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	Thermal energy storage system
Could the model be coupled to a specific system?	It can be coupled with different systems and applications
Does the model use or provide data from/to other models you are using?	No

Model limitations/simplifications	Boussinesq approximation
Approximate run time on a stationary PC	Up to 7/8 hours
Publications connected to the model	Oral lecture at the ENERSTOCK2021 conference
Details of the software	
Simulation environment	COMSOL Multiphysics Ver. 5.2
Software license required?	Yes
Used databases or model libraries? Commercial?	No
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Yes, CoMSOL simulations can be called from Matlab
Why did you choose this software?	Very user-friendly interface and efficient mathematical solver
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	Yes
To what extent is the model available to IEA partners (use, modify, etc.)?	For benchmark calculation and comparison, along with possible modifications for the Carnot Battery application
What are the terms for model users (co-authorship, papers to cite, etc.)?	Co-authorship and paper to cite
Contact person (name and e-mail)	Daniele Nicolini daniele.nicolini@enea.it

IEA Task 36: Model Factsheet

Transient analysis of temperature distribution in the Thermal Energy Storage during the charging and discharging phases. Particularly the Thermal Energy Storage is a thermocline system with molten salt as heat storage medium. The charging phase has been analyzed considering two heat sources: electric heaters and heat exchanger.





Details of the model

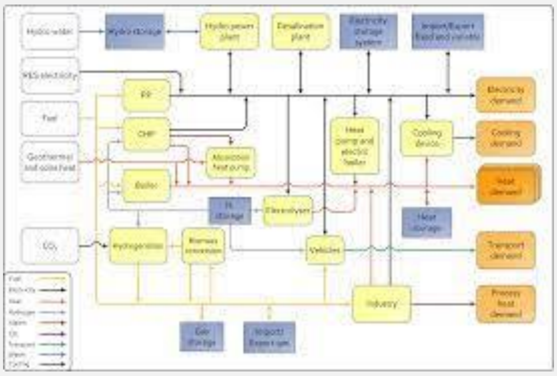
What is the model used for?	Natural and/or forced convective heat transfer in thermal energy storage based on thermocline system.
Model level (component, system or grid)	Component
Model scale (scaling, 1D, 2D 3D, multiscale)	1D
(Major) inputs and outputs	Input: geometry, thermal load and boundary condition Output: temperature distribution and stored energy
Is it static or dynamic?	Dynamic (quasi steady state simulation)
Is it design only or off-design?	Off-design
Is the model validated? How?	The simulation results have been compared with experimental data
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	Thermal Energy Storage has been coupled with concentrated solar power plant and/or photovoltaic plant.
Could the model be coupled to a specific system?	It is a generic model and can be coupled with several thermal energy users.

Does the model use or provide data from/to other models you are using?	No
Model limitations/simplifications	Geometric simplifications
Approximate run time on a stationary PC	Few minutes
Publications connected to the model	SolarPaces 2017 - Thermal Energy Storage with Integrated Heat Exchangers Using Stratified Molten Salt System for 1 MWe CSP
Details of the software	
Simulation environment	Matlab
Software license required?	Yes
Used databases or model libraries? Commercial?	Commercial software. Self-developed model
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Yes
Why did you choose this software?	The developed model can be easily integrated with other module implemented in Matlab
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	Yes
To what extent is the model available to IEA partners (use, modify, etc.)?	The model can be used by other licensed users of the software.
What are the terms for model users (co-authorship, papers to cite, etc.)?	In the papers the use of code and acknowledgments for model developers must be reported
Contact person (name and e-mail)	Valeria Russo, valeria.russo@enea.it

IEA Task 36: Model Factsheet

EnergyPLAN simulates the operation of national energy systems on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors. It is developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University, Denmark [1]. The model is used by many researchers, consultancies, and policymakers worldwide. This is possible due to the key focus on sharing the model during its development. For example, the model has a user-friendly interface, it is disseminated as a freeware, there is a variety of training available including our forum, and existing models are already available for many countries. The model is a deterministic input/output model. General inputs are demands, renewable energy sources, energy station capacities, costs and a number of optional different regulation strategies emphasising import/export and excess electricity production. Outputs are energy balances and resulting annual productions, fuel consumption, import/export of electricity, and total costs including income from the exchange of electricity.

The primary purpose of the model is to simulate the entire energy system on an hourly basis including electricity, heating (district heating and cooling also), transport and industry. EnergyPLAN uses electricity grids, district heating, district cooling and gas infrastructure to enable the analysis of sector integrated smart energy systems. In this, Carnot Batteries is possible to illustrate.



Details of the model

What is the model used for?	Hourly simulation of energy systems, typically country level, but can both bigger and smaller systems.
Model level (component, system or grid)	Entire energy system
Model scale (scaling, 1D, 2D 3D, multiscale)	

(Major) inputs and outputs	Inputs :Energy demands, time series, capacities, efficiencies, costs. Outputs: Energy balances for all demands, total annual costs, fuel balances, emissions.
Is it static or dynamic?	
Is it design only or off-design?	
Is the model validated? How?	EnergyPLAN is a tool, the validation comes from each specific model a user might make. But these has been validated a number of times.
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	It can model the entire energy system, including all mentioned technologies to the left. Included also Carnot Batteries.
Could the model be coupled to a specific system?	If you mean a country, it is possible to model countries in EnergyPLAN
Does the model use or provide data from/to other models you are using?	There are help tools available but EnergyPLAN is designed to work stand-alone
Model limitations/simplifications	Technologies are typically grouped together. For instance, the user models power plants as up to two-three different types instead of modelling all power plants individual
Approximate run time on a stationary PC	1 second
Publications connected to the model	Many studies associated with EnergyPLAN. Key publication in term of documentation: https://www.sciencedirect.com/science/article/pii/S2666955221000071
Details of the software	
Simulation environment	EnergyPLAN is an executable programmed in Delphi Pascal, no external simulation environment needed
Software license required?	Freeware
Used databases or model libraries? Commercial?	www.energyplan.eu
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Yes

Why did you choose this software?	It is developed by AAU
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	Yes
To what extent is the model available to IEA partners (use, modify, etc.)?	EnergyPLAN and the scenario models we investigate Carnot Batteries in will or are all freely available on www.energyplan.eu
What are the terms for model users (co-authorship, papers to cite, etc.)?	Please cite https://www.sciencedirect.com/science/article/pii/S2666955221000071 Also feel free to reach out for research collaboration
Contact person (name and e-mail)	Jakob Zinck Thellufsen, jakobzt@plan.aau.dk

IEA Task 36: Model Factsheet

Dymola is a commercial modeling and simulation environment based on the open Modelica modeling language.

Large and complex systems are composed of component models; mathematical equations describe the dynamic behavior of the system.[1] Developed by the European company Dassault Systèmes, Dymola is available as a standalone product and integrated in 3DEXPERIENCE as part of CATIA (Descrition from Wikipedia; https://en.wikipedia.org/wiki/Dymola)

DYMOLA Systems Engineering
Multi-Engineering Modeling and Simulation based on Modelica and FMI

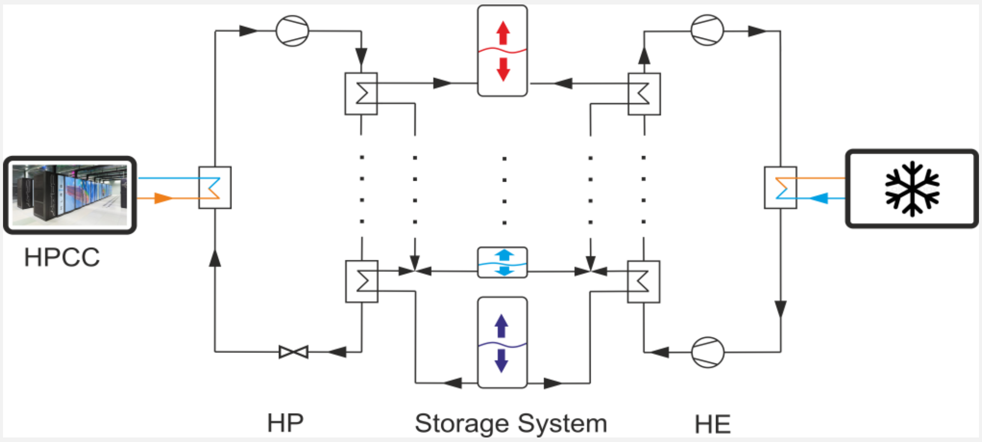
https://www.3ds.com/products-services/catia/products/dymola/

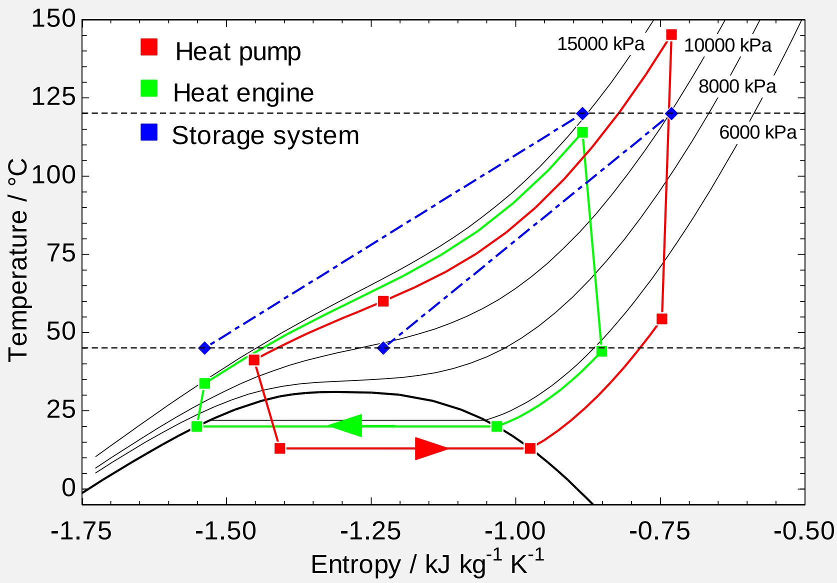
Details of the model

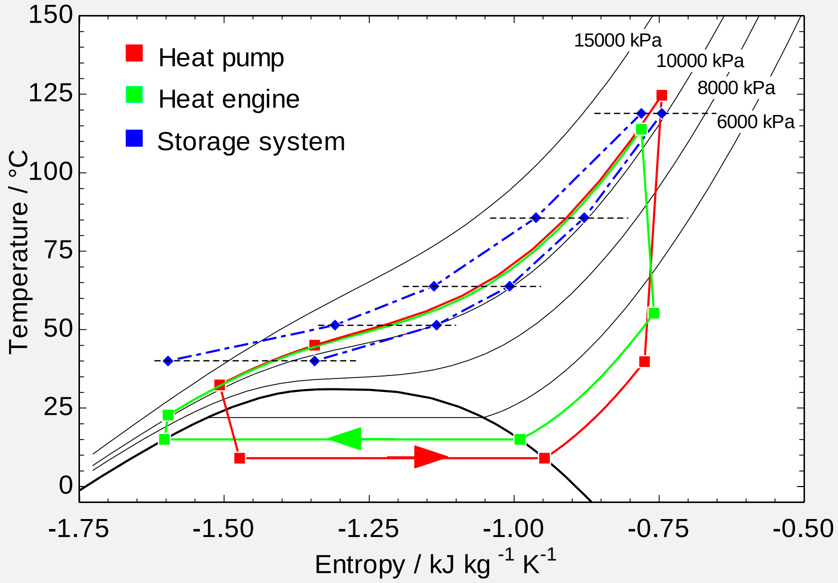
What is the model used for?	Simulation and thermodynamic analysis of hybrid heat pump: transcritical CO2-compression / water adsorption with integrated stratified tank
Model level (component, system or grid)	System
Model scale (scaling, 1D, 2D 3D, multiscale)	1D
(Major) inputs and outputs	Inputs: reference building data (U-values, areas, weather data for location) Outputs:
Is it static or dynamic?	Dynamic
Is it design only or off-design?	Both
Is the model validated? How?	System model not validated yet, some component models (esp. adsorption module) validated with lab measurements from Fraunhofer ISE in project AdoSan
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	The system of interest is currently mainly a hybrid heat pump for renovation of multi-family buildings, could be extended to district heating.

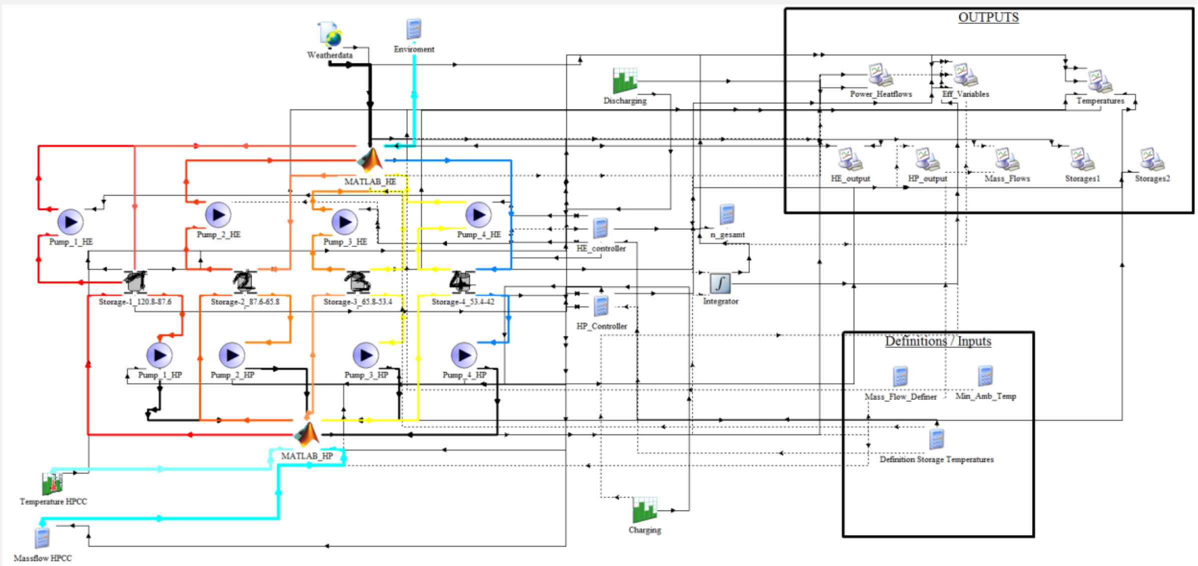
Could the model be coupled to a specific system?	Due to the object orientation and library structures in Modelica/Dymola, coupling to other dymola system models is relatively easy.
Does the model use or provide data from/to other models you are using?	Yes, e.g. time series of heat loads for heating and domestic hot water, generated from TRNSYS models.
Model limitations/simplifications	CO2 cooling loop modeled is quite detailed (TIL library, 2 phase model), adsorption model is more coarse
Approximate run time on a stationary PC	
Publications connected to the model	None yet
Details of the software	
Simulation environment	Modelica / Dymola
Software license required?	Yes, for Dymola (openmodelica might work, untested)
Used databases or model libraries? Commercial?	Commercial TIL library, some open source libraries like Buildings, AixLib
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Should be possible through Functional Mockup Interface (FMI), untested
Why did you choose this software?	Available libraries, request by project partners and industry
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	
To what extent is the model available to IEA partners (use, modify, etc.)?	
What are the terms for model users (co-authorship, papers to cite, etc.)?	
Contact person (name and e-mail)	

IEA Task 36: Model Factsheet









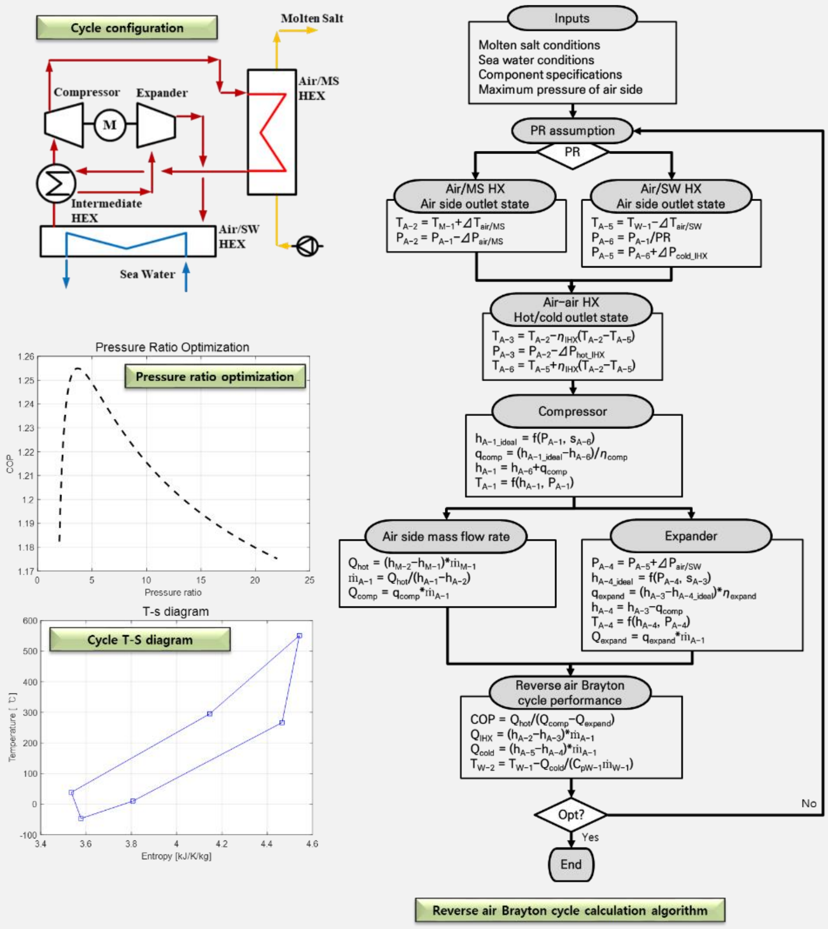
Details of the model	
What is the model used for?	CB-Simulation (CO_2-based with water storages and heat exchanger network)
Model level (component, system or grid)	system
Model scale (scaling, 1D, 2D 3D, multiscale)	1D
(Major) inputs and outputs	Inputs: charge/discharge periods, data center waste heat, weather data Outputs: efficiency, electrical energy/heat flows
Is it static or dynamic?	dynamic
Is it design only or off-design?	design only

Is the model validated? How?	no, CO_2-cycles could not be validated
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	waste heat from a data center
Could the model be coupled to a specific system?	cooling system of the data center, district heating/cooling network
Does the model use or provide data from/to other models you are using?	data from cooling system of the data center
Model limitations/simplifications	simplified CO_2-cycles (constant effectiveness compressor/turbine, …), defined pinch points in heat exchanger network, pressure losses neglected
Approximate run time on a stationary PC	minutes to hours
Publications connected to the model	-
Details of the software	
Simulation environment	TRNSYS coupled with Matlab
Software license required?	yes
Used databases or model libraries? Commercial?	TESS library, commercial
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	not implemented so far except for data export
Why did you choose this software?	transient system, flexibility
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	yes
To what extent is the model available to IEA partners (use, modify, etc.)?	not used so far
What are the terms for model users (co-authorship, papers to cite, etc.)?	if applicable co-authorship
Contact person (name and e-mail)	nils.bayer@igte.uni-stuttgart.de

IEA Task 36: Model Factsheet

High temperature reverse air Brayton heat pump cycle model (>400℃)

- Short description of the model: air Brayton heat pump cycle optimization code
- Governing equation: law of mass / energy conservation
- Modelled components: air-molten salt HX, air-sea water HX, air-air HX, compressor-expander unit
- Inputs: Heat source temperature (sea water), Efficiency of turbomachinery, Target heat generation temperature, Heat storage temperature
- Results: COP, Inlet/Outlet condition of Compressor and Expander



Key illustrations: cycle configuration, calculation algorithm, model results

Details of the model

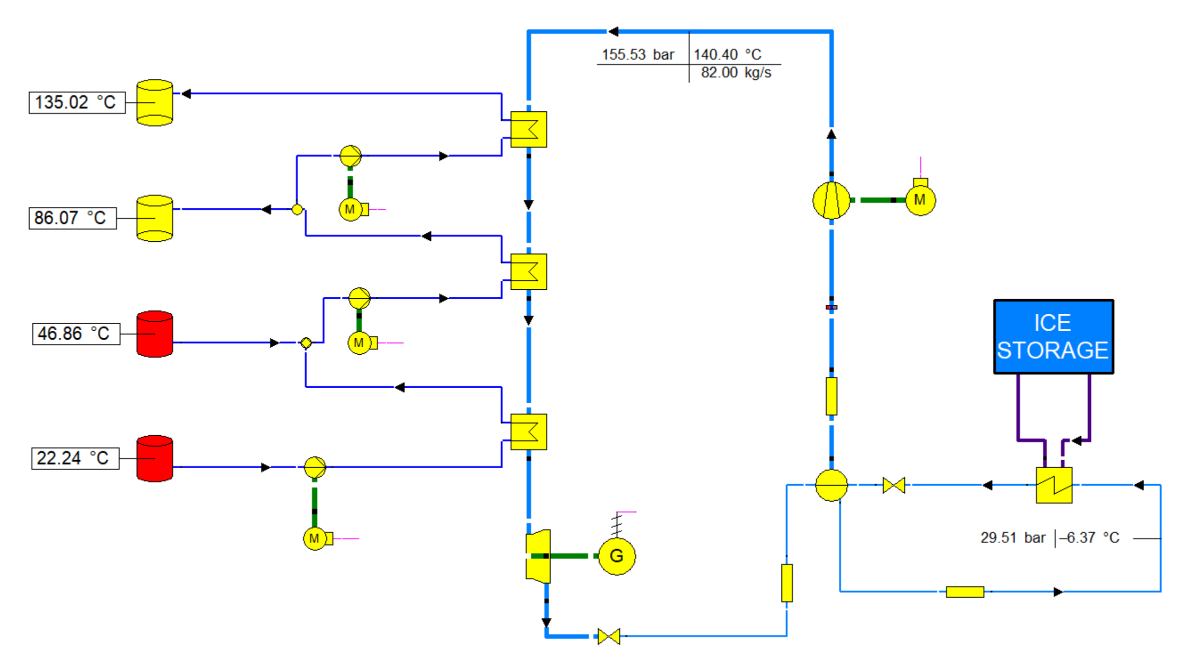
What is the model used for?	High temperature air heat pump (>400℃) for coal-fired plant retrofit
Model level (component, system or grid)	System
Model scale (scaling, 1D, 2D 3D, multiscale)	Point scale (Zero Dimension)
(Major) inputs and outputs	Input: Heat source temperature (sea water), Efficiency of turbomachinery, Target heat generation temperature, Heat storage temperature Output: COP, Inlet/Outlet condition of Compressor and Expander
Is it static or dynamic?	Static
Is it design only or off-design?	Design only
Is the model validated? How?	Validated based on energy conservation law
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	Not yet
Could the model be coupled to a specific system?	Heat Storage and Power Plant
Does the model use or provide data from/to other models you are using?	Not yet
Model limitations/simplifications	Only heat pump simulation in Carnot Battery system
Approximate run time on a stationary PC	~0.6 s
Publications connected to the model	Not yet
Details of the software	
Simulation environment	MATLAB
Software license required?	Yes
Used databases or model libraries? Commercial?	In-house code using basic functions and libraries in MATLAB
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Yes, as a DLL
Why did you choose this software?	MATLAB is a handy software to implement a preliminary calculation algorithm due to its easy interface and flexible debugging mode.
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	Yes

To what extent is the model available to IEA partners (use, modify, etc.)?	Use
What are the terms for model users (co-authorship, papers to cite, etc.)?	co-authorship, papers to cite
Contact person (name and e-mail)	jhcho@kier.re.kr Junhyun Cho

IEA Task 36: Model Factsheet

The MAN ETES system is at core an industrial-scale high temperature heat pump that uses CO2 as process medium in a transcritical cycle to provide up to 50MW heat and 30MW cold. At heart stands the industrial centrifugal compressor HOFIM, a well-proven and oil-free turbomachine on magnetical bearings. In ETES light, the heat pump is complemented with hot water and ice tanks as energy storage.

This factsheet presents the static modeling used to investigate the system design and optimization.



Details of the model	
What is the model used for?	Steady state design and optimization
Model level (component, system or grid)	System
Model scale (scaling, 1D, 2D 3D, multiscale)	1D / 2D (component dependent)
(Major) inputs and outputs	Inputs: - Turbomachinery maps - HEX approach temperatures - Storage temperatures - Mass flow - Charging / Discharging times - Various process conditions. Outputs: - Power

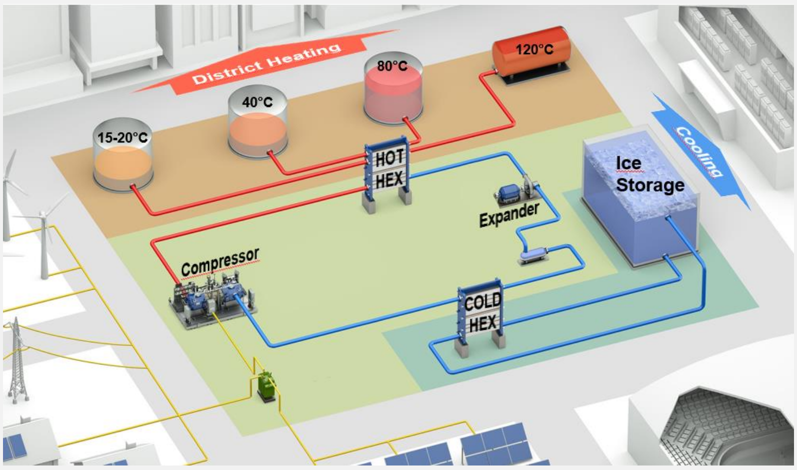
	- Storage capacity - Energy and mass balance - RT efficiency
Is it static or dynamic?	Static
Is it design only or off-design?	Both
Is the model validated? How?	Testbed validation of turbomachinery (November 2020) Scheduled testbed validation of full cycle (April 2022)
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	- District heating - District cooling - Renewable energy
Could the model be coupled to a specific system?	Multiple options
Does the model use or provide data from/to other models you are using?	Coupled to an in-house tool that designs and optimizes the loop in python.
Model limitations/simplifications	Complicated to integrate detailed HEX models of sCO2 without compromising convergence and computational time.
Approximate run time on a stationary PC	< 1 min
Publications connected to the model	- Thermo-economic Heat Exchanger Optimization for Electro Thermal Energy Storage based on Transcritical CO2 Cycles. - Large Scale Tri-Generation Energy Storage System for Heat, Cold and Electricity based on Transcritical CO2 Cycles.
Details of the software	
Simulation environment	Ebsilon Professional
Software license required?	Yes
Used databases or model libraries? Commercial?	REFPROP
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Yes: - Python - Matlab - Excel
Why did you choose this software?	- Computational time - Customer acceptance - Widely used tool within the company
IEA partnership	

Can the provided details be published in the final Task 36 report or in a review article?	Yes
To what extent is the model available to IEA partners (use, modify, etc.)?	Not available
What are the terms for model users (co-authorship, papers to cite, etc.)?	/
Contact person (name and e-mail)	Emmanuel.jacquemoud@man-es.com

IEA Task 36: Model Factsheet

The MAN ETES system is at core an industrial-scale high temperature heat pump that uses CO_2 as process medium in a transcritical cycle to provide up to 50MW heat and 30MW cold. At heart stands the industrial centrifugal compressor HOFIM, a well-proven and oil-free turbomachine on magnetical bearings. In ETES light, the heat pump is complemented with hot water and ice tanks as energy storage.

This factsheet presents the dynamic modeling used to investigate the system performance, control strategy and system integration.



Details of the model	
What is the model used for?	Analysis of system performance and flexibility, control development and testing
Model level (component, system or grid)	Component level, CO_2-system level (ETES heat pump) and extended system level (ETES light)
Model scale (scaling, 1D, 2D 3D, multiscale)	1D & 2D
(Major) inputs and outputs	Inputs: Environmental conditions (Source temperatures, ambient temperatures) and operational parameters (Desired temperatures, duties); Outputs: Thermodynamic properties, valve and compressor settings, power demand
Is it static or dynamic?	Dynamic
Is it design only or off-design?	Design and off-design

Is the model validated? How?	Testbed validation of turbomachinery (November 2020) Scheduled testbed validation of full cycle (April 2022)
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	Yes (district heating supply, storage and grid stabilization)
Could the model be coupled to a specific system?	Yes
Does the model use or provide data from/to other models you are using?	Yes (Characteristic maps of turbomachinery)
Model limitations/simplifications	Start-up & Shut-down simulation is limited due to difficult compressor characterization at minimal rotational speed
Approximate run time on a stationary PC	min - hours
Publications connected to the model	/
Details of the software	
Simulation environment	Modelon Impact
Software license required?	Yes
Used databases or model libraries? Commercial?	Modelica Standard (non-commercial) ThermoFluid (commercial) ThermalPower (commercial) VaporCycle (commercial)
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Yes
Why did you choose this software?	Relevant libraries, GUI and FMU option, customer support, browser-based
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	Yes
To what extent is the model available to IEA partners (use, modify, etc.)?	Not available
What are the terms for model users (co-authorship, papers to cite, etc.)?	/
Contact person (name and e-mail)	Emmanuel Jacquemoud emmanuel.jacquemoud@man-es.com

IEA Task 36: Model Factsheet	
MATLAB is a programming and numeric computing platform used by millions of engineers and scientists to analyze data, develop algorithms, and create models. The model include an ORC design tool. A steady state model is used.	
Details of the model	
What is the model used for?	Basic design of ORC power plants
Model level (component, system or grid)	Component+System
Model scale (scaling, 1D, 2D 3D, multiscale)	0D
(Major) inputs and outputs	Inputs: Mass flows, temperatures; pressures; selected working fluid; boundaries of component dimension Output: power output profile, efficiency, component design
Is it static or dynamic?	static
Is it design only or off-design?	Both
Is the model validated? How?	Validated with experimental data and from literature
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	Developed for geothermal source but any heat source can be used
Could the model be coupled to a specific system?	Depending on the system – should be tested
Does the model use or provide data from/to other models you are using?	No
Model limitations/simplifications	Simplified model for pressure losses and adiabatic System
Approximate run time on a stationary PC	Depending on the selected case, usually in the order of minutes
Publications connected to the model	Yes, e.g. DOI: 10.5445/KSP/1000041450
Details of the software	

Simulation environment	Matlab
Software license required?	Yes
Used databases or model libraries? Commercial?	Commercial
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Extracting of data is possible.
Why did you choose this software?	Very flexible, connection to component physical property database
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	TBD
To what extent is the model available to IEA partners (use, modify, etc.)?	Restricted to KIT internal users
What are the terms for model users (co-authorship, papers to cite, etc.)?	Co-authorship
Contact person (name and e-mail)	Hans-Joachim Wiemer E-mail: hans-joachim.wiemer@kit.edu

IEA Task 36: Model Factsheet	

MATLAB is a programming and numeric computing platform used by millions of engineers and scientists to analyze data, develop algorithms, and create models.

The modelled component is a packed-bed storage. A two-dimensional model is used.

Details of the model

What is the model used for?	Packed-bed storage simulation
Model level (component, system or grid)	Component
Model scale (scaling, 1D, 2D 3D, multiscale)	2D
(Major) inputs and outputs	Inputs: Mass flows, temperatures and physical properties of heat transfer fluid; packed-bed properties Output: Temperature profile of the fluid and packed-bed, storage efficiency
Is it static or dynamic?	static
Is it design only or off-design?	Both
Is the model validated? How?	Validated with experimental data from literature
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	No, any heat source can be used
Could the model be coupled to a specific system?	Depending on the system – should be tested
Does the model use or provide data from/to other models you are using?	No
Model limitations/simplifications	Assumption of plug flow (no velocity profile)
Approximate run time on a stationary PC	Depending on the size of the storage, in the order of hours
Publications connected to the model	Yes, e.g. https://doi.org/10.1016/j.applthermaleng.2018.05.080

Details of the software

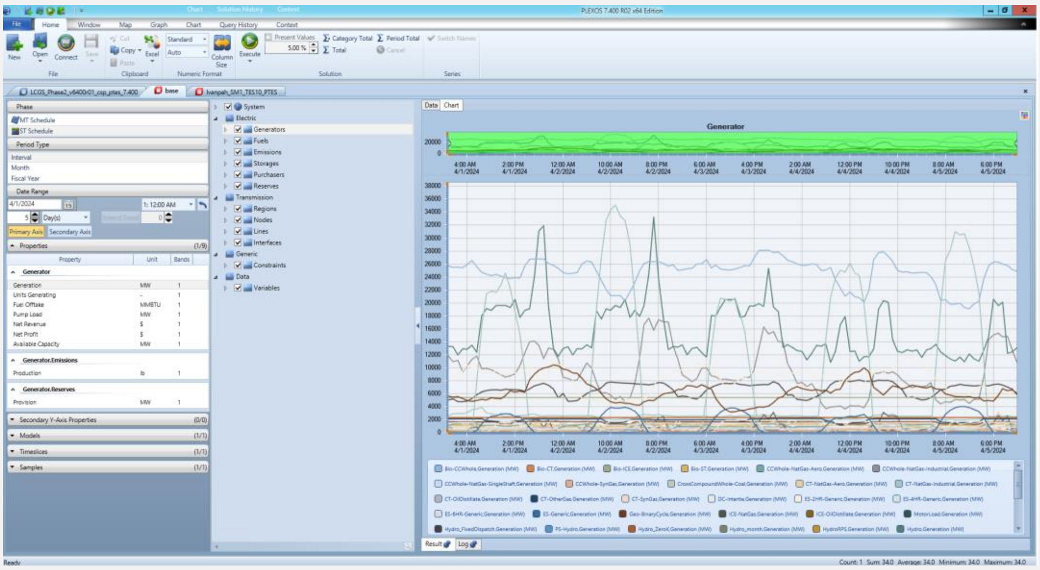
Simulation environment	Matlab
Software license required?	Yes

Used databases or model libraries? Commercial?	Commercial
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Extracting of data possible. Feeding of external data – should be tested
Why did you choose this software?	Very flexible, possible to write solvers
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	TBD
To what extent is the model available to IEA partners (use, modify, etc.)?	Restricted to KIT internal users
What are the terms for model users (co-authorship, papers to cite, etc.)?	Co-authorship
Contact person (name and e-mail)	Klarissa Niedermeier E-mail: klarissa.niedermeier@kit.edu

IEA Task 36: Model Factsheet

This model evaluates the optimal day-ahead operational scheduling and annual value of a Pumped Thermal Energy Storage (PTES) system based on Joule-Brayton thermodynamic cycles and two-tank molten salt hot thermal storage. Production cost models are used, and these simultaneously optimize commitment and dispatch schedules for an entire set of generators to minimize the cost of satisfying electricity demand. They have been used to determine system-optimal operation and day-ahead energy value of the PTES system within six hypothetical near-future grid

scenarios intended to approximately represent the U.S. Western Interconnection or the Texas Interconnection. Sensitivity to grid scenario (including penetration of variable renewable energy sources), thermal storage capacity, relative heat pump and heat engine capacities, and startup/shutdown cycling costs can be evaluated.



Details of the model

What is the model used for?	Estimate the value of a PTES system that is connected to the grid. 'Value' is the avoided cost – i.e. the reduction in cost of operating the grid. The model has been applied to grid scenarios that approximately represent the Western Interconnection or Texas Interconnection in the USA.

Model level (component, system or grid)	Grid
Model scale (scaling, 1D, 2D 3D, multiscale)	
(Major) inputs and outputs	INPUTS: Size and location of the PTES system, efficiency of the heat pump and heat engine, off-design curves for the PTES system, many assumptions required to model the grid. OUTPUTS: value of PTES system, operating profile (duration and power rating of charge and discharge), changes to operating profiles of other generators.
Is it static or dynamic?	Dynamic
Is it design only or off-design?	
Is the model validated? How?	The grid scenarios were developed in previous studies as part of large collaborations. The PTES model was developed in a previous study in which some components were validated against experimental data. Further details are provided in the references below.
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	
Could the model be coupled to a specific system?	
Does the model use or provide data from/to other models you are using?	The PTES model within the grid model is a simplified representation of that obtained from a more detailed model of PTES, as described in another factsheet.
Model limitations/simplifications	The model is a mixed integer linear optimization problem. The objective function and constraints describing the PTES system and all other generators must be linear.
Approximate run time on a stationary PC	Approximately 1-3 days, depending on the scale of the grid scenario
Publications connected to the model	[1] J. Martinek , J. Jorgenson, J. D. McTigue, "On the operational characteristics and economic value of pumped thermal energy storage", submitted to Journal of Energy Storage, 2022 [2] J. D. McTigue, P. Farres-Antunez, K. Sundarnath, C. N. Markides, A. J. White, "Techno-economic

	analysis of recuperated Joule-Brayton Pumped Thermal Energy Storage systems", Energy Conversion & Management, vol. 252, 115016, 2022, https://doi.org/10.1016/j.enconman.2021.115016
Details of the software	
Simulation environment	PLEXOS
Software license required?	Yes
Used databases or model libraries? Commercial?	
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Possibly
Why did you choose this software?	NREL has used PLEXOS for various other grid modelling research.
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	Yes
To what extent is the model available to IEA partners (use, modify, etc.)?	Some aspects of the model (e.g. how PTES is represented) may be available.
What are the terms for model users (co-authorship, papers to cite, etc.)?	
Contact person (name and e-mail)	Josh McTigue jmctigue_nrel@outlook.com

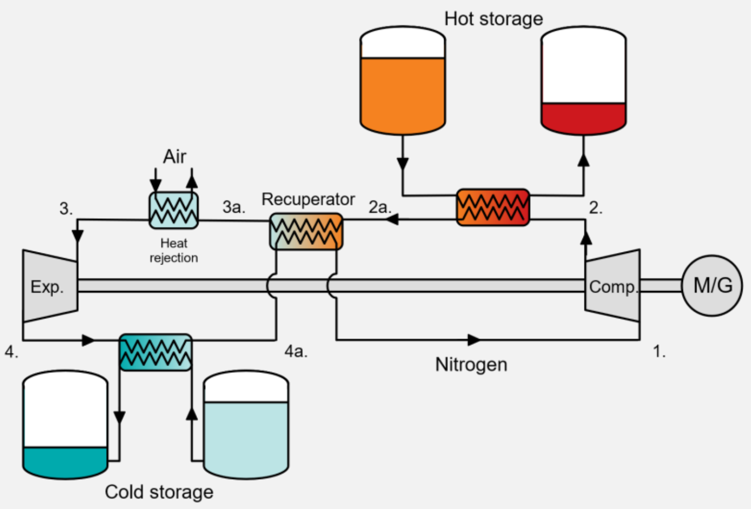
IEA Task 36: Model Factsheet

A techno-economic model of Pumped Thermal Energy Storage (PTES).

It is assumed that the PTES system uses liquid storage (such as molten salts) and is based on a Joule-Brayton cycle – the working fluid does not need to be modelled as an ideal fluid. The main components are the turbomachinery and heat exchangers, but models of storage tanks, pumps, motors/generators are also included.

The model calculates the technical performance (e.g. round-trip efficiency) and economic performance (e.g. levelized cost of storage, uncertainty) for the system. The model calculates the heat exchanger geometry and includes part-load maps of the turbomachinery. Thus, once the nominal design is established, the off-design performance (as a function of mass flow rate and ambient temperature) can be calculated.

The model is constructed in such a way that parametric studies of the variables can be easily conducted. The model is also integrated with a multi-objective optimization algorithm.



Details of the model

What is the model used for?	Techno-economic analysis and multi-objective optimization of Pumped Thermal Energy Storage with liquid storage. Component sizing and costing.
Model level (component, system or grid)	Component, system

Model scale (scaling, 1D, 2D 3D, multiscale)	1D
(Major) inputs and outputs	Inputs: efficiency of turbomachinery, heat exchanger effectiveness and pressure loss, maximum temperature (or pressure ratio), fluid in liquid tanks, working fluid, mass flow rate, ambient temperature Outputs: round-trip efficiency, exergy density, power input and output, capital cost, levelized cost of storage (LCOS), heat exchanger geometry, Pareto fronts
Is it static or dynamic?	Static
Is it design only or off-design?	Design and off-design
Is the model validated? How?	Heat exchanger models are validated against experimental data taken from the literature.
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	The model is primarily for stand-alone PTES (see Refs. 1, 3 and 4) but it has also been modified to integrate a solar heat input (see Refs. 2 and 5).
Could the model be coupled to a specific system?	
Does the model use or provide data from/to other models you are using?	Off-design data is used to model PTES in grid simulations (another Factsheet is provided with details).
Model limitations/simplifications	Turbomachinery: assume a polytropic efficiency. Off-design performance is calculated using estimated curves. Heat exchangers: Assume an effectiveness and pressure loss. Geometry is calculated (for a shell-and-tube design). This allows off-design performance to be calculated, as the heat transfer coefficients and pressure losses are estimated from correlations. Fluids with variable heat capacities/densities can be handled. Pumps: Modelled simply with just an isentropic efficiency Motor/generator: Modelled with an efficiency term, and an off-design curve is also included. Working fluid: Properties are obtained from CoolProp so non-ideal or real fluids may be used. Storage liquids: A selection of liquids (nitrate and chloride molten salts, thermal oil, mineral oil,

	glycol, isopropane) is available. Custom fluids can easily be added. Storage tanks: Heat losses are neglected (well-insulated) Economics: Several cost correlations for each component were obtained from the literature. The user can choose one or several correlations for each component. The cost is calculated large number of times, each time choosing a random sample of the selected cost correlations. Consequently, a probability distribution of the cost is obtained so that the uncertainty may be evaluated. The levelized cost of heat is calculated using the fixed charge rate method, and is also calculated using the random-sampling method. Optimization: the model is currently coupled with a stochastic multi-objective optimization algorithm that uses particle-swarm optimization.
Approximate run time on a stationary PC	2 seconds
Publications connected to the model	[1] J. D. McTigue, P. Farres-Antunez, K. Sundarnath, C. N. Markides, A. J. White, "Techno-economic analysis of recuperated Joule-Brayton Pumped Thermal Energy Storage systems", Energy Conversion & Management, vol. 252, 115016, 2022, https://doi.org/10.1016/j.enconman.2021.115016 [2] P. Farres-Antunez, A. J. White, C. N. Markides, J. D. McTigue, "Energy storage in steam power plants retrofitted with Brayton heat pumps", manuscript in preparation, 2022 [3] J. D. McTigue, P. Farres-Antunez, C. N. Markides, A. J. White, "Pumped thermal energy storage with liquid storage", chapter in Encyclopedia of Energy Storage, Elsevier, 2021, https://doi.org/10.1016/B978-0-12-819723-3.00054-8 [4] A. Olympios, J. D. McTigue, P. Farres-Antunez, A. Romagnoli, W-D. Steinmann, A. Thess, L. Wang. H. Chen, Y. Li, Y. Ding, C. Markides, "Progress and prospects of thermo-mechanical energy storage – a critical review", IOP Progress in Energy, vol. 3, number 2, 2021, https://doi.org/10.1088/2516-1083/abdbba [5] J. D. McTigue, P. Farres-Antunez, K. Sundarnath, C. N. Markides, A. J. White, "Integration of Heat

	Pumps With Solar Thermal Systems for Energy Storage", Encyclopedia of Energy Storage, Elsevier, 2021, https://doi.org/10.1016/B978-0-12-819723-3.00067-6
Details of the software	
Simulation environment	MATLAB
Software license required?	Yes
Used databases or model libraries? Commercial?	Uses CoolProp (which is opensource)
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Probably
Why did you choose this software?	Familiarity.
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	Yes
To what extent is the model available to IEA partners (use, modify, etc.)?	Available
What are the terms for model users (co-authorship, papers to cite, etc.)?	Cite papers. Ref 1 above contains the most detail about the model.
Contact person (name and e-mail)	Josh McTigue. jmctigue_nrel@outlook.com

IEA Task 36: Model Factsheet

Simulink is a programming and numeric computing platform used by engineers and scientists to analyze data, develop algorithms, and create models.

The model include an ORC analyze tool. A transient model is used.

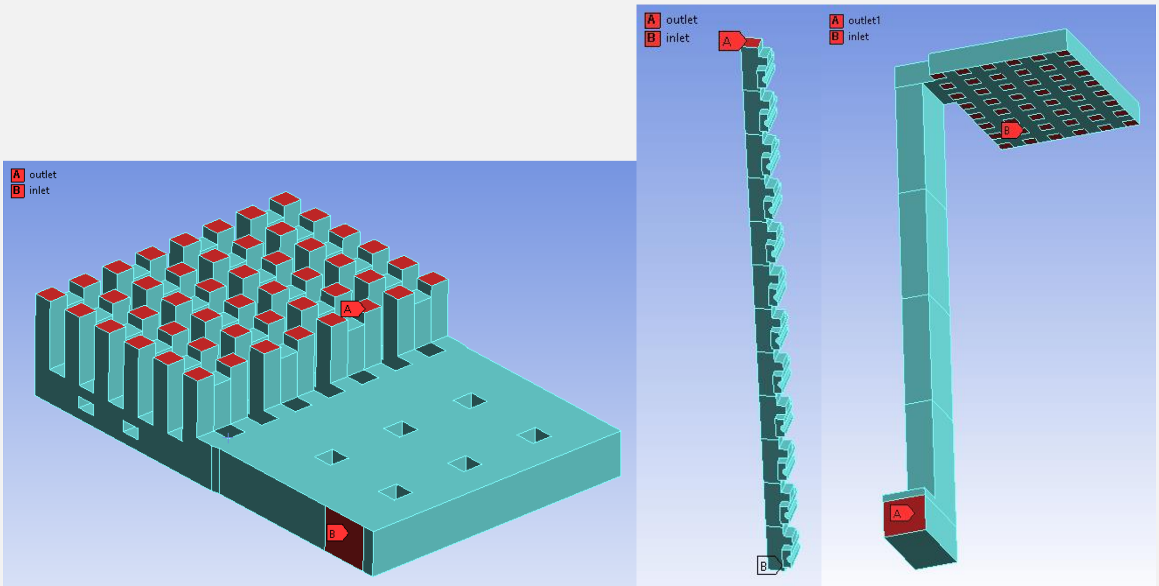
MathWorks®

Details of the model	
What is the model used for?	Analyze of ORC power plants
Model level (component, system or grid)	Components (heat exchanger; condenser; turbine+generator; control system)
Model scale (scaling, 1D, 2D 3D, multiscale)	1D
(Major) inputs and outputs	Inputs: Mass flows, temperatures; pressures; selected working fluid; Output: mass flow, temperatures; pressures of the model
Is it static or dynamic?	dynamic
Is it design only or off-design?	Both
Is the model validated? How?	Validated with experimental data
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	Developed for geothermal source but any heat source can be used
Could the model be coupled to a specific system?	Depending on the system – should be tested
Does the model use or provide data from/to other models you are using?	Coupling of components possible
Model limitations/simplifications	Simplified heat loss model
Approximate run time on a stationary PC	Depending on the selected case, usually in the order of minutes
Publications connected to the model	No
Details of the software	
Simulation environment	Matlab-Simulink
Software license required?	Yes

Used databases or model libraries? Commercial?	Commercial
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Extracting of data is possible.
Why did you choose this software?	Very flexible, connection to fluid physical property database
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	TBD
To what extent is the model available to IEA partners (use, modify, etc.)?	Restricted to KIT internal users
What are the terms for model users (co-authorship, papers to cite, etc.)?	Co-authorship
Contact person (name and e-mail)	Hans-Joachim Wiemer E-mail: hans-joachim.wiemer@kit.edu

IEA Task 36: Model Factsheet

It is a three divided CFD model of the flow channels of a high-temperature energy storage system. They provide each other with initial conditions and as the final output heat transfer coefficients for each section in the h-tes for another transient simulation model in Modelica.



Details of the model

What is the model used for?	Calculating heat transfer and pressure loss in a high temperature energy storage as a sub model for a 2D model in modellica
Model level (component, system or grid)	Component
Model scale (scaling, 1D, 2D 3D, multiscale)	3D
(Major) inputs and outputs	Inputs: air mass flow, wall temperature, inlet-temperature; Outputs: HTC, dp
Is it static or dynamic?	static
Is it design only or off-design?	
Is the model validated? How?	Experimental Data

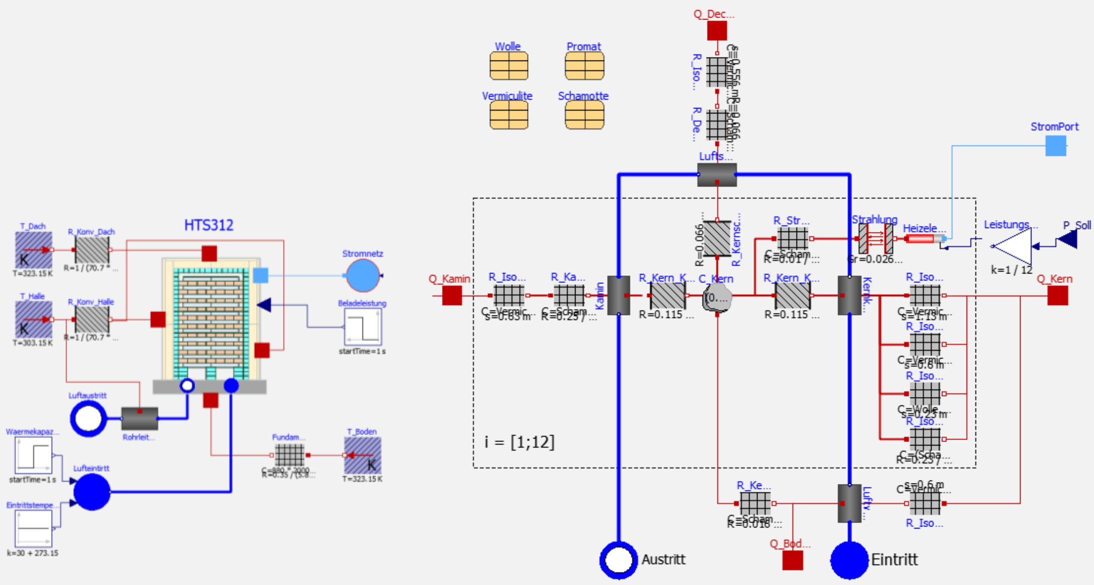
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	no
Could the model be coupled to a specific system?	no
Does the model use or provide data from/to other models you are using?	Siehe Modelica Modell
Model limitations/simplifications	Steady-state simulation, uniform wall temperature
Approximate run time on a stationary PC	Seconds to minutes depending on model
Publications connected to the model	Conference contribution to the international energy conference (IEWT21) in Vienna https://iewt2021.eeg.tuwien.ac.at/download/contribution/fullpaper/133/133_fullpaper_20210831_083200.pdf
Details of the software	
Simulation environment	Ansys Fluent
Software license required?	yes
Used databases or model libraries? Commercial?	
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	yes

Why did you choose this software?	Common CFD Software and personal experience with it
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	Not yet
To what extent is the model available to IEA partners (use, modify, etc.)?	-
What are the terms for model users (co-authorship, papers to cite, etc.)?	-
Contact person (name and e-mail)	THM

IEA Task 36: Model Factsheet

Im Rahmen des Projektes FlexQuartier wird ein direkt-elektrisch beheizter Hochtemperaturspeicher (HTS) mit extern-beheiztem Gasturbinenprozess entwickelt, aufgebaut und theoretisch wie praktisch untersucht. Der „digitale Zwilling“ des HTS-Systems wird vollständig in Modelica (OpenModelica) abgebildet und simuliert. Die Speichereinheit ist dabei ein Bestandteil des gesamten HTS-Systems und wurde bereits in einem Vorprojekt untersucht. https://doi.org/10.2314/KXP:1745063919

Nach einer stationären Untersuchung möglicher Rückverstromungskonzepte https://doi.org/10.1016/j.est.2021.103283 wird die HTS-Komponente zusammen mit einem dynamischen Modell der Rückverstromung entwickelt. (Aktuell noch in Arbeit)



Details of the model

What is the model used for?	Design, Simulation and Validation
Model level (component, system or grid)	Component
Model scale (scaling, 1D, 2D 3D, multiscale)	2D

(Major) inputs and outputs	Modelica.FluidPorts (Inlet and Outlet), Modelica.Thermal.HeatPort (Heatflow on surface), Real-Input for electrical power
Is it static or dynamic?	Dynamic
Is it design only or off-design?	Off-design
Is the model validated? How?	A previous Model is explained and validated in https://iewt2021.eeg.tuwien.ac.at/download/contribution/fullpaper/133/133_fullpaper_20210831_083200.pdf
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	Is coupled to a central energy station with heat pumps, hot water storage and district heating
Could the model be coupled to a specific system?	
Does the model use or provide data from/to other models you are using?	Siehe CFD
Model limitations/simplifications	- Constant spez. heat capacity of the solid - Homogenous flow distribution - Temperature is only calculated along the direction of flow
Approximate run time on a stationary PC	Ca. 1 min for 1 week simulation time
Publications connected to the model	https://iewt2021.eeg.tuwien.ac.at/download/contribution/fullpaper/133/133_fullpaper_20210831_083200.pdf
Details of the software	
Simulation environment	OpenModelica
Software license required?	No

Used databases or model libraries? Commercial?	ModelicaStandardLibrary
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	
Why did you choose this software?	Opensource, multipysical, object-oriented
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	Not yet
To what extent is the model available to IEA partners (use, modify, etc.)?	
What are the terms for model users (co-authorship, papers to cite, etc.)?	
Contact person (name and e-mail)	THM

IEA Task 36: Model Factsheet for TransiEnt Library

Dynamic system simulation model library, which can be applied to investigate the ETES energy storage technology. ETES is based on high temperature thermal energy storage in a packed bed, direct electric heating and uses air as heat transfer fluid. The library is written in the Modelica language and tested with the Dymola simulation environment.

Details of the model	
What is the model used for?	ETES System Simulation
Model level (component, system or grid)	System Level
Model scale (scaling, 1D, 2D 3D, multiscale)	1D Finite Volume Approach
(Major) inputs and outputs	Input: System Design (Setup and Parameters), Output: Performance
Is it static or dynamic?	Dynamic
Is it design only or off-design?	Off-Design is possible
Is the model validated? How?	Validated with SGRE ETES Demo Plant
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	Flexible system coupling is feasible due to model integration in dynamic energy system simulation environment
Could the model be coupled to a specific system?	yes
Does the model use or provide data from/to other models you are using?	yes
Model limitations/simplifications	1D
Approximate run time on a stationary PC	Approx. 10 hours run time for 1 month model time
Publications connected to the model	Models available at **www.tuhh.de/transient-ee**
Details of the software	
Simulation environment	Modelica - Dymola
Software license required?	Yes
Used databases or model libraries? Commercial?	-
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Yes, for example using FMI Standard
Why did you choose this software?	Object-oriented, equation-based modeling
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	yes
To what extent is the model available to IEA partners (use, modify, etc.)?	Available under 3-clause BSD License
What are the terms for model users (co-authorship, papers to cite, etc.)?	3-clause BSD License
Contact person (name and e-mail)	Michael von der Heyde (michael.vonderheyde@siemensgamesa.com)

For questions or comments regarding the model factsheet template: Kai Knobloch, kaikn@dtu.dk

IEA Task 36: Model Factsheet	
Steady-state part load model of a Rankine Carnot Battery	
Details of the model	
What is the model used for?	Sizing and performance simulation
Model level (component, system or grid)	Heat pump + ORC
Model scale (scaling, 1D, 2D 3D, multiscale)	1D
(Major) inputs and outputs	Inputs: Heat source and heat sink conditions Outputs: COP, efficiency…
Is it static or dynamic?	Yes
Is it design only or off-design?	Off design
Is the model validated? How?	Yes based on the RENEWBAT prototype
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	Just oil boiler for now
Could the model be coupled to a specific system?	yes
Does the model use or provide data from/to other models you are using?	No
Model limitations/simplifications	Small to medium power range (<100 kWe)
Approximate run time on a stationary PC	Few seconds
Publications connected to the model	https://orbi.uliege.be/bitstream/2268/ 251724/1/ECOS_2020_PAPER_reviewed.pdf
Details of the software	
Simulation environment	Matlab
Software license required?	Yes
Used databases or model libraries? Commercial?	Open source
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance	Yes
Why did you choose this software?	Used widely
IEA partnership	

Can the provided details be published in the final Task 36 report or a review article)?	Yes
To what extent is the model available to IEA partners (use, modify, etc.)?	Open source
What are the terms for model users (co-authorship, papers to cite, etc.)?	No terms
Contact person (name and e-mail)	Olivier.dumont@uliege.be

IEA Task 36: Model Factsheet

EBSILON®Professional

www.ebsilon.com

steag

EBSILON®Professional (product of STEAG company) is a simulation system for thermodynamic cycle processes that is used for plant planning, design and optimization. Maximize the benefits of repowering and retrofitting measures by simulating them in EBSILON®Professional. Design a performance-optimized plant for your application scenario by introducing specific parameters into the model. Calculate the effects of component degradation, various load cases and changes in environmental conditions. Simulate the operation of newly developed components in a cycle.

Details of the model

What is the model used for?	DEMO fusion power plant simulation
Model level (component, system or grid)	System
Model scale (scaling, 1D, 2D 3D, multiscale)	0D/1D
(Major) inputs and outputs	Inputs: powers of heat sources, coolant temperatures, pressures and flowrates, pressure drops for all pipelines connecting system components (where available). Outputs: energy balances for all components and the whole system
Is it static or dynamic?	Mainly static (Quasi-Dynamic/Transient simulation is possible)
Is it design only or off-design?	Both
Is the model validated? How?	Validated with such codes as Apros and GateCycle
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	The main source of energy for the model is fusion power plant demonstrator (DEMO)
Could the model be coupled to a specific system?	Depending with what system – should be tested
Does the model use or provide data from/to other models you are using?	Yes, it provides energy balances for Apros and GateCycle codes
Model limitations/simplifications	Model does not include inertia, nor real geometry of the components

Approximate run time on a stationary PC	In the order of minutes
Publications connected to the model	Yes, mainly in FED, also in Energies
Details of the software	
Simulation environment	Ebsilon
Software license required?	Yes
Used databases or model libraries? Commercial?	Commercial
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Extracting of data possible. Feeding of external data – should be tested
Why did you choose this software?	It is the best what is available from the industry
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	TBD
To what extent is the model available to IEA partners (use, modify, etc.)?	Restricted to KIT internal users
What are the terms for model users (co-authorship, papers to cite, etc.)?	Co-authorship
Contact person (name and e-mail)	Evaldas Bubelis E-mail: evaldas.bubelis@kit.edu

IEA Task 36: Model Factsheet

tespy['tɛs.paɪ]
open energy modelling framework

TESPy stands for "Thermal Engineering Systems in Python" and provides a powerful simulation toolkit for thermal engineering plants such as power plants, district heating systems or heat pumps. It is an external extension module within the Open Energy Modeling Framework and can be used as a standalone package.

Key Features

- **Open** Source
- **Generic** thermal engineering applications
- **Automatic** model documentation in LaTeX for high transparency and reproducibility
- **Extendable** framework for the implementation of custom components and component groups
- **Postprocessing** features like exergy analysis and fluid property plotting

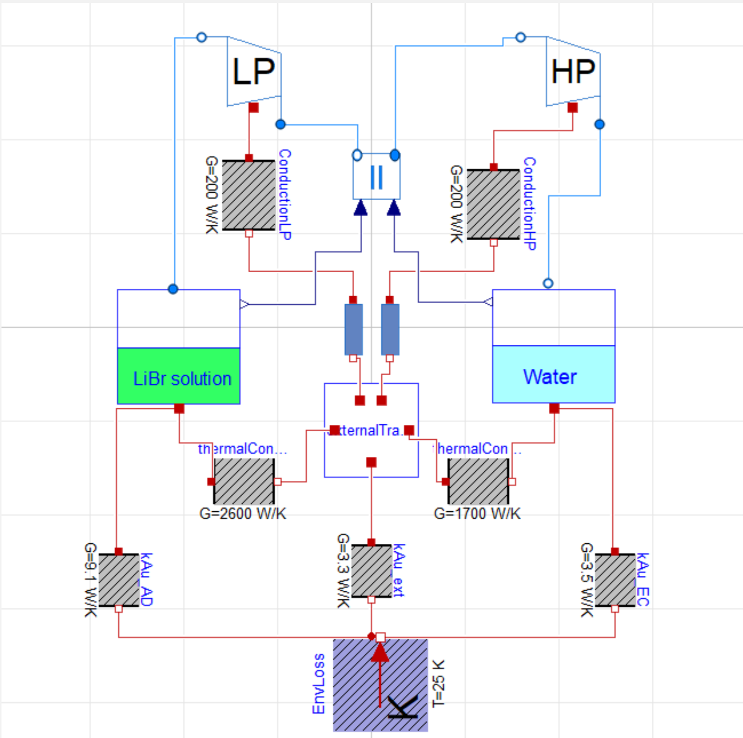
https://tespy.readthedocs.io/en/main/index.html

Details of the model	
What is the model used for?	CO2 Heat pump, phase diagrams
Model level (component, system or grid)	Component, system to some extend
Model scale (scaling, 1D, 2D 3D, multiscale)	0D/1D
(Major) inputs and outputs	Inputs: type of working gas, thermodynamic parameters like temperatures, pressures etc.
Is it static or dynamic?	Mainly static (Quasi-Dynamic/Transient simulation is possible)
Is it design only or off-design?	off
Is the model validated? How?	- (All component and connection property equations derive from balance equations for fluid composition, mass flow and energy in regarding thermal as well as hydraulic state and thermodynamic fluid property equations respectively. The corresponding literature is linked on the homepage)
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	District heating, power plants, heat pumps etc.

Could the model be coupled to a specific system?	Application programming interface well documented.
Does the model use or provide data from/to other models you are using?	-
Model limitations/simplifications	Dynamic, comprex processes – see homepage
Approximate run time on a stationary PC	In the order of minutes
Publications connected to the model	https://tespy.readthedocs.io/en/main/zliterature.html
Details of the software	
Simulation environment	Linux, Windows, MacOS
Software license required?	-
Used databases or model libraries? Commercial?	References to literature, non-commercial
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	Based on the requirements – open structure enables to integrate Python code
Why did you choose this software?	Free software, good for teaching for students that know Python, good example codes that can be adapted.
IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	yes
To what extent is the model available to IEA partners (use, modify, etc.)?	Open source
What are the terms for model users (co-authorship, papers to cite, etc.)?	TBD
Contact person (name and e-mail)	Joachim Fuchs, Ferdinand Schmidt E-mail:joachim.fuchs@kit.edu; ferdinand.schmidt@kit.edu

IEA Task 36: Model Factsheet

Lamm Honigmann thermochemical energy storage based on liquid sorption
- it comprises different models for the expansion/compression device (e.g. simplified turbine, rotary vane expander or piston expander/compressor)
- possibility of an internally heated expansion/cooled compression
- absorber/desorber and evaporator/condenser are highly simplified



Details of the model	
What is the model used for?	instationary process simulation for charging and discharging
Model level (component, system or grid)	component based system model
Model scale (scaling, 1D, 2D 3D, multiscale)	1D; Scaling around 1kW but scalable
(Major) inputs and outputs	Input: component properties (expander/compressor geometry, rpm or output/input power, working fluid masses, thermal masses of HX's and storage tanks, overall heat transfer coefficients) and thermodynamic start values, working fluid pair's thermodynamic property data (equilibrium data and sorption enthalpies of the mixture, general data of the sorbate)

	Output: power or rpm, mass flow rate, energetic and exergetic efficiencies, thermodynamic states of the working fluids
Is it static or dynamic?	dynamic
Is it design only or off-design?	off-design
Is the model validated? How?	not yet, validation is work in progress in TU Berlin's laboratories (results ready probably in 2023)
Is the model coupled to a specific system (district heating, wind, solar, power plant, waste heat, geothermal, LNG, etc.)?	currently no, but modifications to couple to a system without changing the model are possible
Could the model be coupled to a specific system?	yes, Modelica models of heat or electricity sources/sinks could be connected to the system model
Does the model use or provide data from/to other models you are using?	some input parameters for the piston engine are calculated in MATLAB with data from an independent Dymola component
Model limitations/simplifications	main assumptions in the heat exchangers and storage tanks: thermodynamic equilibrium, ideal mixing, no vapor room (immediate absorption/condensation of incoming vapor/ immediate outflow of desorbed/evaporated vapor), constant overall heat transfer coefficients
Approximate run time on a stationary PC	few seconds to a few minutes depending on discharge duration and simulation tolerance
Publications connected to the model	doi: 10.1093/ijlct/ctt022, uri: 10.14279/depositonce-8201 non-published: Bachelor and Master theses (available on request)
Details of the software	
Simulation environment	dymola (Modelica)
Software license required?	yes
Used databases or model libraries? Commercial?	in-house dymola libraries for the working fluid pair properties of LiBr/water and NaOH/water, ModelicaStandardLibrary, ThermoCycleLib
Is it possible to fit it into another structure, e.g. calling it externally and extracting data of relevance?	possibility of running scripts to import model parameters and export simulation data, e.g. for use in MATLAB
Why did you choose this software?	graphical interface and component-based approach are advantageous; dynamic system - the engineer can focus on the modeling equations while dymola creates the system of differential equations and chooses functional solvers automatically

IEA partnership	
Can the provided details be published in the final Task 36 report or in a review article?	yes
To what extent is the model available to IEA partners (use, modify, etc.)?	generally available after consultation with the contact person
What are the terms for model users (co-authorship, papers to cite, etc.)?	depending on the use case - please contact us.
Contact person (name and e-mail)	Elisabeth Thiele (e.thiele@tu-berlin.de)

3.6 Appendix 6: Definition and Description of Technology Readiness Level Ranking System

Table 27: Definition and description of TRL ranking system

TRL	Definition and description
TRL 1	Basic principles are observed, scientific research is beginning, and the new concept is proposed.
TRL 2	The technology concept is formulated. The basic principles have been studied and the first evaluation about the feasibility is performed. It is a very speculative stage, as there is little to no experimental proof of concept for the technology.
TRL 3	Active research and design begin, both analytical and laboratory studies are required at this level to see if a technology is viable and ready to proceed further through the development process, i.e., experimental proof of concept.
TRL 4	The technology is validated in lab. Multiple component pieces and key enabling technologies are tested with one another.
TRL 5	The technology is validated in relevant environment. The technology undergoes more rigorous testing than technology that is only at TRL 4. Simulations should be run in environments that are as close to realistic as possible.
TRL 6	The technology is demonstrated in relevant environment. A fully functional prototype or representational model is built and to be tested in relevant environment. Manufacturing approach is defined. Environmental, regulatory and socio-economic issues are addressed.
TRL 7	The system prototype is demonstrated in an operational environment at pre-commercial scale. Compliancy with relevant environment conditions, authorization issues, local/national standards is guaranteed, at least for the demo site.
TRL 8	The system is complete and qualified. First of a kind commercial system is built. Manufacturing issues are resolved for entering a low-rate production.
TRL 9	The actual system (commercial scale) is proven in operational environment. The technology starts its full commercial application, with the technology available for consumers. Full production chain is in place and all materials are available.