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IEA Technology Collaboration Programme

International Energy Agency
Technology Collaboration Programme on Energy Storage
(ES TCP)

Task 36
Carnot Batteries
Executive Summary

TASK 36 CARNOT BATTERIES

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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. <u>Tech to Market Transition Barriers:</u>
   - 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. <u>Commercialization Barriers:</u>
   - 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. <u>Clarity and Fairness in Policy and Regulation:</u> 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. <u>Financial Support Policies:</u> 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. <u>Demand-Supporting Policies:</u> Create policies that incentivize private investment in Carnot Batteries to drive demand for deployment.
4. <u>Valuation of Full Spectrum of Services:</u> 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.

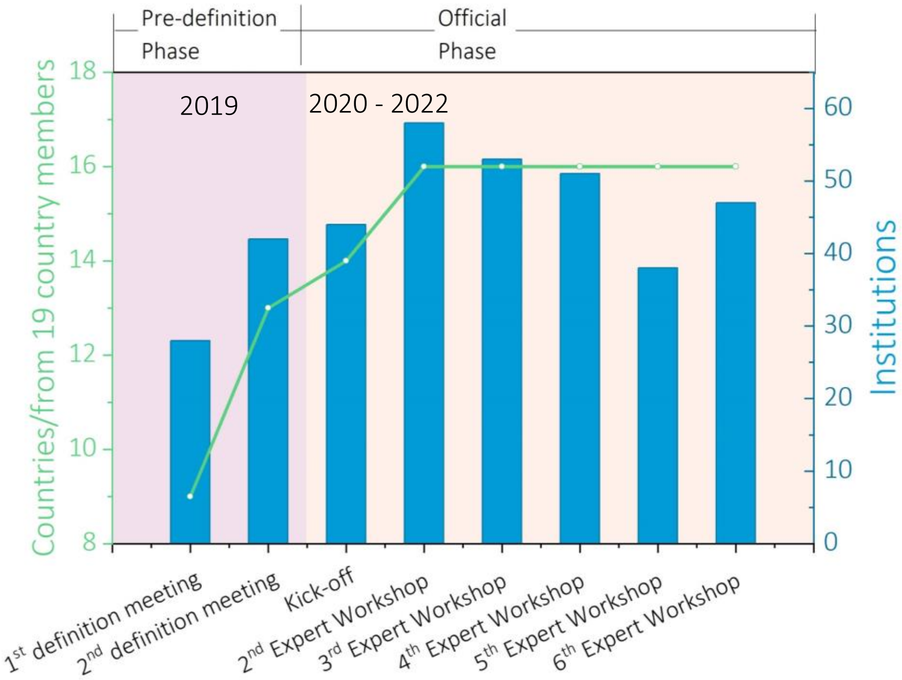


Figure 1: Overview of countries and institutions participating from 2019 to 2022.

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 0 and 0 Appendix 2), white paper on thermal energy storage methods for Carnot Batteries (see 0 and 0 Appendix 3), and the assessment of TRL of Carnot Battery systems and components (see 0). 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 0.

- 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 0 and 0 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 0. 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 0.
- 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 0. 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 0 and all the fact-sheets are included in 0 Appendix 3. The modelling and simulation Factsheets are summarized in subsection 0 and al the fact-sheets are included in 0 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 0. 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:

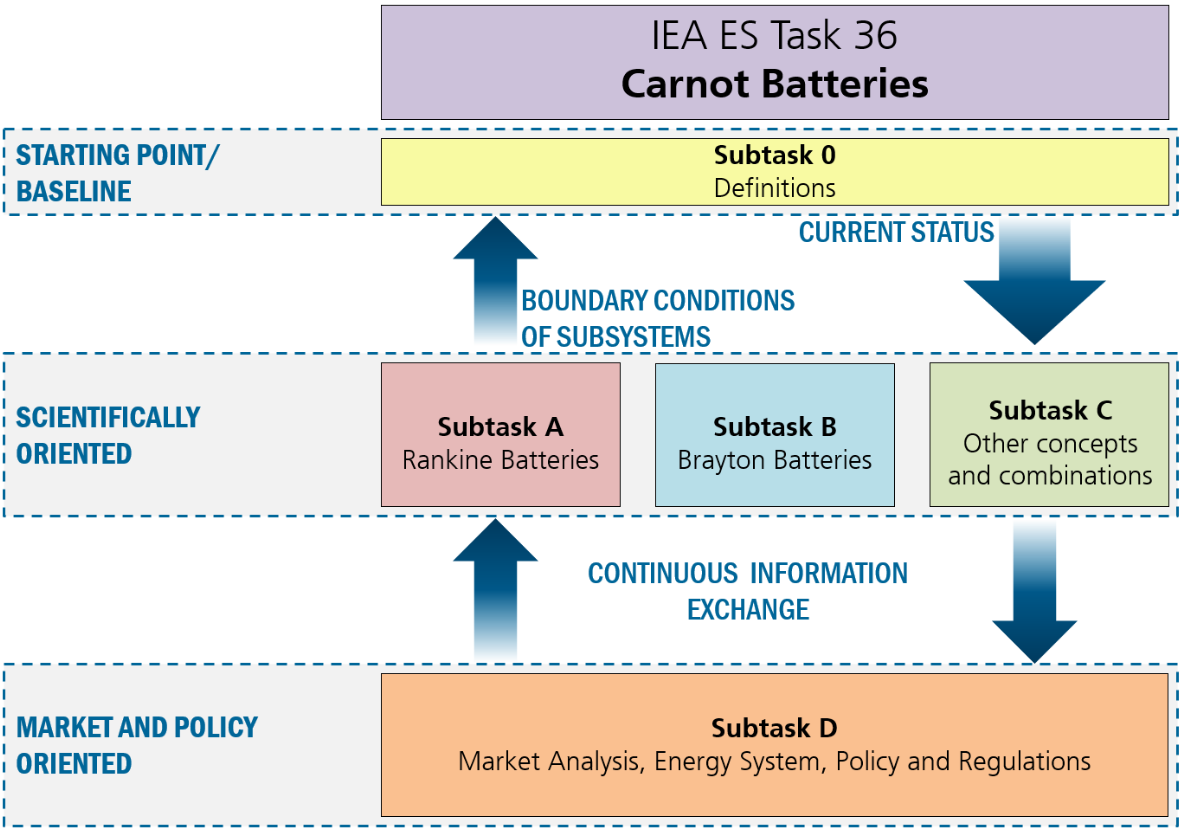


Figure 2: Structure of the IEA ES TCP Task 36.

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

[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 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	☑ (0)	☒
ST0-2	Key performance indicators	☑ (0)	☒
ST0-3	State-of-Art Carnot Batteries	☑ (0)	☑ (Appendix 2; White paper)
ST0-4	TES Methods for Carnot Batteries	☑ (2.1.4)	☑ (Appendix 3; White paper)
ST0-5	Wikipedia Page	☑ (0)	☑ (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).

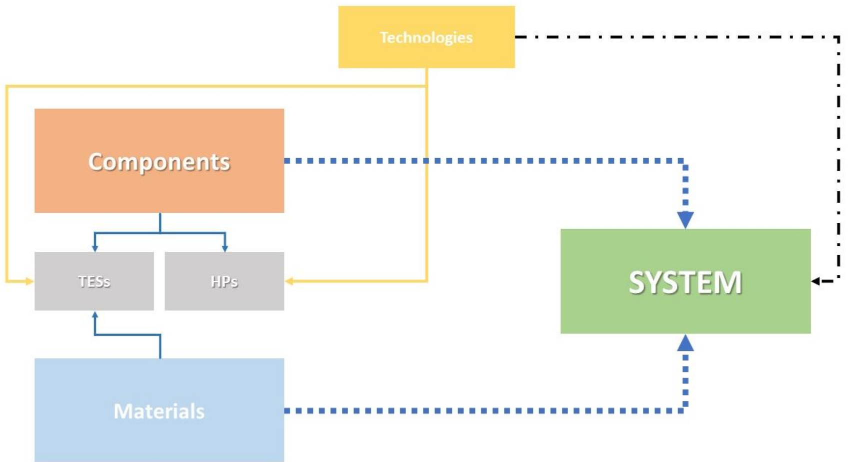


Figure 3: KPIs' structure definition.

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 0 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.

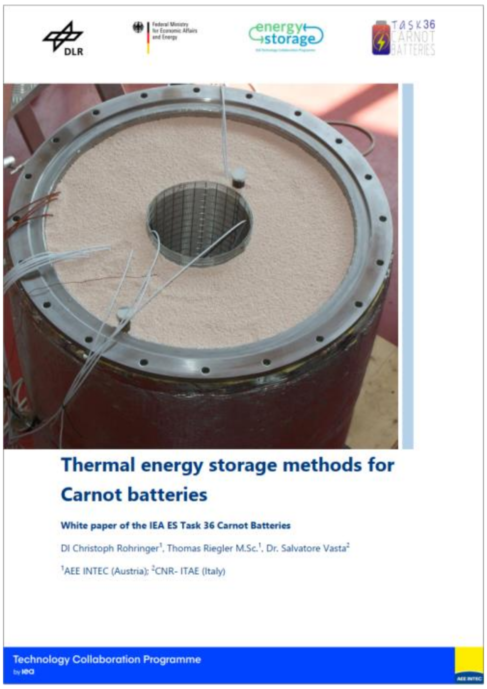


Figure 4: Cover of white paper on TES methods for Carnot Batteries.

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.

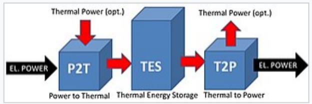
Carnot battery

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]



A simplified scheme of a typical Carnot battery system

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]

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.

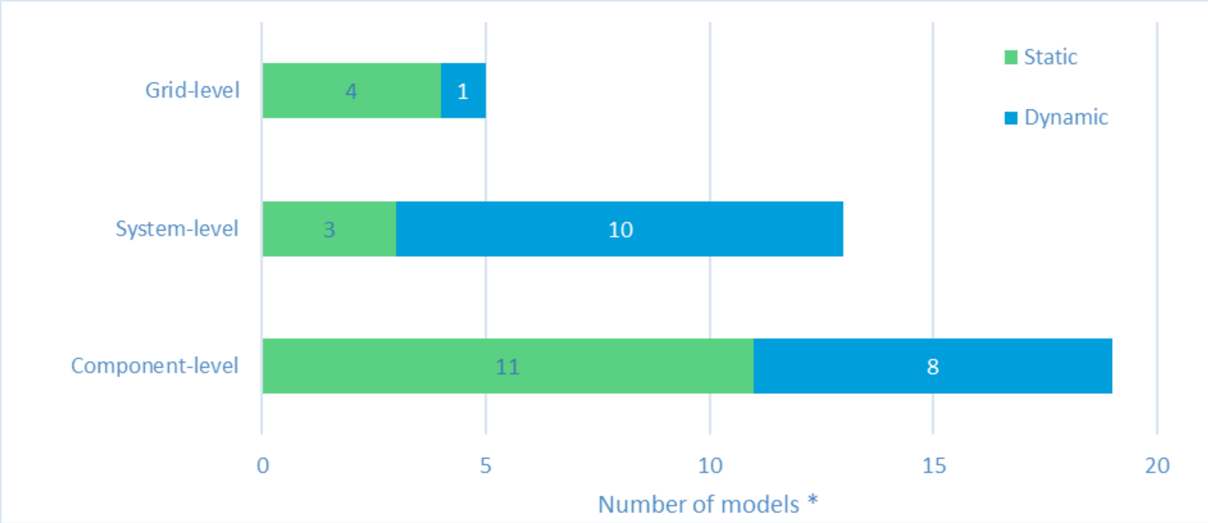


Figure 6: Overall categorization of models from gathered Factsheets.
* Please note that the sum of these numbers is above 35 since some models were categorized by two model levels.

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 0, 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 0 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.

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 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.

Commercialization Barriers

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.