Powering a Revolution:

The Potential of Carnot Batteries in the Built Environment

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“In the midst of chaos, there is also opportunity.”

Sun Tzu

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Abstract

The world needs reliable, sustainable, and longer duration energy storage solutions as the share of intermittent renewable energy increases in energy systems. Carnot batteries are a promising, emerging technological class of energy storage that store electricity in the form of thermal exergy. They can be made from abundant materials and existing technology, are durable, have a low specific cost, store energy for medium-to-long periods, and cogenerate heat and power. Previous studies have simulated thermodynamic components, optimized system design and control, and investigated application potential of Carnot batteries at different scales and environments with promising findings that suggest the energy storage can be competitive and even outperform mature energy storage technologies on the market.

Carnot battery potential in the metropolitan environment is still being explored and specific case-studies are needed to further validate the functional utility of the technology. The aim of this research is to investigate Carnot battery potential for a practical use-case with an existing building through a research-for-design approach. Data is gathered through literature, commercial sources, and interviews with experts informed the design and application of the energy storage system in an urban context in the Netherlands. With the goal of net-positive energy building performance, an analysis based on energy balance, hypothetical onsite renewable energy potential, spatial considerations, and two different scenarios was conducted on an existing building using real energy data.

The implementation of Carnot batteries to existing buildings can manage electricity and heat services, provide a cost-competitive energy storage option, and reduce carbon emissions released into the environment when coupled to renewable energy systems over the lifetime of the technology. The findings indicate massive potential for Carnot batteries to contribute to urban energy storage needs.

Keywords: *Carnot battery, energy storage, renewable energy systems, net-positive energy buildings (PEB), design, analysis, metropolitan, urban, cities, buildings*

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Nomenclature

CapEx: Capital Expenditure

CB: Carnot Batteries

CES: Chemical Energy Storage

CHP: Combined Heat and Power Generation

COP: Coefficient of Performance

CCGT: Combined Cycle Gas Turbine

DoD: Depth of Discharge

DHW: Domestic Hot Water

EcES: Electrochemical Energy Storage

EES: Electrical Energy Storage

ESS: Energy Storage Systems

ETES: Electro-Thermal Electricity Etorage

EV: Electric Vehicle

FES: Flywheel Energy Storage

GHG: Greenhouse Gas

HP: Heat Pump

LAES: Liquid Air Energy Storage

LCOE: Levelized Cost of Energy

LiB: Lithium-ion Battery

MES: Mechanical Energy Storage

mTIPTES: Multi-energy Thermally Integrated Pumped Thermal Energy Storage, can provide final user electricity, heating, and cooling.

Ni-Cd: Nickel-Cadmium

NZEB: Net-zero Energy Building

OpEx: Operational Expenditure

ORC: Organic Rankine Cycle

P2H2P: Power to Heat to Power

PEB: Positive Energy Buildings

PHES: Pumped Heat Electricity Storage

PHS: Pumped-Hydro Storage

PTES: Pumped Thermal Electricity Storage

RES: Renewable Energy Sources

SR: Sub-Research question

TES: Thermal Energy Storage

TIPTES: Thermally Integrated Pumped Thermal Electricity Storage

TRL: Technology Readiness Level

VRB: Vanadium Redox Batteries

1: Introduction

1.1 Context

The world is adopting renewable energy at a rapid pace in response to global climate change driven by greenhouse gas (GHG) emissions (Mitali et al., 2022; Sadeghi, 2022). In an unprecedented global response to GHG emissions, hundreds of countries encompassing the majority of emitters commit to keeping global temperature rise as close as possible to a maximum of 1.5°C above pre-industrial levels (UNFCCC, n.d.). Renewable energy is crucial to implement into global energy systems because in contrast to fossil fuel sources of energy, little to no greenhouse gases are emitted during operation (Mitali et al., 2022). Energy systems need to transition from fossil fuel-based production to renewable energy to reduce negative consequences on our environment. This urgent call-to-action builds on decades of rigorous scientific study into the impacts of human activity on Earth's system and is echoed in the latest release of the Intergovernmental Panel on Climate Change AR6 Synthesis Report (IPCC, 2023).

However, many renewable energy sources (RES) are intermittent in their production. In a practical sense, this often entails that energy generated in times of low demand and This challenge of intermittency impacts all sectors that use energy, especially the built environment where we work, play, and live most of our lives. Buildings make up nearly 40% of global energy demand (Anand et al., 2023). Beyond this, overall energy consumption is expected to increase as societies electrify, continue to evolve, and industrialize (Kabeyi & Olanrewaju, 2022; Mitali et al., 2022; Sadeghi, 2022). Further related to the challenge of improving energy performance and consequently reducing negative GHG externalities, new architectural approaches to energy in the built environment, such as positive energy building (PEB), have been gaining traction in recent years (Rehman & Ala-Juusela, 2022). PEBs are broadly discussed as buildings that produce more energy than they consume, through renewable sources (Rehman & Ala-Juusela, 2022).

As more cities and buildings transition to intermittent renewable energy sources, the demand for energy storage is growing (Chakraborty et al., 2022). We need sustainable, affordable, and versatile energy storage systems (ESS) to store and supply energy at the time it is needed.

1.2 General Overview of ESS

As of 2021, renewable energy sources represent 30% of the global power generation mix (Mitali et al., 2022). ESS are viewed as the most efficient and practical solution to balance mismatch in energy supply and demand. Furthermore, ESS can help alleviate overload that occurs when too much produced electricity from renewables flows into the grid (Mitali et al., 2022).

The scope of ESS encompasses a range of technologies. Classified by the form of energy stored, there are five major categories of ESS with examples: thermal energy storage (TES) like aquifer thermal energy storage, mechanical energy storage (MES) such as pumped hydro-storage, chemical energy storage (CES) where energy is stored in chemical bonds like gasoline, electrochemical energy storage (EcES) that encompasses tech such as Li-ion batteries, and electrical energy storage (EES), like supercapacitors (Chakraborty et al., 2022; Mitali et al., 2022).

1.3 Carnot Batteries

Carnot Batteries (CB) are seen as a promising subcategory of ESS as it blends thermal and mechanical storage concepts. CBs are defined as “energy storage solutions where electricity is stored as thermal exergy” consisting of a charge, storage, and discharge phase (Vecchi et al., 2022). The basic working concept is depicted in **Figure 1.1**.

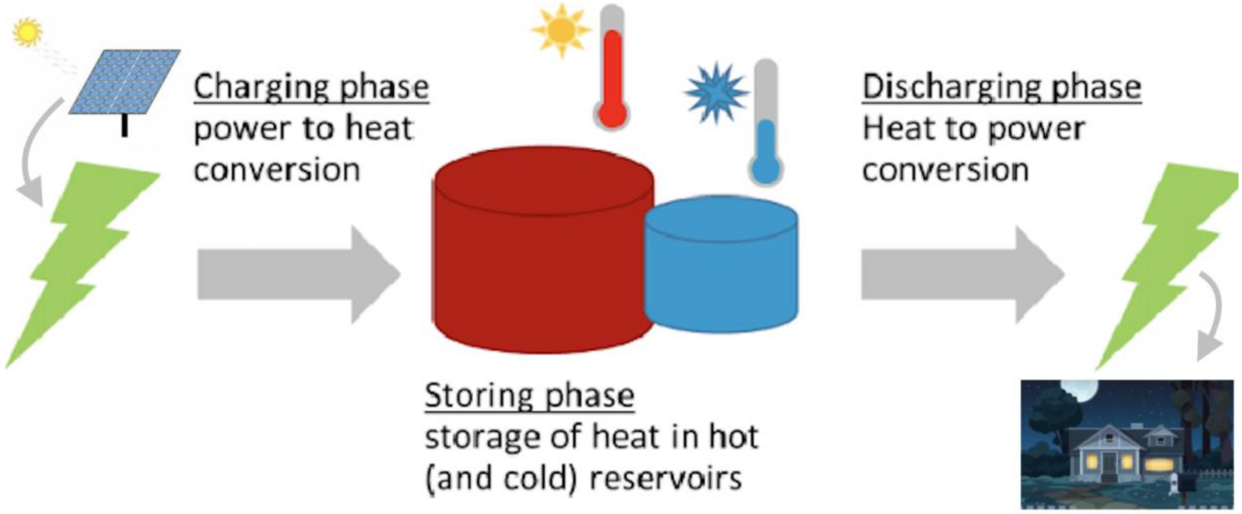


Figure 1.1. Carnot battery principle as presented in Rindt et al. (2021).

CBs combine mechanical components such as heat pumps (HP), electric resistance heaters (charge), and heat engines (discharge) with thermal storage mediums. It is possible to configure CBs with hot and cold storage reservoirs, or just one of the two. CBs are named after an ideal thermodynamic cycle, the Carnot cycle. The Carnot cycle was proposed by French Physicist Sadi Carnot in which energy is transferred in the form of heat between two reservoirs, with no generated entropy (Dickerson & Mottmann, 2019).

At a glance, CBs have power densities ranging from 0.5-17 kW/m^3, energy densities of 10-100 kWh/m^3, efficiencies ranging from 50-75%, and lifetimes of >25 years (Mitali et al., 2022). It is worth noting that these value ranges are derived from multiple forms of pilot prototypes and theoretical CB projects, which have differences in their configurations, use-cases, and components—such as working fluids. As a term, CB covers a range of thermomechanical storage concepts, such as liquid air energy storage (LAES) and pumped thermal energy storage (PTES), with examples shown in **Figure 1.2** (Vecchi et al., 2022).

Furthermore, CBs can be distinguished by working cycles. Brayton and Rankine cycles are two power cycles for the conversion of thermal energy to mechanical work, and the distinction between 'Brayton' and 'Rankine' PTES reflects specific characteristics of the cycles (Vecchi et al., 2022). Brayton cycles employ a gaseous working fluid with no phase change and is found in gas turbine engines like aircraft, with Brayton PTES having typical temperature ranges of -170 to 950 °C and pressure ranges of 1 to 20 bar (Vecchi et al., 2022). The Rankine cycle has a couple key differences. The Rankine cycle employs a working fluid (e.g., water) that undergoes a phase change such as the basic combustion to heat water (steam) process found in a typical coal fired power plant, with Rankine PTES operating at ranges of -30 to 400 °C and pressures ranges between 1 and 200 bar (Vecchi et al., 2022).

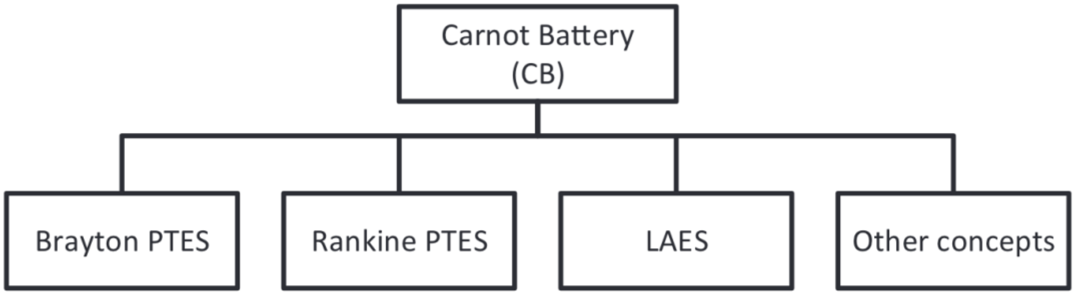


Figure 1.2. Basic overview of thermomechanical concepts that are considered CBs, categorized by broad working principles and cycles (Vecchi et al., 2022).

CBs are a promising emerging ESS that have experienced a surge in research interest due to a lack of geographical limitations, low specific cost, ability to integrate multiple energy forms and systems (e.g. thermal, electric), independence from the need for fossil fuel streams, and the ability to use many "off-the-shelf" components already on the market (Dumont & Lemort, 2020; Frate et al., 2020; Mitali et al., 2022; Sadeghi, 2022; Vecchi et al., 2022). These features mean CBs can be charged with electricity (from solar, wind, nuclear, etc.) or heat, store energy for long periods, and discharge both heat and electricity. CBs may also be synonymously referred to as: pumped heat electricity storage (PHES), PTES, electro-thermal electricity storage (ETES), thermo-electric energy storage, thermal batteries, and LAES (J. McTigue, 2019).

Emerging from researchers, engineers, and innovators across the global community are numerous CB prototypes and system designs at various stages of commercial development. An overview of system techno-economic performance, applications, and commercial state-of-the-art is presented in Vecchi et al (2022). In their analysis of discrepancies between scientific research and implementation of systems in ongoing projects—the authors identify the gap between scales, considered layouts (e.g., Rankine cycle vs. Brayton PTES), the integration of thermal supply and demand, and the need for case-specific analysis as further directions for CB research.

1.4 Problem Statement

Decarbonizing energy systems in the built environment is a massive challenge and can contribute to reducing significant amounts of GHG emissions. The confluence of the state of development of CBs, the need for energy storage, and sustainable building approaches provide strong motivation for this research in a metropolitan context. The call for application and analysis of CB systems to representative, specific case-studies from Vecchi et al. (2022) has been further echoed in Frate et al. (2020) and represents a knowledge gap this research aims to address. The synergy between CBs and PEBs is a promising area of research. CBs are an emerging, under-researched technology that have potential to be a cost-effective ESS in the built environment energy transition.

1.5 Research Aim and Questions

The aim of this research is to investigate the state of Carnot battery (CB) systems, understand how the current market is developing, identify important economic and environmental criteria of ESSs, explore how impact is assessed, compare CBs with existing mature energy storage technologies, investigate CB potential for application in practical use-cases with existing buildings, and employ these insights to design and analyze a basic energy system with CBs as energy storage. The potential intersection of CBs with positive energy building practices—paired with increasing renewable energy source penetration, contributes to goals of reducing emissions from energy systems and networks (Rehman & Ala-Juusela, 2022). PEBs are an important progression of net-zero energy building (NZEB) in the pursuit of increasing energy independence, resilience, security, and sustainability. This work serves to build upon the potential synergy of this vision with an emerging, promising ESS.

Main Research Question

What potential economic considerations and environmental impacts does the implementation of Carnot batteries have on the energy profile of existing buildings?

Sub-research Questions

1. What is the current state of Carnot battery research and commercial development?
2. What are important techno-economic and environmental indicators for energy storage systems and how is this impact assessed?
3. What mature energy storage systems exist on the market, what are their key features, and how do CBs compare?
4. What conditions in the built environment are relevant for a CB-based energy storage system?
5. What is an example design or structure of an existing building using a Carnot battery?

1.6 Scope

The scope of this study will center around employing existing techno-economic performance and indicators of emerging CB projects to conduct research-for-design, with the design being the implementation of a CB to a case study. The research will not focus extensively upon exact materials, engineering, or the particle technology of the various CB configurations, but rather the cohesive system's performance as energy storage as a part of an energy ecosystem. The research will be conducted from a perspective that aims at integrating disciplinary research and commercial progress of CBs to explore their potential in buildings. Mature ESS technologies for comparison will be selected through the technology readiness level (TRL). The foundation for systematic review of CB technology is drawn from Vecchi et al. (2022).

Energy efficiency and performance characteristics will be derived from existing structures unless otherwise noted, therefore environmental conditions will be determined by where actual buildings are located and real-world performance data has been gathered. The role of PEB in this study is as an organizing architectural vision towards the goal of annual net-positive energy production. CBs are focused upon as the means towards this visionary end-state, as a constituent technology of an energy system. Data for PEB performance, energy systems, scale, and characteristics can be adopted from the scholarly literature. This same approach applies to CBs.

Scaling of the CB system to the optimal built environment scale will be determined by the gathered data to maximize feasibility of the end design. The end design will be on a basic conceptual level.

Potential Ethical Dilemmas

A potential ethical dilemma that arises from this research can be related to stakeholder interests. Since qualitative expert interviews are part of the methodology, private stakeholders may act in their own interest and misrepresent or embellish data about CB prototype performance, pilot projects, and general economics of these emerging systems. This dilemma can be reduced by seeking a range of input from various sources, companies, or stakeholders who represent different entities involved with development of CB technology.

2: Theoretical Framework

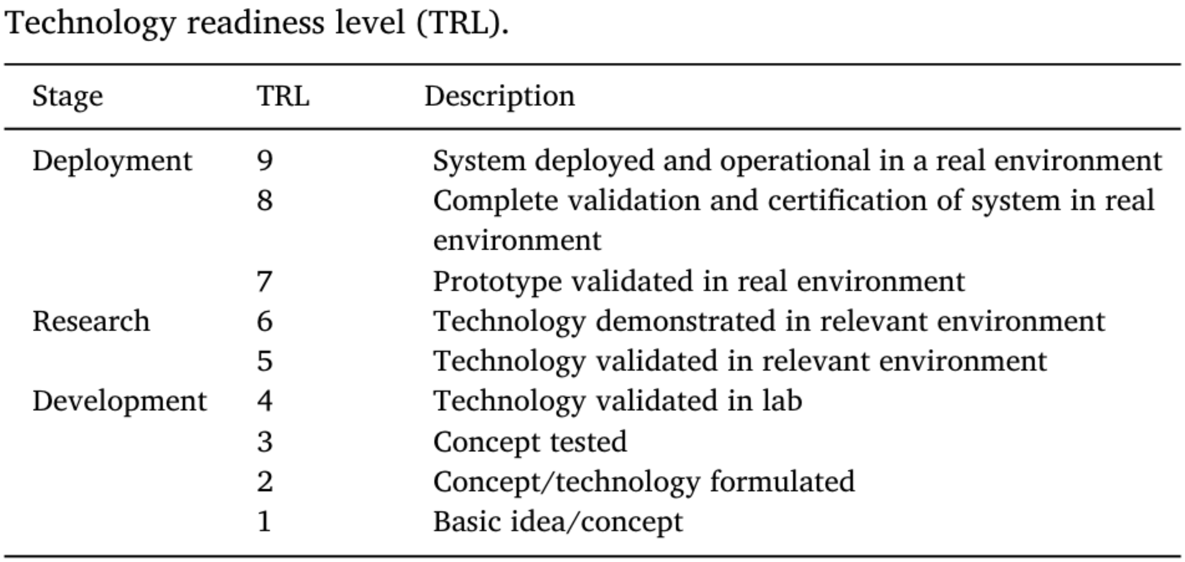
The two main frameworks that inform the theoretical basis for answering the main research question are research-for-design (Section 2.1, also referred to as *research-based-design*) and technological readiness level (Section 2.2). This chapter will explore both and present how they will be applied to this report.

2.1 Research-for-design

Through the approach of research-for-design, “research feeds the design process with the ultimate objective to improve the quality of the designed object and increase its credibility” (Nijhuis & Bobbink, 2012). In the context of this research, the designed object is a CB embedded in the energy ecosystem of a PEB. This builds upon the disciplinary research of CBs. While the specific energy portfolio, scale, and use-case of the PEB is included as a piece of the design, the main objective is to increase the credibility of CB systems in an envisioned practical application. This necessitates aligning the end-design with the common criteria of PEBs (e.g., renewable sources of energy, high energy efficiency). This methodology also encourages creative and interdisciplinary analyses of the research to inform the end-design (Nijhuis & Bobbink, 2012). This aspect of research-for-design further synchronizes the approach of the study with the defined sub-questions and associated methods. For example, qualitative research input from experts with various stakes and backgrounds related to CB technology can strengthen the ‘feeding’ of the design process.

2.2 Technology Readiness Level

The Technology Readiness Level (TRL) will be employed to judge which ESS are mature technologies and thus useful for comparison to the emerging CB technology. The TRL is a scale developed by NASA that standardizes the progress of a technology’s development and was later adopted by the New Research Framework (Mankins, 1995; Mitali et al., 2022). The nine-level scale starts with the most primitive technological state and ascends to the fully mature stage of a technology (Mitali et al., 2022). The levels are detailed in Figure 2.1.



Technology readiness level (TRL).

Stage	TRL	Description
Deployment	9	System deployed and operational in a real environment
	8	Complete validation and certification of system in real environment
	7	Prototype validated in real environment
Research	6	Technology demonstrated in relevant environment
	5	Technology validated in relevant environment
Development	4	Technology validated in lab
	3	Concept tested
	2	Concept/technology formulated
	1	Basic idea/concept

Figure 2.1 Technological Readiness Levels (TRL) and descriptions of the associated stage of a technology's development (Mitali et al., 2022).

Employing the TRL to assess maturity of different energy storage technology contributes to replicability and consistency within the foundation of this research.

Relation of the Frameworks

The methodological approach of research-for-design serves to drive interdisciplinary insights into designing a PEB system that includes CB as energy storage. To assess the performance and validity of the proposed design, the TRL serves to provide a consistent foundation for selecting, comparing, and contrasting proven mature energy storage technology with an emerging ESS. The economic and environmental performance indicators in the literature associated with mature technology will serve to inform and therefore increase the credibility of the design application of CBs to PEB environments.

3: Methodology

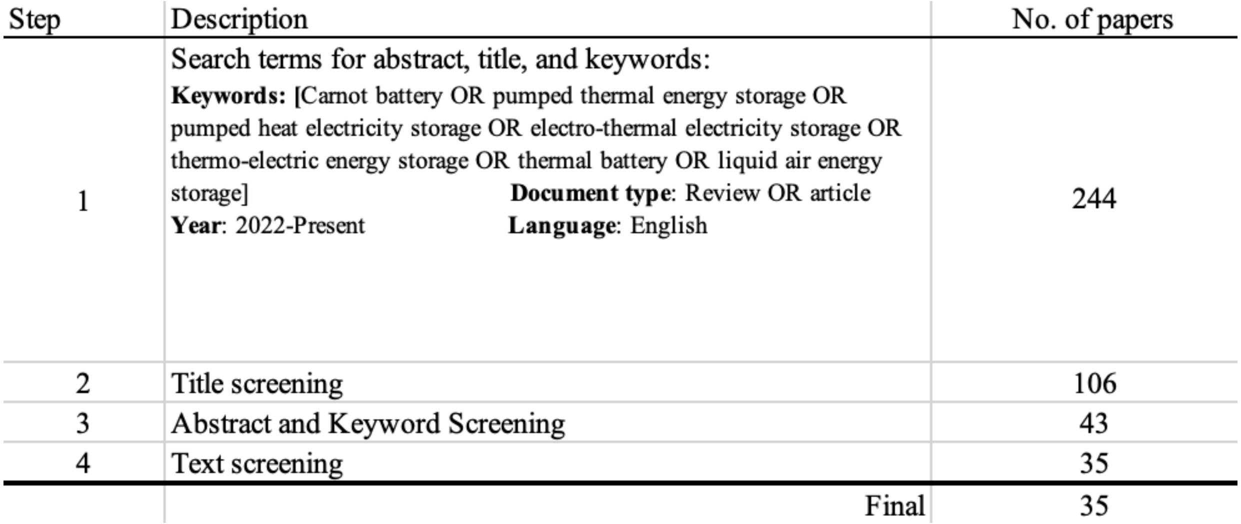
This work will be executed from a research-for-design approach with the use of the TRL as presented in Chapter 2. Mixed qualitative and quantitative methods from current literature, commercial projects, and expert input will inform design choices to explore the environmental and economic sustainability of Carnot batteries as a part of a positive energy building ecosystem.

3.1 SR1: Current State of Carnot Battery Research

Literature Review and Interviews

The current state of CB research and commercial development will be investigated through the scholarly literature, commercial data, and expert semi-structured interviews to answer SR1. Firstly, a systematic literature review into relevant research papers around the subject of CBs will be conducted. The systematic review will begin from the year of the most recent review work by Vecchi et al. (2022) up to the present. Articles or reviews including the specified key terms in their title, abstract, and keywords that relate to the emerging CB class of technology will be identified through the Scopus database according to this criterion. Title, abstract, and text screening for relevance to the research will follow. The criteria for inclusion in the systematic literature review is depicted in **Table 3.1**.

Table 3.1. Search criterion for inclusion in the systematic literature review.



Step	Description	No. of papers
1	Search terms for abstract, title, and keywords: **Keywords:** [Carnot battery OR pumped thermal energy storage OR pumped heat electricity storage OR electro-thermal electricity storage OR thermo-electric energy storage OR thermal battery OR liquid air energy storage] **Document type**: Review OR article **Year**: 2022-Present **Language**: English	244
2	Title screening	106
3	Abstract and Keyword Screening	43
4	Text screening	35
	Final	35

Additionally, qualitative input from professionals with relevant proximity to CBs, ESS in general, electrical engineering, renewable energy, and net-zero building will also be included to augment the literature insights. Interview participants will be located and contacted through LinkedIN, by email, and through contact lines through commercial webpages if applicable. Semi-structured interviews will be conducted through Microsoft Teams online meeting software, in-person, and online via email or messaging channels. Consent about participation in the research will be issued verbally prior to the conducting of the interviews. Names and individual likeness not related to the function of the research will be anonymized. Questions for each interviewee will be tailored to their unique background and experience in relation to the research (see sample as follows).

Sample Interview Questions (for a CB researcher):

- How did you first come across the concept of pumped thermal/Carnot batteries?
- Who is interested in your research/where does funding come from?
- What were your biggest takeaways from your Carnot battery/PEB research?
- What performance criteria do you think Carnot batteries must meet to be competitive with other mature technologies?
- How would you compare the state-of-the-art of Carnot batteries to other mature energy storage systems?
- Where is research and commercial interest coming from for CB technology?
- On what scale do you believe CBs are most effective on?
- How do you see the future of this technology evolving? 2 years, 5-10 years?
- What are directions for your future research?
- What conditions do you think would make Carnot batteries attractive for cities or metropolitan environments?

3.2 SR2: ESS Indicators

Literature Review and Interviews

Techno-economic and environmental indicators will be located through scholarly literature, especially review papers. The emphasis on review papers contributes towards gathering standardized indicators for comparisons across different technologies later in the research process. Case studies, systematic reviews, commercial data, and independent reports in addition to expert input will further the design process by enabling the research to orient CBs in context of the larger ESS picture.

Impact assessment will be explored through scholarly literature for techno-economic and environmental angles of ESS impact on the surrounding world, informing analysis about the sustainability of energy storage technologies. Qualitative input from interviews (e.g., researchers, employees of CB companies, etc.) about key economic and environmental performance indicators regarding ESS, subjective challenges, integration with different systems, and opportunities for advancement of CB application will be sought out.

3.3 SR3: Current State of ESS

Literature Review and Interviews

Building on the indicators identified and discussed in SR2, mature ESS technology will be located by literature review. Key features and distinct performance characteristics of the various technologies will be used to paint a more complete picture. Recent review articles will serve as the foundation for comparisons. Inclusion criteria for technologies is operationalized by the TRL, in which only mature systems will be eligible for comparison.

Furthermore, expert experience across different ESS systems and power systems in general will be used to augment the literature review. The goal of stakeholder outreach here is to harvest diverse perspectives on different scales, use-cases, and dynamics of the ESS technologies that ultimately serve to inform the end design. A specific CB system will be identified and explored to aid in anchoring any comparisons across mature technologies. Criteria for this selection will be based off availability of data and technological maturity.

3.4 SR4: Relevant Built Environment Conditions for ESS

Interviews and Literature Review

The purpose of this sub-research question is to set the table for the design. The previous sub-questions were aimed at understanding ESS and CB aspects that are important from a techno-economic and environmental impact perspective. The relevant conditions for application of CBs to the built environment will be set through the culmination of review of scholarly literature, commercial materials, and qualitative input from experts. Due to the wide reach of potential application and use-cases of ESSs, subjective decisions will have to be made to narrow down the scope to an adequate case study. However, the direction of the design will be guided by the data, insight, and experience gathered from the process of the previous research questions in addition to relevant studies that provide some model basis for replication.

As the research is conducted heavily from an energy perspective, conditions regarding the energy system of the case study will be weighted heavier as opposed to economic or social conditions. The topic of CB compatibility with other technologies and energy systems is an area of primary consideration due to its relevance in the design approach of this research. Expert input from real-world experience is favored over theoretical literature for the purposes of answering this sub-research question, but insight from all reputable sources will be considered.

3.5 SR5: Application of Carnot Battery

Data Collection, Design, and Analysis

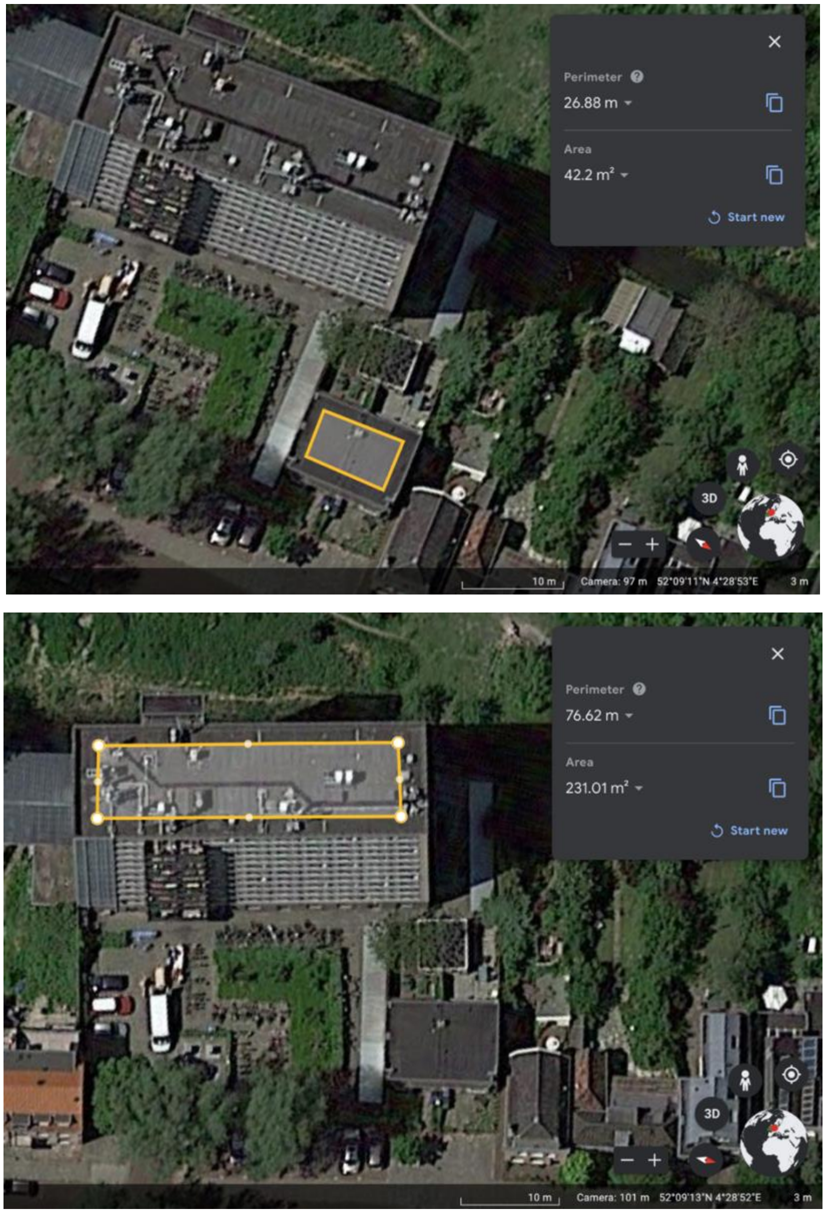
The goal of this sub-research question is to conceptualize an example of a CB applied to the built environment. For the design a case study location will be selected, onsite renewable power system estimated, energy balance analyzed, and economic aspects reported to contribute to answering the main research question.

3.5.1 Case Study

The case study building data comes from the e-portal Joulz (2023) and includes real measured energy consumption. Design drawings of the floorplan, facades, and descriptions of building characteristics come from DUWO (2013). The building energy data details the energy balance subdivided by electricity and gas consumption over timescales of representative days in summer and winter, 12-months, and annually. The days of June 20th and December 23rd are selected as representative days. This data will serve as the consumption side of the energy balance. For the production side of the energy balance, onsite renewable power system potential will be modelled.

3.5.2 Renewable Power System Potential

The basis for the onsite RES potential will be based off estimations of the compatible surface area in the facades and roof for photovoltaic (PV) panels. The 465W monocrystalline silicon Aiko N-Type ABC White Hole Series 54-cell panel is used as the reference solar panel for calculations. For the rooftops, Google Earth is used for a rough spatial estimate of surface area (see **Figure 3.1**). A safe zone of ~1.4m is assumed for the detached house rooftop while a ~2.2m safe zone borders the compatible area of the 11-story roof.



Perimeter 26.88 m

Area 42.2 m²

Perimeter 76.62 m

Area 231.01 m²

Figure 3.1. Aerial view of the case study location with spatial estimates of detached house (top) and 11-story (bottom) rooftop areas compatible with PV panel placement from Google Earth (2021).

For the facades, PV panels were scaled according to the 1:200 scale in the design drawings to roughly estimate and visualize panel placement on the east and west facing sides of the 11-story building. It is assumed that eleven rows of panels—beginning from the first level—could be placed on either façade. Example rows for visual estimation are depicted in **Figure 3.2** and **Figure 3.3**.

Figure 3.2. Visual of spatial estimation of 2m^2 Aiko solar panels applied to the east facing façade of the 11-story case study building, drawings from DUWO (2013).

Figure 3.3. Visual of spatial estimation of 2m^2 Aiko solar panels applied to the west facing façade of the 11-story case study building, drawings from DUWO (2013).

After analyzing the areas compatible for PV panels from a spatial standpoint, energy output modelling will be conducted. The energy output estimation will be divided into four zones due to their different slope, azimuth, and irradiation properties. The zones will be the 1) west facing façade, 2) the east facing façade, 3) the 11-story rooftop, and the 4) detached house rooftop. The total PV power system of the four zones will be taken together to reach the total potential of the entire site and represent the RES energy output potential. The latitude and longitude of Leiden (approximately the city center) will be used as the location coordinates.

The power system rating estimate of each zone and its distinct azimuth and slope will be fed into the European Commission's Photovoltaic Geographic Information System, and calculated using the PVGIS-SARAH2 database as the source of solar radiation calculations (European Comission, 2022). It is assumed that the PV system is grid connected. The energy output(s) calculated for each zone will contribute to the energy balance when taken together with the building's consumption data.

The energy balance and differences between consumption and production will be used to estimate the role of a CB as energy storage in the power system. Calculations on hourly, monthly, and annual energy balances will be conducted in Microsoft excel and represented using basic tables and figures. Gas consumption in m^3 is converted to kilowatt-hours (kWh) under the assumption that one cubic meter of gas equals ten kWh.

Analysis to explore impact of the CB on the building's energy system from an economic perspective will be aided by the Detailed PV System Design tool in the Dutch PV Portal from Klement (n.d.) in addition to average consumer energy price data for electricity and natural gas in the Netherlands from the Centraal Bureau voor de Statistiek or Statistics Netherlands. This will be augmented by commercial data of a specific CB product.

Total Electricity and Gas Prices

Total electricity and gas prices for the case study building will be calculated from the monthly rates defined for June and December 2022 from cbs.nl. These calculations will be used to analyze energy scenarios before and after CB integration from the perspectives of economic considerations (measured in €) and environmental impacts (in CO_2 emissions). **Eq. 3.1** and **Eq. 3.2** can be applied to calculate the total electricity and gas price, respectively.

Equation 3.1. Total Electricity Price

$$P = \frac{t + d + r + (v + o + e)kWh}{a}$$

Variables and rates* in **Eq. 3.1**:

- P = Total Electricity Price (€/kWh)
- t = Electricity Transport Rate: €267.12/year
- d = Electricity Delivery Rate: €72.55/year
- r = Energy Tax Refund: -€824.77
- v = Variable Delivery Rate: €0.3342/kWh
- o = ODE Tax (Environmental Taxes Act): €0.03691/kWh
- e = Energy Tax: €0.04452/kWh
- a = Total Annual Electricity Consumption (kWh)

*June 2022 rates (CBS Statistics Netherlands, 2023).

Equation 3.2. Total Natural Gas Price

$$G = \frac{t_g + d_g + \left(v_g + o_g + e_g\right)m^3}{a_g}$$

Variables and rates* in **Eq. 3.2**:

- G = Total Gas Price (€/m^3)
- t_g = Natural Gas Transport Rate: €191.32/year
- d_g = Natural Gas Fixed Delivery Rate: €72.74/year
- v_g = Variable Delivery Rate: €1.2181/m^3
- o_g = ODE Tax (Environmental Taxes Act): €0.10467/m^3
- e_g = Energy Tax: €0.43950/m^3
- a_g = Total Annual Gas Consumption (m^3)

*June 2022 rates (CBS Statistics Netherlands, 2023).

Energy Efficient Scenario

Calculations relevant for the energy efficient case study scenario are detailed below. The coefficient of performance (COP) is assumed for the heat pump and heat recovery system, which may vary by technology.

Space Heating Energy Demand Reduction = (274,613.68 x 0.25) / 6

- 274,613.68 kWh = annual space heating demand
- 6 = COP of ground-source HP
- 75% = reduction in space heating needs from better insulation, tighter windows, less thermal bridging, etc.

Domestic Hot Water (DHW) Energy Demand Reduction = (168,179.44 x 0.50) / 3

- 168,179.44 kWh = annual DHW demand
- 3 = COP of heat recovery system
- 50% = reduction in demand because of recovered heat

Cooktop Energy Demand Reduction = 33,636 x 0.50

- 33,636 kWh = annual cooking demand (gas)
- 50% = reduction from switch to induction type stove top cookers

Appliance Energy Demand Reduction = 151,634.6 x 0.75

- 151,634.6 kWh = annual electricity demand
- 0.75 = 25% reduction in appliance electricity demand

The ratio of the annual total energy consumption of the energy efficient scenario to the annual total energy consumption of the business-as-usual scenario is used to estimate the hourly energy balance for the representative days in June and December. This ratio and basic equation are presented below.

Equation 3.3 Hourly Energy Balance for Energy Efficient Scenario

$$a = d \times \left(\frac{b}{c}\right)$$

$\boldsymbol{a}$ = New Hourly Consumption Value
$\boldsymbol{b}$ = Energy Efficient Total Energy Demand
$\boldsymbol{c}$ = Business-as-Usual Total Energy Demand
$\boldsymbol{d}$ = Real Hourly Consumption Value

4: Results

4.1 Current State of Carnot Battery Research

This section details the state of Carnot battery (CB) research and development. This builds upon the most recent review paper by Vecchi et al. (2022) and: i) reviewed existing research and commercial CB projects around the globe, ii) explored application potential and trends, and iii) investigated the intersection with the approach of positive energy building (PEB) in the literature.

4.1.1 Current Projects

CB development has increased in recent years. Notably, an intergovernmental agency that provides analysis, policy recommendations, and data on the global energy sector, the International Energy Agency (IEA), established "Task 36: Carnot Batteries" and held the first workshop in 2019. At the workshop, industry and academic experts met to establish a common definition for CB technology and facilitated R&D into the potential role of CBs in the energy transition (International Energy Agency, n.d.). This trend is further observed in the rising number of publications with CB keywords in their titles, illustrated in **Figure 4.1**. Interviewee 1, a leading CB researcher involved in Task 36, commented that the task organization has greatly helped the field in establishing common language and performance parameters.

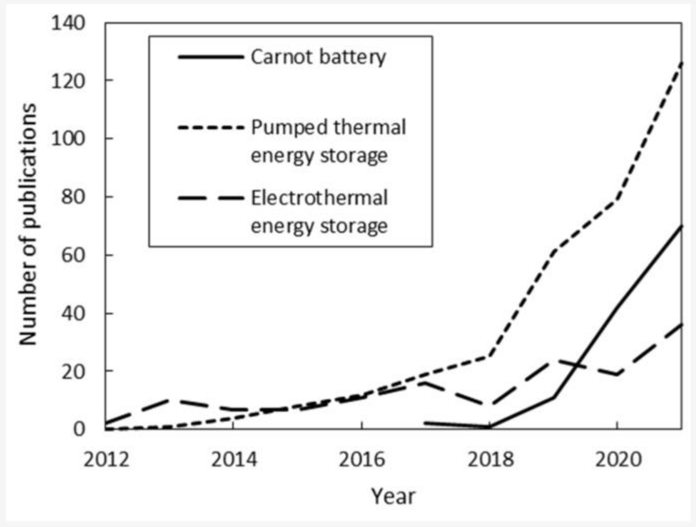
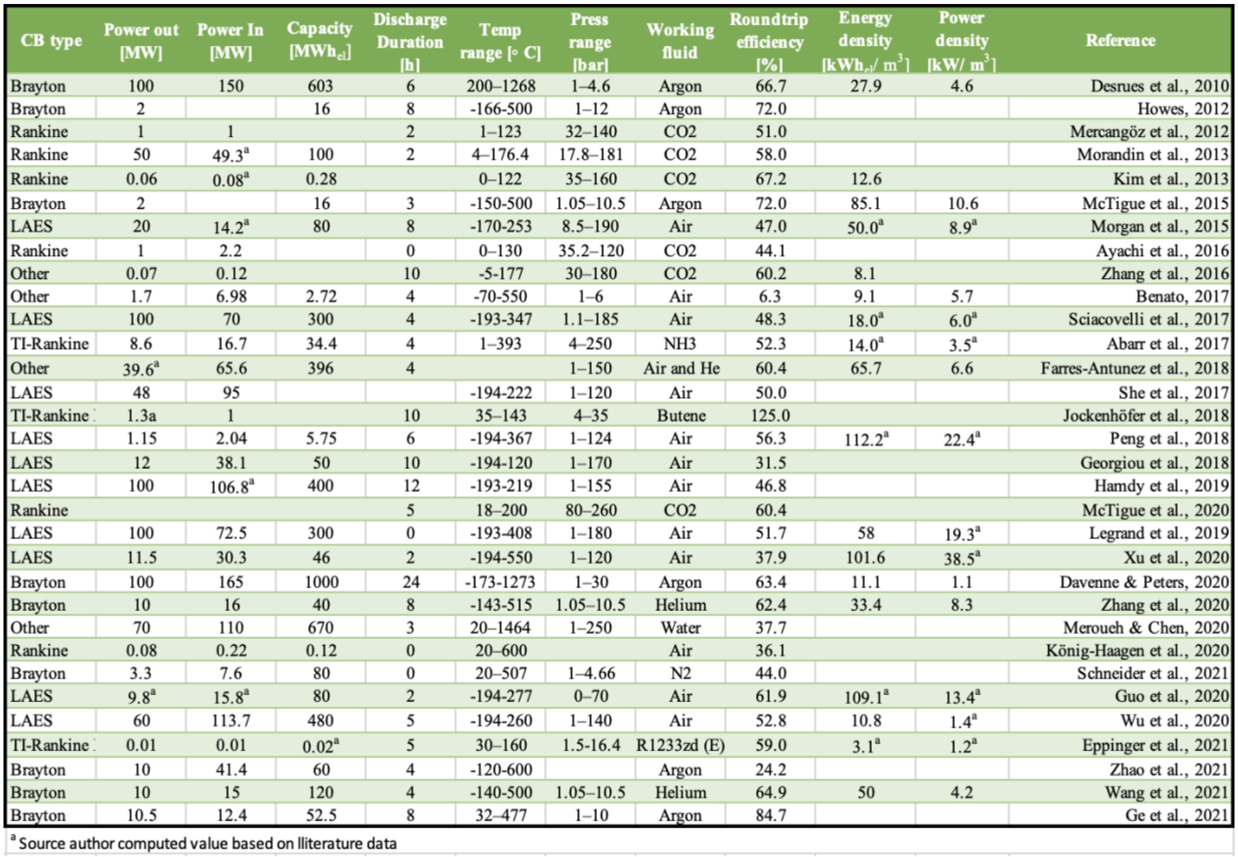


Figure 4.1. Number of publications with CB keywords in title year-over-year presented in (Novotny et al., 2022).

Although CB technology is relatively new as a uniform concept, work has been ongoing for decades into various configurations and aspects of optimizing systems with the principle of storing electricity as thermal energy. Research and commercial interest paired with the need for long duration energy storage is captured in the variety of individual systems represented in the literature from 2010 onwards in **Table 4.1**.

Table 4.1. Overview of 32 individual Carnot battery systems and technical performance indicators as identified in Vecchi et al. (2022).



CB type	Power out [MW]	Power In [MW]	Capacity [MWh$_{el}$]	Discharge Duration [h]	Temp range [° C]	Press range [bar]	Working fluid	Roundtrip efficiency [%]	Energy density [kWh$_{el}$/ m^3]	Power density [kW/ m^3]	Reference
Brayton	100	150	603	6	200–1268	1–4.6	Argon	66.7	27.9	4.6	Desrues et al., 2010
Brayton	2		16	8	-166-500	1–12	Argon	72.0			Howes, 2012
Rankine	1	1		2	1–123	32–140	CO2	51.0			Mercangöz et al., 2012
Rankine	50	49.3^a	100	2	4–176.4	17.8–181	CO2	58.0			Morandin et al., 2013
Rankine	0.06	0.08^a	0.28		0–122	35–160	CO2	67.2	12.6		Kim et al., 2013
Brayton	2		16	3	-150-500	1.05–10.5	Argon	72.0	85.1	10.6	McTigue et al., 2015
LAES	20	14.2^a	80	8	-170-253	8.5–190	Air	47.0	50.0^a	8.9^a	Morgan et al., 2015
Rankine	1	2.2		0	0–130	35.2–120	CO2	44.1			Ayachi et al., 2016
Other	0.07	0.12		10	-5-177	30–180	CO2	60.2	8.1		Zhang et al., 2016
Other	1.7	6.98	2.72	4	-70-550	1–6	Air	6.3	9.1	5.7	Benato, 2017
LAES	100	70	300	4	-193-347	1.1–185	Air	48.3	18.0^a	6.0^a	Sciacovelli et al., 2017
TI-Rankine	8.6	16.7	34.4	4	1–393	4–250	NH3	52.3	14.0^a	3.5^a	Abarr et al., 2017
Other	39.6^a	65.6	396	4		1–150	Air and He	60.4	65.7	6.6	Farres-Antunez et al., 2018
LAES	48	95			-194-222	1–120	Air	50.0			She et al., 2017
TI-Rankine	1.3a	1		10	35–143	4–35	Butene	125.0			Jockenhöfer et al., 2018
LAES	1.15	2.04	5.75	6	-194-367	1–124	Air	56.3	112.2^a	22.4^a	Peng et al., 2018
LAES	12	38.1	50	10	-194-120	1–170	Air	31.5			Georgiou et al., 2018
LAES	100	106.8^a	400	12	-193-219	1–155	Air	46.8			Hamdy et al., 2019
Rankine				5	18–200	80–260	CO2	60.4			McTigue et al., 2020
LAES	100	72.5	300	0	-193-408	1–180	Air	51.7	58	19.3^a	Legrand et al., 2019
LAES	11.5	30.3	46	2	-194-550	1–120	Air	37.9	101.6	38.5^a	Xu et al., 2020
Brayton	100	165	1000	24	-173-1273	1–30	Argon	63.4	11.1	1.1	Davenne & Peters, 2020
Brayton	10	16	40	8	-143-515	1.05–10.5	Helium	62.4	33.4	8.3	Zhang et al., 2020
Other	70	110	670	3	20–1464	1–250	Water	37.7			Merouch & Chen, 2020
Rankine	0.08	0.22	0.12	0	20–600		Air	36.1			König-Haagen et al., 2020
Brayton	3.3	7.6	80	0	20–507	1–4.66	N2	44.0			Schneider et al., 2021
LAES	9.8^a	15.8^a	80	2	-194-277	0–70	Air	61.9	109.1^a	13.4^a	Guo et al., 2020
LAES	60	113.7	480	5	-194-260	1–140	Air	52.8	10.8	1.4^a	Wu et al., 2020
TI-Rankine	0.01	0.01	0.02^a	5	30–160	1.5-16.4	R1233zd (E)	59.0	3.1^a	1.2^a	Eppinger et al., 2021
Brayton	10	41.4	60	4	-120-600		Argon	24.2			Zhao et al., 2021
Brayton	10	15	120	4	-140-500	1.05–10.5	Helium	64.9	50	4.2	Wang et al., 2021
Brayton	10.5	12.4	52.5	8	32–477	1–10	Argon	84.7			Ge et al., 2021

^{a} Source author computed value based on lliterature data

Existing and planned CB installations are front run by Highview Power (U.K.), MAN Energy Solutions (Germany), Azelio (Sweden), Malta Inc. (U.S.), Alfa Laval (Sweden), Siemens Energy (Germany), Stiesdal Storage Technologies (Denmark), EnergyDome (Italy), EnergyNest (Norway), Hyme Energy (Denmark), SaltX (Sweden), 1414degrees (Australia), and Echogen (U.S) to name a few (Vecchi et al., 2022). Major studies from 2020 onwards into ETES and retrofit potential have been completed by MAN Energy Solutions, RWTH, Stawag Energie BV, Malta Inc., Duke Energy, the Electric Power Research Institute, AECOM and ongoing retrofit and component development studies from the German Aerospace Center (DLR), Rheinisch-Westfälisches Elektrizitätswerk, the Southwest Research Institute, and Echogen Power Systems are in progress at the time of writing (Vecchi et al., 2022). A more thorough and complete overview of commercial projects is presented in Novotny et al. (2022).

Further significant developments are the establishment of international organizations around the challenges that decarbonization of our energy systems present. A prominent example is the global non-profit Long Duration Energy Storage Council (LDES), whose mission is to accelerate the market for long duration energy storage ranging from thermal, chemical, electrochemical, and mechanical ESS solutions (LDES, 2023). Many of the aforementioned companies are members in addition to: Google, Microsoft, Breakthrough Energy, Shell, Baker Hughes, Reliance Industries Limited, Alfa Laval, Orsted, Ambri, Rondo, Brenmiller Thermal Energy Storage, Build to Zero, Ceres, Electrified Thermal Solutions, ESS Inc., and Storworks Power (LDES, 2023). The trends captured by the International Energy Agency's Task 36, the LDES Council, and the individual projects discussed in Vecchi et al., (2022) taken together represent *hundreds of millions* ($€) of capital investment surging into CB technology.

4.1.2 Application Potential and Trends

CBs are flexible in layout and scale, making the range of explored applications of the technology diverse. CBs can provide power and thermal services, when electricity and heat is transferred to/from CB systems respectively (Vecchi et al., 2022). Applications for CBs are like other ESS, with further adaptability enabled by the unique and varied breadth of different system scales, configurations, and energy integration. This adaptability according to need is due to the central role of heat in the energy nexus, illustrated in **Figure 4.2**.

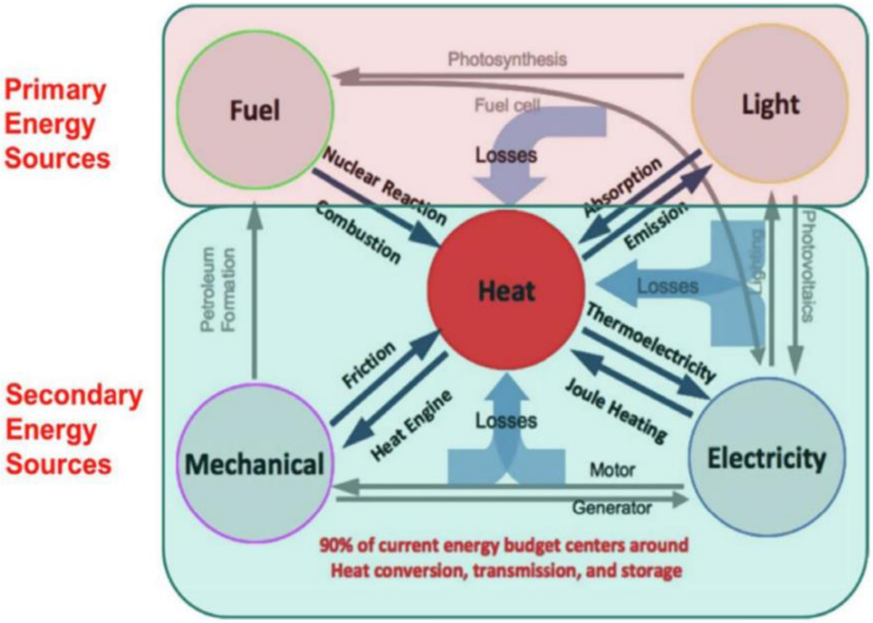


Figure 4.2. Visualization of the energy nexus and relations between electricity, light, fuel sources, and mechanical energy from Sadeghi (2022).

These fundamental energetic and thermodynamic relations build upon the practical strengths of CBs over other ESS and their wide-ranging application potential. CBs have been investigated to augment intermittent renewable energy sources (RES), so that power is available for use at all times of the day—like other ESSs. In addition, CB systems coupled to a wide array of energy systems is a rich area of research interest, demonstrated by the dozens of studies across applications such as integration (defined as part of the energy system the CB is physically and/or virtually connected to) with RES, power plants, consumers, mini grids, natural water, geothermal, solar heat, ambient air, and thermal networks (Novotny et al., 2022; Vecchi et al., 2022). Interviewee 2 also indicated that CB potential in multi-vector integration was one of the strongest take-aways from their research. The performance of a 50kW solar thermal collector installation providing electricity and heat to an organic Rankine cycle (ORC) CB was simulated and found an 81% total roundtrip electrical efficiency with exergy efficiency of 0.39, demonstrating that CBs can be suitable for electrical energy storage for photovoltaic (PV) systems across all seasons (Frate et al., 2022).

Furthermore, two configurations of hot and cold TIPTES integrated with residential multi-energy sources were modelled, simulated, and compared to LiB batteries economically and thermodynamically with findings that indicate a lower operational expenditure (OpEx), as well as improved performance for multi-energy TIPTES (mTIPTES) versus a TIPTES system which only discharges electricity (Frate et al., 2023). A review on Rankine CBs with integrated thermal energy sources asserted that use in district heating networks shows promise, and echo Vecchi et al. (2022) in having identified case-specific application as necessary directions for further study (Frate et al., 2020). Since power-to-power efficiency for CBs mainly depend on the temperature level of the TES, studies conclude that low temperature (<150°C) CBs generally required waste heat sources to achieve feasible power-to-power ratios (Wang et al., 2022; Weitzer et al., 2022). However, a theoretical preliminary thermodynamic analysis of an ORC CB for cogeneration and trigeneration (provisioning of heat, cooling, and electricity services) aimed at optimum use of volatile renewable energy in the building sector reported maximum energy efficiency up to 322.16% (Bellos et al., 2022). LAES with waste heat recovery for industrial purposes found a competitive levelized cost of storage (LCOS) of 382-888 USD/MWh at the lower end of the range based on an economic analysis in Chinese market conditions (Q. Liu et al., 2023). This area of research highlighted important developments in application cases and energy system integration for CB technology.

CBs versatility in storing different forms of energy, across different scenarios, is reflected in the breadth of the literature. A San Francisco, California case study analyzing LAES with cascading phase change materials found total efficiencies of 42.5% with a payback period of 6.7 years on a system that generates 1.8MWh of electricity during peak times (Bashiri Mousavi et al., 2022). Cascading phase change materials are noted to increase performance of compressed heat energy storage (CHEST), a promising CB configuration (Tafone et al., 2023). In a production cost model study by the U.S. National Renewable Energy Laboratory, analysis of hypothetical grid scale scenarios dominated by variable renewable of either wind or photovoltaics found fundamental differences in diurnal patterns in electricity prices and PTES operation, however both scenarios (i.e., PV & wind) reduced curtailment of RES (Martinek et al., 2022). A recent study out of Korea University also analyzed exergy and thermo-economics of massive, grid scale layouts of CBs, finding a cost of produced electricity per unit to be 70 USD/GJ (Lee et al., 2022).

The integration of CBs with combined heat and power (CHP) plants at the utility scale is an application that has also garnered attention in research. Interviewee 2 further highlighted the wide-ranging versatility of CBs, pointing out that applications can range from the small-scale (i.e., single home) to the power plant scale. Recent studies that investigate CBs to facilitate CHP in standalone plants or integrate with existing fossil fuel plants have shown positive potential for grid-scale services (Basta et al., 2022; Blanquiceth et al., 2023; Eggers et al., 2022; Trieb et al., 2022). Dynamic simulations concluded that a large-scale biomass plant with a CB with a small fluidized bed volume were sufficient at yielding high energy efficiencies and effectively absorbed variable renewable energy fluctuation, but at a higher LCOS than other energy storage systems (Uchino et al., 2023). TIPTES with concentrated photovoltaic thermal systems at large scales found that lower LCOS can be achieved as the amount of solar radiation increases (Kurşun & Ökten, 2022). These applications are especially promising as existing technology and equipment found at power plants can be converted for use within a CB system, such as the steam turbines found in coal-fired power plants (Novotny et al., 2022; Vecchi et al., 2022). Additionally, a LAES system was found to have a 17% reduction in levelized cost of energy (LCOE) when integrated with a nuclear power plant versus a standalone LAES system, at a competitive round trip efficiency and higher energy density than other grid-scale ESS (Park et al., 2022).

The relationship between increasing scale and performance of CBs is apparent in the current research. An ETES system with a charging power of 5.4MW—at a plant in Hamburg, Germany using crushed volcanic rock as the TES—demonstrated the ability to constantly discharge thermal power of over 3.8MW for >22 hours (Eggers et al., 2022). A related pattern is that higher temperatures (>500°C) of the thermal storage medium of CB systems are associated with greater energy densities and thermal cycle efficiencies, an assertion posited by a recent review centered around high temperature sensible TES in CBs (Paul et al., 2022). A thermo-economic feasibility study of a high temperature, Brayton cycle PTES on the utility scale found costs of the CB to be \$476/kWh$_e$, which is comparable to other storage technologies—costs could be lowered by over \$100/ kWh$_e$ if the cost of steel and graphite were reduced (Jacob & Liu, 2022). The presence of feasibility studies such as this indicated robust commercial interest in the revenue model and scaling of CB technology in the energy sector.

Another notable trend is the exploration of CB potential in distributed, mini-grid, and coupled RES ecosystems. LAES type CBs have been investigated in mini-grids, with results suggesting that their ability to provide multiple services increased their value and decreased carbon emissions by ~60% in a mini-grid with 75% wind (T. Liang, Webley, et al., 2022). One recent study has even explored the potential of transporting liquid air energy through rail, road, and shipping infrastructure to end-use locations (T. Zhang et al., 2022). The performance of a novel biomass-driven LAES system for heat and power production was evaluated using wind data from Ireland and found that the system had an energy efficiency of 79.2% and could be used to enhance stability of renewable wind power (Cao et al., 2022). A recent review on LAES CBs presented applications of peak-shaving, load shifting, dealing with volatile RES, integration for heat, cold energy recovery and utilization, and sector coupling for carbon capture and chemical production (T. Liang et al., 2023).

Since CB technology is still emerging as a uniform class of ESS, technoeconomic optimization of configurations, processes, as well as components is ongoing (Yu et al., 2023). Regenerators that capture waste-heat are concluded to improve the performance of a Rankine cycle CB system (Zhao et al., 2022). Regenerative systems presented better thermo-economic performance in an analysis comparing ORC CBs (Fan & Xi, 2022). Organic Rankine CB with the use of regenerators was analyzed and lowered the LCOS by 11.5%, with higher temperature TES associated with greater system performance (S. Liu et al., 2022). In another study of two layouts of an ORC CB, embedded regenerators in the charge and discharge phase was found to reduce LCOS by nearly 10% (Y. Zhang et al., 2022). In addition to lower lifetime costs at discharging durations over 6h compared to LiBs, PTES with optimized power component (i.e., turbomachinery, heat exchangers) selection was concluded to be competitive over a wider range of energy storage applications, especially when integrated with multi-energy inputs and outputs (J. D. McTigue et al., 2022). A recent technology review of key components has been explored further to aid research and development of CB systems (T. Liang, Vecchi, et al., 2022).

CBs are a promising technology that have experienced a surge in interest due to no geographical limitations, low specific cost, ability to integrate multiple energy forms and systems (e.g. thermal, electric), independence from fossil fuel streams, clean operation, and the ability to use many "off-the-shelf" components already on the market (Dumont & Lemort, 2020; Frate et al., 2020; Mitali et al., 2022; Sadeghi, 2022; Vecchi et al., 2022). Notably, grid-scale and utility sized CB application, integration of multiple heat/energy sources, and optimization of system components are rich areas of research. CBs utilized in the context of the built environment has attracted interest as well.

4.1.3 Carnot Batteries and Positive Energy Buildings

As the world transitions to cleaner energy, the volatility and intermittency of renewable energy like wind and solar has changed the energy nexus of built environments. In a high-RES penetrated built environment energy system, systems responsible for provisioning of services to buildings must adapt and enable resilient grid handling of intermittency. These factors have drove interest into the intersection of CB technology and provisioning of services for our built environment.

Analyses of economic and technical performance of CBs in PEB contexts have been explored for several years. In a 2016 paper comparing the performance of a water-to-water HP/PV system versus a HP/ORC (CB) system coupled to a thermal roof associated with a PEB found that while the HP/PV system presented better overall performance related to net electrical production, the HP/ORC system saw advantages in 1) low investment cost and 2) lower electrical consumption due to the heat provided by the roof (Dumont, Carmo, Randaxhe, et al., 2016). Both technologies achieved PEB performance (net-positive energy production) and the highest HP/ORC efficiencies were found in climate locations close to Torino, Italy (Dumont, Carmo, Randaxhe, et al., 2016). In a further modelling study of load shifting, integration of batteries in PEBs analyzed from an economic angle found a battery size between 2.6 and 4.5 kWh lead to the minimum payback period (Dumont et al., 2017).

Related to the idea of multi-energy integration of CBs at the power plant and industrial scale, the trigeneration (visualized in **Figure 4.3**) and cogeneration of energy services needed at smaller scales for buildings has been theoretically explored. Cogeneration feasibly allowed for higher energy utilization rates (Eggers et al., 2022). Based on a thermodynamic simulation in steady-state conditions of a CB unit 'ideal for buildings', exergy efficiency was maximized at 45.28% and maximum energy efficiency was 213.09% and 378.29% for the cogeneration and trigeneration scenarios respectively (Bellos et al., 2022).

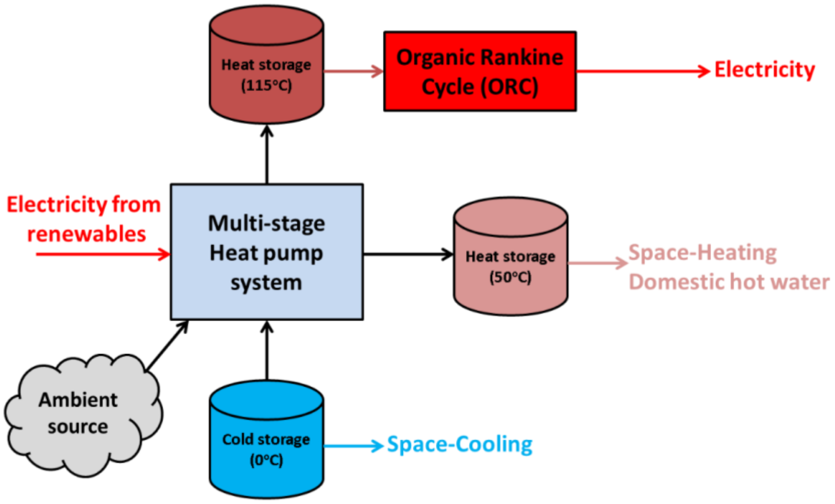


Figure 4.3. General description of a trigeneration scenario, or "Power to XYZ" presented in Bellos et al. (2022).

One study analyzed the technoeconomic performance of a 5 kWe reversible HP/ ORC unit coupled to a single-family Danish passive house with a 138.8m^2 solar roof and found an annual positive net electrical production and complete coverage of the heat demand of the building could be achieved, even in cold climates (Dumont, Carmo, Fontaine, et al., 2016). A feasibility study into a CB system integrated with a solar energy harvesting system for a hotel found a reduction in consumed electric and thermal energy by 19.6% and 22.0% respectively could be achieved (Kim et al., 2022). For load-shifting of solar PV production in a non-residential office building with an annual electricity demand of 2600MWh, a CB system based on the subcritical Rankine cycle and sensible thermal storage was not cost effective (i.e., positive net present value) compared with LiBs (Tassenoy et al., 2022). These studies demonstrated an exploration of varied PEB application cases for CB systems.

Sizing and optimal operation of CB systems is crucial to the feasibility of the ESS. A study analyzed a pilot plant reversible HP/ORC cycle system coupled with hot water storage and found that for a community of 30-40 houses, CB application was technically feasible and generated up to €180 in savings per year per house in future German market conditions—however, economic potential differed greatly depending on market conditions (i.e., feed-in tariffs, heat costs) (Scharrer et al., 2022). In a state-of-the-art review of PEBs and positive energy communities (PEC), the authors posited that in addition to sizing and controlling of energy storage, the selection, mixing, and designing of ESS is crucial for increased grid independence and self-consumption of generated renewable energy (Kumar & Cao, 2021). Both economic and technical feasibility of the analyzed benefits of CBs with PEB environments differ depending on the objectives of the specific system.

While the literature differs in approaches, objectives of analysis, disciplinary perspectives, applications, system configurations, and system sizes—the number of studies and the breadth of reach validated the promising intersection between CBs and sustainable building practices.

4.1 Section Summary

In this section a review of the state of CB research and commercial development was presented. CBs have attracted hundreds of millions of euros of research and commercial funding due to their promise and simple working principles. CB technology can be engineered with resources that are cheap and plentiful, existing technologies, and shows promise over a wide range of scales, from single buildings to whole regions. Thermodynamic optimization of working fluids, components, and research is ongoing to investigate how best to employ these storage systems. The potential relationship between CB energy storage and sustainable building practices in metropolitan environments was also briefly explored.

4.2 ESS Indicators

In this section important techno-economic and environmental indicators for ESS in general are identified, defined, and organized. Impact, for use in this context, is a noun defined as "the powerful effect that something has on someone or something" (Oxford Advanced American Dictionary, 2023). Techno-economic and environmental indicators related to ESS in this research are performance parameters, metrics, and information that can be used to assess impact. While factors such as application, geography, context, energy system integration, etc., impact the performance metrics and outcomes of ESS, key performance indicators (KPIs) are regarded as an effective way to compare and contrast different technologies (Palomba & Frazzica, 2019). The section will first i) identify and describe important techno-economic indicators, ii) environmental indicators, and finish by iii) exploring how impact is assessed.

4.2.1 Techno-economic Indicators

Performance metrics for applying energy storage to the building scale is based off the work of Del Pero et al. (2018), with various other sources cross-referenced to increase robustness. To assess heterogenous technologies for use in buildings, the authors proposed and defined ten simplified main KPIs, including six additional indicators that can be calculated from the main KPIs for more detailed analyses. The indices allow for basic comparison at the decision-making and design stage (Del Pero et al., 2018). These indicators, definitions, and further notes about aim and utility have been detailed in **Table 4.2**.

Table 4.2.
KPIs related to ESS in buildings with definitions and aim as presented in Del Pero et al. (2018)

Indicator	Definition	Aim/Comments
Storage capacity (Wh)	Amount of energy stored in the ESS or available immediately after a complete charge	Easily evaluate energy that can be stored and released under normal conditions
Recharging energy (kWh)	Amount of energy necessary for the storage to reach storage capacity	To understand energy required to fully charge system
Maximum charge and discharge power (kW over time [h])	Maximum amount of charge and discharge power that can be released constantly	Useful to assess flexibility and peak management
Depth of discharge (DoD)	Indicates how deeply an ESS can be discharged and provide usable energy without incurring negative damages	Can help relate application and intensity of use
Durability (years)	Maximum assumed number of working cycles which an ESS can release at least 80% of useful capacity, expressed in years	Estimates useful working life of a storage system
Specific cost of the storage (€/kWh)	Overall cost of ESS	Normalized by total useful energy delivered over lifetime
Maximum self-discharge rate (%)	Percentage (%) of stored energy lost during standby period	Quantifies unwanted discharge, typically measured over 1 h, 10 h, 100 h, 1000 h standby periods
Storage size, weight (m^3 / kg)	Total volume and mass of an ESS	Provides insight into transportation and placement of system
Stored energy factor	Portion of total energy demand for a certain purpose (and/or of the RES generation), related to building(s) that the ESS is installed, that is released by storage	Helps to assess which part of the gross total energy required for a building could be provided by the ESS (during a certain period)
Generated energy/cost saving (kWh or €)	Expected energy/cost savings generated within scope	Always defined over a certain reference period. Depends on what services are provisioned by the ESS (e.g., peak shaving, arbitrage, self-consumption, etc.)
Fastest charge/discharge durations (h)	Quickest durations to charge/discharge the ESS which can be constantly realized	Useful to identify minimum time in which an ESS can be charged or discharged
Charging efficiency (%)	Efficiency of charging phase	
Discharging Efficiency (%)	Efficiency of discharging phase	
Total charging/discharging efficiency (%)	Total efficiency of complete cycle	Useful for comparison between ESS technologies
Mass and volume densities of energy (kWh/kg and kWh/m^3)	Maximum useful energy per mass or volume unit	Can be helpful for certain applications with spatial limitations
Specific cost of the stored energy (€/kWh)	Cost of each unit of energy released by the storage system	To find overall cost of energy within applied scope

In order to validate the KPIs defined in the work of Del Pero et al. (2018) and further understand important indicators for ESS, four other studies were cross-referenced to identify the presence of various indicators as seen in **Table 4.3**. It is important to note that the underlying equations and how the KPI is defined may differ slightly according to the source author.

Table 4.3

Techno-economic KPIs identified and included in ESS literature.

**An X indicates KPI found in corresponding source.*

<table>
<tr><th colspan="6">Techno-economic KPIs for ESS in the literature</th></tr>
<tr><td>KPI</td><td>Del Pero et al. 2018</td><td>Mostafa et al. 2020</td><td>Vrenne et al. 2021</td><td>Mitali et al. 2022</td><td>Vecchi et al., 2022</td></tr>
<tr><td>Storage capacity (Wh)</td><td>X</td><td>X</td><td>X</td><td></td><td>X</td></tr>
<tr><td>Power range (MW/kW)</td><td></td><td>X</td><td></td><td>X</td><td>X</td></tr>
<tr><td>Recharging energy (kWh)</td><td>X</td><td></td><td></td><td></td><td>X</td></tr>
<tr><td>Maximum charge and discharge power (kW over time [h])</td><td>X</td><td></td><td></td><td>X</td><td></td></tr>
<tr><td>Depth of discharge (DoD)</td><td>X</td><td>X</td><td></td><td></td><td></td></tr>
<tr><td>Durability/lifetime (years)</td><td>X</td><td></td><td></td><td>X</td><td></td></tr>
<tr><td>Specific cost of the storage (€/kWh) / Capacity specific cost</td><td>X</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Maximum self-discharge rate (%)</td><td>X</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Storage size, weight (m^3 / kg)</td><td>X</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Stored energy factor</td><td>X</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Generated energy/cost saving</td><td>X</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Fastest charge/discharge durations (h)</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Charging efficiency (%)</td><td>X</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Discharging Efficiency (%)</td><td>X</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Total charging/discharging efficiency (%)</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Mass and volume densities of energy (kWh/kg and kWh/m^3)</td><td>X</td><td>X</td><td></td><td>X</td><td>X</td></tr>
<tr><td>Specific cost of the stored energy (€/kWh)</td><td>X</td><td></td><td></td><td></td><td>X</td></tr>
<tr><td>CAPEX</td><td></td><td></td><td>X</td><td></td><td></td></tr>
<tr><td>OPEX</td><td></td><td></td><td>X</td><td></td><td></td></tr>
<tr><td>T Range (◦C)</td><td></td><td></td><td></td><td></td><td>X</td></tr>
</table>

Robustness in the referenced studies provided a basic operationalization of importance for the KPIs. Across the five studies cross-referenced, only fastest charge/discharge duration (h) and total charging/discharging efficiency (%) were present in all five. Storage capacity (Wh) in addition to mass and volume densities of energy (kWh/kg and kWh/m^3) were present in all but one of the sources. Power range (MW/kW) was found in three sources. Maximum charge and discharge power (kW over time [h]), depth of discharge (DoD), durability/lifetime (years), and specific cost of the stored energy (€/kWh) appeared in two each.

Through techno-economic KPIs, the technical and economic impact of ESSs are measured. Fastest charge and discharge dynamics convey information about how rapidly a ESS can respond to energy needs such as support voltage, frequency fluctuation, or other ancillary services for example (Mostafa et al., 2020). Interviewee 4, a senior energy storage engineer, spoke on the process of analyzing ESS and how it related to the application. Commercial buildings may have an acceptable lag time of ~five minutes after a power outage to respond with little consequences, whereas a datacenter needs backup power delivered in less than a minute. This conveyed the importance of the application-KPI relationship.

As the only other parameter shared between the five sources, total efficiency (%), is used as a cornerstone parameter, measuring the relationship between absorbed and discharged energy (Mitali et al., 2022; Vecchi et al., 2022). Total efficiency conveys information such as how much energy is stored from onsite renewable generation and the percentage of this energy that can ultimately be used for an application. The higher the efficiency of an ESS, the less energy lost in transit, conversion, and travel through the system which in turn, impacts financial returns and the business case of an ESS. When asked about the financial case of CBs specifically, Interviewee 2 noted that Siemens in Germany had a system in place with low total efficiencies, but benefitted from negative energy prices and were actually paid to consume energy. This example provides a hint into the relationship between technical efficiency, electricity markets, and economically profitable cases.

Stored capacity (Wh) is used to communicate the capacity of an ESS. Here, the relationship between produced power (i.e., from PV panels on the roof of a building), demand, and the amount of energy able to be stored in an ESS is important for selecting an appropriate technology for an application (Del Pero et al., 2018). Interviewee 4 further emphasized this KPI as a crucial parameter to ensure resilience and security of an ESS in an energy system. Mass and volume densities of energy (kWh/kg and kWh/m^3) relate the size and weight of a technology to its stored capacity. Mass density (kWh/kg) can also be referred to as specific energy (Hossain et al., 2020). These densities enable an objective analysis of how much space and gravitational force the technology places on the environment. It is especially important when ESS is placed within a building adding to structural stress or in the transportation sector where every kilogram counts towards optimal performance.

Whereas stored capacity (Wh) is the amount of water a bathtub could hold, power (MW/kW) is the rate of flow of the water (i.e., energy) in and out (Andlinger Center for Energy + the Environment, 2014). Maximum charge and discharge power (kW over time [h]) can be understood as the maximum and minimum power range, over a specific reference period. Depth of discharge (DoD) plays into this equation too, since it indicates how deeply an ESS can be discharged without incurring negative damages (Del Pero et al., 2018). If a building has an evening demand of 50kWh, ensuring that an ESS has the necessary capacity and discharge power to deliver enough stored energy without degrading is important to the flexibility of an energy system. Interviewee 4 asserts this important dynamic as well in the example of a datacenter building, where every minute an energy system is offline could mean *millions (€)* in financial losses.

Lastly, durability (years) and specific cost of the stored energy (€/kWh) two further important KPIs. Durability describes the working life of the ESS, which is a crucial component of calculating costs and impact over time (Mostafa et al., 2020). ESS technology with a relatively lower durability requires replacement sooner, incurring more cost—both financially and environmentally. The sympatheia (mutual interdependence) of these bottom lines is a profound common thread. Specific cost of the stored energy (€/kWh) explored the financial cost per energy unit of an ESS and is an important KPI that contributed to objective comparison between heterogenous technologies in the next section (section 4.3).

4.2.2 Environmental

The environmental impact of a product process or activity can be measured through different methods. For this research, a life cycle assessment (LCA) is the primary method employed to investigate the impact of ESS and CB systems. This choice was influenced by accepted market standards, the guidelines of the International Organization for Standardization standards 14040:2006 and 14044:2006 (International Organization for Standardization, 2022), and availability of compatible studies. While CBs are a relatively young product, LCAs have been applied to objectively evaluate environmental burden by quantifying material and energetic use and waste since 1969, when the first LCA was done on beverage containers (LeVan, 1995). The LCA method can also be referred to as the life cycle impact assessment (LCIA) (Mostert & Bringezu, 2019). The term LCA is used for simplicity and to match the nomenclature in reported findings from the technical and commercial literature. A visual of a typical life cycle of a product is seen in **Figure 4.4**.

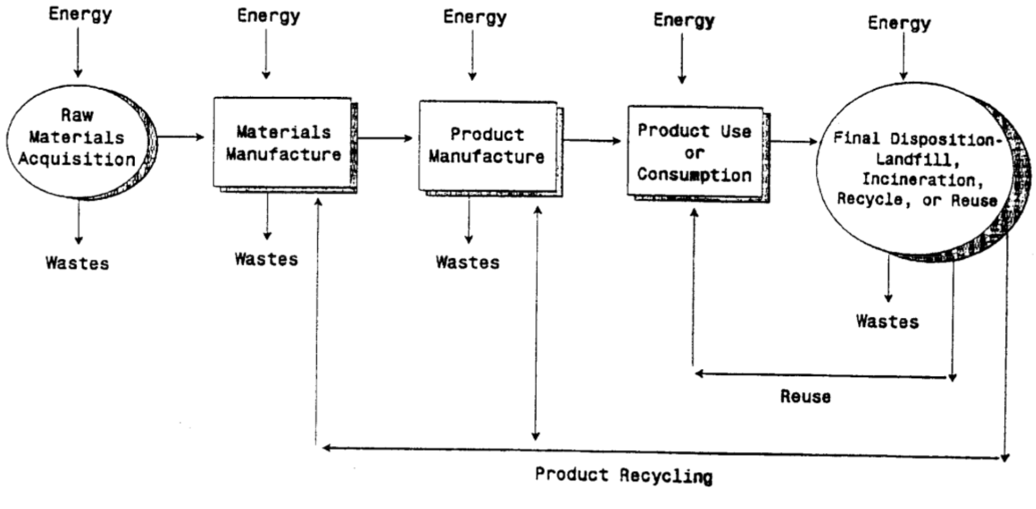


Figure 4.4. General overview of traditional material flow of a typical product life cycle presented in Levan (1995).

The method for conducting an LCA can be broken down into four main steps as summarized by Dumont et al. (2022):

1. Goals and scope definition
2. Inventory of relevant inputs and outputs
3. Assessment of associated environmental impacts related to inventory
4. Interpretation and analysis of results related to defined goal

Important indicators needed for the execution of an LCA are quantities of material and energetic inputs from the production stage, transport of materials, through to the disposal stage of the product’s life cycle. For example, in a CB, the material and energy needed for the components such as the charging system (e.g., heat pump, resistance heater, etc.), the thermal storage medium, storage material, working fluid, thermal insulation, steel for the container, and discharging system are necessary to inventory and quantify—to assess the associated environmental impacts. A strong LCA also includes reflection on the limitations, especially the challenge of setting boundary conditions and defining indirect impacts on the environment (LeVan, 1995).

Despite inherent limitations, the LCA method is recognized as a valuable tool. Just as a uniform definition for CB systems was established from the IEA’s Task 36 working group, the congruent application and shared operating guidelines of the LCA helps in unifying industry, researchers, and policymakers under a common understanding of complex concepts. The strategic goal of the LCA and accompanying standardization guidelines by the International Organization for Standardization is to promote a “common approach to environmental management” (LeVan, 1995). This objective helped facilitate the objective comparison of intrinsically different and diverse ESS in the context of their environmental impact, to inform and improve credibility for the end design of this research.

In addition to the LCA method, some researchers have developed their own methods to assess impacts of ESS on a common playing ground. With the LCA as a foundation, inclusion of additional methods increased the robustness and validity of comparison of mature ESS with CBs in the following section.

4.2 Section Summary

The assessment of impact across technical, economic, and environmental indicators enables engineers, policymakers, consultants, end-users, etc. to place solutions in context. In the strategic picture, it is imperative to transition away from energy systems that generate negative externalities (i.e., carbon emissions, other GHGs, environmental degradation, etc.) and thus important to identify KPIs. The KPIs and impact tools detailed in this section are necessary to design, plan, and place ESS in effective contexts. These techno-economic indicators of total efficiency, storage capacity, fastest charge/discharge duration, power range, specific cost of storage, maximum charge/discharge power, durability, and mass/volume densities of energy and the environmental impact indicator of the LCA contribute to an objective comparison across storage technologies as detailed in the following section (section 4.3). The powerful effect of the performance of ESS on the natural world, financial considerations, and provisioning of services to buildings comes into focus through the lens of KPIs.

4.3 Current State of ESS

Understanding where CBs fit required understanding the features, merits, and disadvantages of mature ESS technologies on the market. In this section, mature ESSs are identified, key features discussed, and comparisons drawn to CBs in the context of techno-economic and environmental impact.

The basis for selected ‘mature’ technologies for inclusion in this research is made based off of the TRL levels defined for technologies presented in the review paper on ESS technology offered by Mitali et al. (2022). Where applicable additional sources are cross-referenced to bolster insight into the features and evolution of technological development, including insights from professionals working in the field. For the purposes of this research, a specific product (Azelio TES.POD) is identified to represent the CB class. This is motivated by the TES.POD’s relatively high TRL (for CBs) and the availability of data. A basic overview of the TES.POD is presented in the beginning of this section. Where appropriate, this practice of selecting a specific product is followed for the other ESS classes to facilitate specific, granular, and detailed insight that widely applicable averages or general features cannot capture.

Azelio’s TES.POD

The TES.POD is a complete CB that includes charge, discharge, and storage. The size of the product is roughly comparable to a small shipping container at 3.65m long, 2.81m tall, and 2.67m wide with a volume of approximately 27m^3. Most of this volume is occupied by the thermal storage medium; a large bowl-like container filled with recycled aluminum that phase changes at 600°C (1110°F) from solid to liquid when heated. The charging of the TES.POD is done through electric resistance heaters and discharging occurs through a Stirling engine—a quiet, closed-cycle regenerative heat engine. A heat transfer fluid transfers heat from the aluminum to the Stirling engine, which is connected to a generator crankshaft to generate 13kW of electricity for 13 hours in electricity production mode at nominal conditions. In CHP mode, the TES.POD can produce 11kW electricity and 25kW of heat simultaneously throughout the 13 hour discharge cycle at nominal conditions (Nilsson et al., 2022). A visual render and component diagram of the TES.POD is depicted in **Figure 4.5** and **Figure 4.6**.

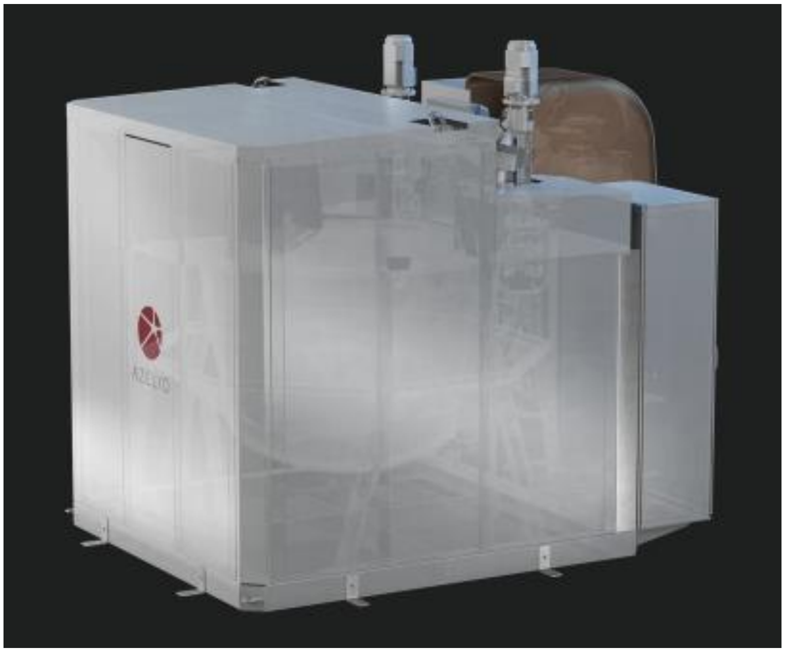


Figure 4.5. 3D render of the TES.POD CB from Azelio (2023).

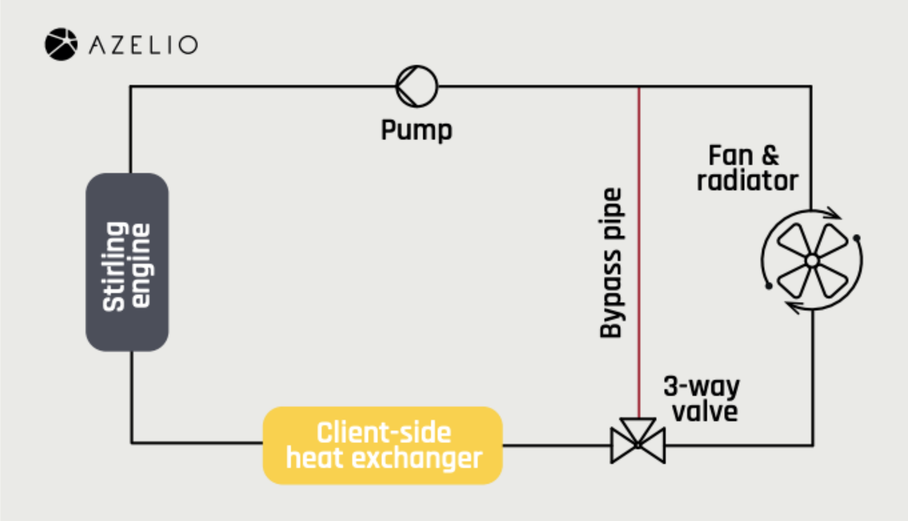


Figure 4.6. Piping and instrumentation diagram of the CHP version of the TES.POD from Azelio (2023).

4.3.1 Mature Technologies and Key Features

The energy storage sector is vast. Different jobs require vastly different tools. In this light, ESSs have evolved based off market demand, to solve unique challenges, and to meet specific needs of users. A small, dense, and portable battery is needed in smartphones whereas a wind farm could employ massive, heavy arrays of stationary batteries with fewer weight constraints. A review of the breadth of ESS is illustrated in **Figure 4.7**.

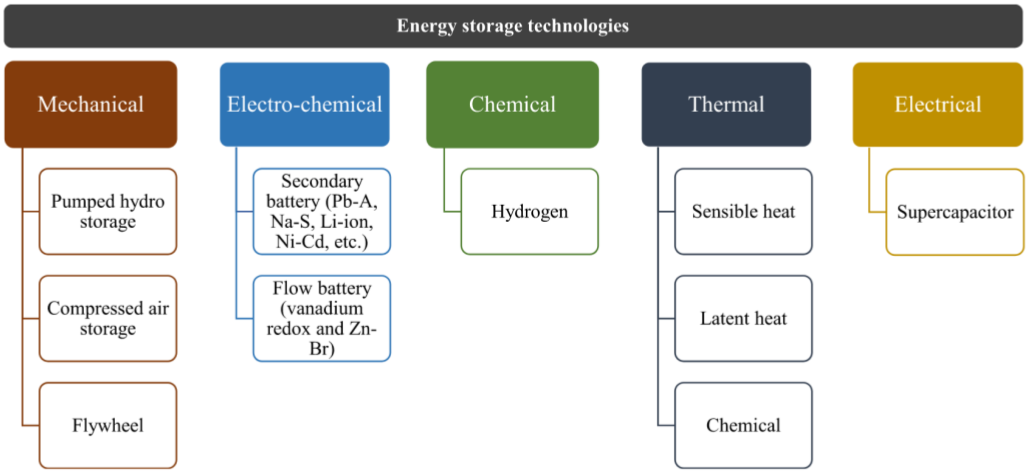


Figure 4.7. Organization of ESS technologies by category as presented in Rahman et al. (2020).

The most mature storage technologies (TRL 9) are Lead-Acid, Lithium-ion batteries (LiB), Nickel-cadmium (Ni-Cd), pumped-hydro storage (PHS), flywheel energy storage (FES), and vanadium redox batteries (VRB)—which have all been deployed and operational in real environments (Mitali et al., 2022). Hydrogen energy storage is included due to its promising potential, even though the technology is at a relatively early development stage.

4.3.1.1 Lead-Acid

Lead-Acid batteries are the oldest and most widespread electrochemical ESS, and are made up of lead in a sulphuric acid and water electrolyte (Mitali et al., 2022). Lead-acid batteries are used in micro-grids, hybrid energy systems, frequency regulation, bulk storage, etc., with the largest installations reaching 10MW as of 2020 (Rahman et al., 2020). Key benefits of lead-acid batteries are the wide versatility of sizes/designs, high efficiencies, low capital cost, and high mass densities of energy (also referred to as specific power). Disadvantages include slow charge rate, durability, high self-discharge, and its environmental footprint (Mitali et al., 2022).

4.3.1.2 Lithium-ion

LiBs are the most widely deployed electrochemical ESS technology and dominate the storage market (Rahman et al., 2020). Interviewee 3 and interviewee 4 corroborated the assertion that LiBs are the leading ESS on the market. LiBs are constructed with a graphite carbon anode, a lithium metal oxide cathode, and employ lithium salt as the electrolyte that ions move through during the charge and discharge cycles (Mitali et al., 2022). Features of LiBs are high efficiencies, longer life cycles, a light weight, and high energy and power density which have led to the widespread success of the technology—especially for use in electronic and transportation sectors like the battery in your phone or electric vehicle (EV) (Mitali et al., 2022; Rahman et al., 2020). Interviewee 3 pointed out that LFP chemistry for LiB has become dominant, prices have decreased, and energy density has grown. However, safety concerns such as the fire risk interviewee 3 spoke on, and demand for still lower cost alternatives continue to drive research and development into the technology (Gao et al., 2022). High efficiencies, longer lifecycles, and high energy/power densities are some of the important features that make LiB attractive across stationary, mobile, and both small- and large-scale application. Economies of scale have contributed to the decreasing price of LiBs.

4.3.1.3 Nickel-cadmium

Ni-Cd batteries have been around since their invention in 1899, made with electrodes of nickel oxyhydroxide and metallic cadmium in an electrolyte of potassium hydroxide (Mitali et al., 2022). Key features of Ni-Cd batteries are a long shelf life, low cost per cycle, ability to charge rapidly, and decent low-temperature performance (Krishan & Suhag, 2019; Mitali et al., 2022). These features make Ni-Cd attractive for applications in electric power appliances, where the longer life cycle and good performance under electrical loads outweigh the disadvantages of using toxic materials (i.e., Nickel, Cadmium) and a low specific energy (Mitali et al., 2022).

4.3.1.4 Pumped-hydro Storage

PHS is the most widely deployed storage technology by far, with 95-96% of the installed global power capacity (Blakers et al., 2021; Mitali et al., 2022; Rahman et al., 2020; Topalović et al., 2023; Vecchi et al., 2022). PHS consists of an upper reservoir, a lower reservoir, a pump, and a turbine. In times of low energy demand water is pumped against gravity to the upper reservoir and when energy is needed water flows downwards to the lower reservoir turning a turbine to produce electricity (Blakers et al., 2021). PHS is used especially for load leveling and peak shaving (Hossain et al., 2020). Features of PHS are its conceptual simplicity, massive energy capacity, high efficiency, and ability to store energy over long periods of time. Disadvantages of PHS are massive water demands and geographical limitations (Blakers et al., 2021; Mitali et al., 2022).

4.3.1.5 Flywheel Energy Storage

FES stores energy in the rotational kinetic energy of a cylinder in a vacuum (Hossain et al., 2020). An electric motor rotates the cylinder at very high speeds during the charging stage and in the discharge stage the kinetic energy rotating the cylinder is used in reverse to rotate the motor, producing electric energy (Mitali et al., 2022). FES range from KW to GW scales, have high efficiencies, and high energy and power density making them attractive for a breadth of applications like satellites, power system support, military applications, transportation, etc. (Hebner et al., 2002; Hossain et al., 2020). Quick response time, longer cycles, and a low DoD make FES favorable for situations that need short term storage and rapid response, such as uninterruptible power supply applications and managing electrical disturbance, especially peak shaving connected to electric vehicle charging demands (Hossain et al., 2020; Topalović et al., 2023). Disadvantages of FES are low storage capacity, high self-discharge, and high capital cost (Mitali et al., 2022).

4.3.1.6 Vanadium Redox Batteries

VRBs are categorized as a flow battery system, where two electrolytes are stored in separate tanks. VRBs use electron transfer between two ionic vanadium materials separated by a protein membrane to store electrochemical energy (Mitali et al., 2022). A main advantage of VRBs are that power (number of cells/size of electrode) and energy rating (volume of reservoirs, concentration of electrolyte) can be designed independently, increasing the application potential (Mostafa et al., 2020; Nadeem et al., 2019; Rahman et al., 2020). VRBs have a high efficiency at light loads, low self-discharge rates, long life cycles (>10,000), quick response times, can maintain a constant voltage at all operating conditions, and be recharged instantly by replacing the electrolyte (Nadeem et al., 2019). These features of VRBs make the technology useful for large-scale peak shaving, uninterruptible power supply, RES integration, power quality, and load levelling applications (Hossain et al., 2020). Disadvantages include high production cost, large spatial requirements, and low energy density (Mitali et al., 2022).

4.3.1.7 Hydrogen

There are several different types of hydrogen systems, but in general hydrogen energy storage systems are typically made up of three components: 1) a generation unit (e.g., electrolyzer) to convert electrical energy into hydrogen, 2) a storage system (i.e., a pressurized tank), and 3) an energy conversion unit like a fuel cell to convert chemical energy back into electricity (Mitali et al., 2022). Hydrogen fuel is regarded as one of the cleanest, most efficient, and lightweight zero-emission fuels available, a feature that has catalyzed massive research and development into improving the technology (Rahman et al., 2020). Hydrogen's advantages are the clean nature of its byproducts (water and heat), its versatility across many different applications, quick response times, cycling capacity, scalability, and duration of storage (Mitali et al., 2022; Mostafa et al., 2020). Interviewee 4, who has experience in green hydrogen, pointed out that as development is progressing the efficiency of electrolyzers is increasing and hydrogen is becoming more reliable in power production which is attracting commercial attention from large industry players. Disadvantages of hydrogen are low efficiency, storage challenges like leakage, and high capital cost (Koohi-Fayegh & Rosen, 2020).

4.3.2 Comparison to a Carnot Battery

Understanding and identifying features, strengths, and weaknesses of mature energy storage technologies on a general level helped to position CBs in context as an emerging ESS. Because CB technology has a vast range of possible configurations, scales, working fluids, components, operating contexts, and are still in active development, a single CB product was focused upon and enabled a more detailed comparison. In a research-for-design approach, the purpose of this sub-research question followed the path of acquiring generic knowledge to set the basis for specific knowledge to be developed later in the design (Nijhuis & Bobbink, 2012).

The most recent review paper on ESS from Mitali et al. (2022) is referred to as the primary source of values and further sources are referenced where necessary to validate certain data or to include the most up-to-date metrics.

Table 4.4.
Technoeconomic and environmental parameters for ESS technologies- I (Mitali et al., 2022).

ESS	**discharge duration (at rated power)**	**total charging/discharging efficiency (%)**	**Storage capacity (MWh)[a]**	**mass density of energy (Wh/kg)**	**Suitable storage duration[a]**
Lead-Acid	Secs-hours	63-90	0.001-40	30-75	Minutes-days; short to medium term
LiB	Mins-hours	75-97	0.004-10	100-200	Minutes-days; short to medium term
Ni-Cd	Secs-hours	60-90	6.75	40-90	Minutes-days; short and long term
PHS	1-24 hours	70-85	180-8000	0.5-1.5	Hours-months; long-term
FES	Sec-min	70-95	0.0052-5	5-80	Seconds-minutes; short term
VRB	<10 hours	70-85	<60	35-60	Hours-months; long term
Hydrogen	Secs-24 hours	20-66	0.312-39	600-1200	Hours to months
CB (TES.POD)	13 hours	~30%[b] up to 90%[d]	0.165_e 0.6_h	N-A	minutes to months[a]

[a] (Hossain et al., 2020)
[b] (Novotny et al., 2022)
$_e$ electricity
[d] in CHP mode, data from Azelio's website (https://www.azelio.com/the-solution/)
$_h$ heat

Table 4.5.
Technoeconomic and environmental parameters for ESS technologies- II (Mitali et al., 2022).

ESS	**Power range (MW)**	**Discharge efficiency (%)[a]**	**durability/lifetime (years)**	**specific cost of the stored energy (€/kWh)**	**Response time[ac]**	**Environmental Footprint[c]**
Lead-Acid	0-40[b]	85	5-15	46.66-373.32[a]*	Milli-seconds	Moderate
LiB	0.1-100	85	5-15	85-3230[c]	Milli-seconds	Moderate
Ni-Cd	0-40	85	10-20	340-2040	Milliseconds	Moderate
PHS	10-5,000	87	30-60	4.25-85	Seconds-minutes	Large
FES	0.1-20	90-93	15-20	340-11900	<4 milliseconds-seconds	Almost none
VRB	<3	75-82	10	127.5-850	<1 millisecond	Moderate
Hydrogen	0.1-58.8[c]	59	10-20	12.75	<1 second	Small
CB (TES.POD)	8.45-13.2[e]	N-A	20-30+	N-A	Minutes	Small

[a] (Hossain et al., 2020)
[b] (Rahman et al., 2020)
[c] (Topalović et al., 2023)
*converted USD to EUR with an exchange rate of 0.9321
[e] electricity

The wide range of ESS performance is observed in **Table 4.4** and **Table 4.5**. The CB (represented by Azelio's TES.POD) stood out and distinguished itself in several ways. Firstly, amongst the mature ESS technologies included, the CB can discharge for one of the longest time periods second only to PHS. Secondly, besides PHS, durability of the CB outperforms all other ESS. With regards to how long the CB can feasibly store energy, the range of the TES.POD hypothetically enables it to compete with both medium-term storage duration technologies like VRBs or hydrogen, and long-term storage systems such as PHS. CB's ability to store energy over longer durations gave the technology an edge over LiBs, lead-acid, and Ni-Cd in this respect. However, the TES.POD's response time limits its application in services that require near-instantaneous power delivery, especially situations that necessitate response times under one-to-two minutes such as uninterruptible power supply, where FES and the electrochemical batteries thrive. Additionally, the power range of the CB falls on the higher end of the systems presented, with its upper range only surpassed by the ranges of PHS, LiBs, and hydrogen technology. Finally, the ability to deliver both electricity and heat is unique to the CB, setting the technology apart and resulting in increased market access to consumers (refer back to **Fig. 4.2**). Interviewee 1 talked about this unique position and how it opens more avenues of value, as many customers value heat more than electricity. Perhaps the most significant theme extracted out of comparing the TES.POD to mature ESS from a techno-economic perspective is the versatility of the technology. The ability to discharge for long durations, high durability, a wide power range, and cogeneration functionality are all aspects that positively impact the economics of the CB technology (Mostafa et al., 2020).

Despite hydrogen storage's promise, Interviewee 4 pointed out that challenges in transportation, electrolyzer efficiencies, safety, and large-scale application are still present.

From an environmental impact perspective, the qualitative scale from Topalović et al. (2023) provided a preliminary comparison. FES is presented as the least impactful on the environment. Hydrogen and CBs have a small environmental footprint. The electrochemical batteries all fall under the 'moderate' category, while PHS is the only ESS with a large environmental footprint. The method behind these simplified categorizations is justified by electrochemical batteries' disposal of materials and the necessary geography required for PHS (Topalović et al., 2023). These easy-to-communicate classifications of environmental footprint are employed in Vrenne et al. (2021) as well, which can be useful for policy- and decision makers. On a more granular level, LCAs from various sources and estimates of emissions and impact provided insight into where ESS technologies stack up against one another and is presented in **Table 4.6**. Only studies with LCA boundaries of cradle-to-grave were included in the reported values, unless otherwise stated.

Table 4.6.
CO_2eq/kWh emission ranges for ESSs from various studies presented in Rahman et al. (2020).

ESS	**Estimated Emissions from LCA studies (g-CO_2eq/kWh)**	**Comments**
Lead-Acid	21.91-770	Lower value assumes lifetime of 20 years; upper value includes emissions from electricity production
LiB	72.30-600	Emissions from various electricity production sources included
Ni-Cd	0.04-0.05	Cradle-to-gate; only environmental impact from production considered
PHS	5.43-650	Lower value based on 60 year project lifetime; upper value includes emissions from electricity production from various sources
FES	6785-838,315	Cradle to gate and operation; estimated for lifetime of 20/15 years respectively
VRB	7.26-840	Upper value: cradle to gate and operation; various applications and jurisdictions considered
Hydrogen	50.60-1620	Emissions from electricity production from various sources included in analysis
CB (TES.POD)	23[a]	650 components included in assessment; carbon-free electricity source assumed
TES	5-47	Lower value sensible heat storage

[a](Azelio, 2020)

The ranges of the results of LCA studies clearly demonstrated that CBs (and TES overall) performed exceptionally well in environmental impact assessments. Only the lower value ranges of VRBs, lead-acid, and PHS rivaled the estimated values for the CB. The findings from the LCA conducted by the independent Swedish research institute (RISE) (in compliance with ISO14044:2006 and third-party reviewed) are especially impressive given that the TES.POD consists of latent heat (phase-change) storage, which has been found to be more environmentally impactful than sensible heat storage mediums (Azelio, 2020; Dumont & Lemort, 2022; Rahman et al., 2020).

Furthermore, special attention has been paid to CB configurations and their impact on the environment in recent studies. In an LCA conducted in 2022 that built off an earlier 2021 sister-study, a reversible 10kW$_e$ HP/ORC CB was compared to an equivalent 10kW Tesla LiB battery and findings indicated that environmental impact was consistently lower except for abiotic depletion related to the HP/ORC machine (Dumont, Léonard, et al., 2022; Dumont & Lemort, 2022). However, only production was considered, excluding end of life or maintenance. In a multi-criteria decision analysis across technical, environmental, social, and economic indicators, results found that thermal and mechanical storage are the most sustainable energy storage technologies (Balezentis et al., 2021). The ESS included the study were hydrogen, VRBs, LiBs, PHS, lead-acid batteries, and TES (represented by molten salts), and the sustainability assessment was non-site-specific. Interviewee 2 also weighed in on the comparison of Tesla’s LiBs and CBs which they said was not a fair comparison for two reasons: 1) PTES is much more environmentally friendly than LiBs, with a longer lifetime and that 2) the potential for the integration of heat flows (i.e., waste heat, district heating) sets PTES apart. These results validated the general performance of CB systems compared to other ESS, but more depth can still be found for the TES.POD.

In the LCA conducted on the TES.POD, the climate impact of Azelio’s system was found to be 29% lower than a LiB system and 96% lower than a high efficiency diesel generator, as depicted in **Figure 4.8** (Azelio, 2020).

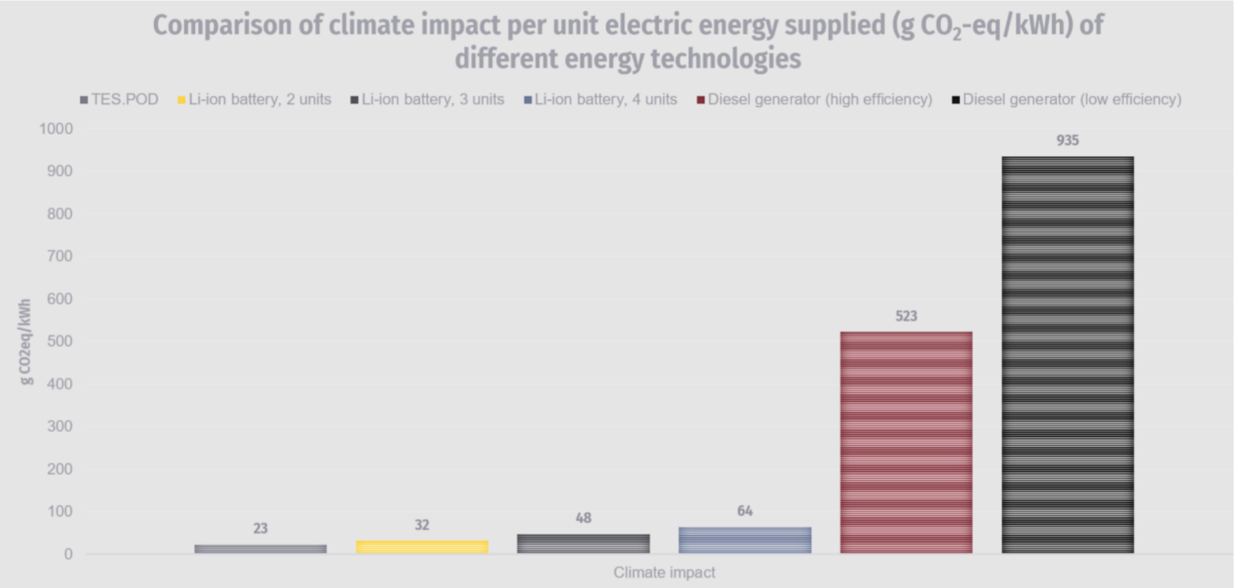


Figure 4.8. Climate impact of various LiBs, the TES.POD, and diesel generators from the TES.POD LCA report from Azelio (2020).

The inclusion of diesel generators for comparison sheds light on the prospective market reach of the TES.POD and further demonstrated the versatility of a CB system beyond simply storing energy. This is supported by Interviewee 1 who spoke to the TES.POD often replacing diesel generators, and often as a complement to electrochemical batteries. The LCA report included transportation, production of materials/components, equipment manufacturing, transportation, assembly, and installation of components, operation, and end of life with an assumed constant delivery of electric power for 13h daily for 25 years (Azelio, 2020). When asked how CBs compare to already mature ESS, Interviewee 2 stated that the storage system class could be just a few years away from full maturity, due in part to the fact that CBs are made from already existing, off-the-shelf components. Moreover, generated energy is stored as heat in recycled aluminum in the TES.POD which suffers no degradation, and Azelio assert that the modular system is fully recyclable (Azelio, 2020). Interviewee 1 pointed towards molten salt as the only other TES technology that rivaled Azelio’s level of commercial development. The stage of maturity, the inclusion of the full solution of storage plus how to use it is unique to Azelio’s TES.POD-- to Interviewee 1’s knowledge at the time of writing.

4.3 Section Summary

Mature energy storage technologies were detailed in this section and techno-economic and environmental performance discussed in relation to CBs. Lead-Acid, lithium-ion batteries (LiB), nickel-cadmium (Ni-Cd), pumped-hydro storage (PHS), flywheel energy storage (FES), and vanadium redox batteries (VRB) were compared across features and indicators with CBs. The CB class was represented by a specific product (Azelio's TES.POD) to tap further depth of comparison. The CBs strengths are its ability to store energy for medium to long durations, durability, long discharge duration, cogeneration ability, versatility in power ranges/applications, and its low environmental footprint in relation to the mature ESSs discussed.

4.4 Relevant Built Environment Conditions for ESS

In the previous section, CBs are situated amongst other mature ESS and compared across techno-economic and environmental performance. This helped to build credibility as to what niche CBs could be most effective at providing energy storage services in an increasingly renewable, intermittent world. In this section, the intersection between the buildings and CBs is expanded upon further to explore what conditions in the built environment are relevant for the use of CBs as ESS, ultimately to facilitate a PEB.

There are numerous application scenarios where CBs can be employed: greenhouse, geothermal, residential, electrolyzers, district heating, schools, thermal solar, industry, supermarkets, CHP cogeneration, and even mobile applications like trucks and boats (Dumont, Thomé, et al., 2022). This versatility and chameleon-like ability of the ESS is one of its strongest selling points for its widespread adoption into our energy fabric. The type of building, its energy system and needs, and application are guided by qualitative data and the research literature.

The TES.POD can be applied across numerous sectors from agriculture, commercial facilities, to residential communities for different applications (Azelio, 2020). In this research, the CB will be conceptually applied to the residential built environment at the single building scale. The selection of the residential sector is motivated by the novelty of case studies in the sector. The intersection of residential energy consumers' needs with CB performance parameters also contributes to these conditions. Energy storage applications for power use in the residential sector are typically "energy-intensive", meaning they are suited to store/release energy for periods ranging from minutes to months, not for managing power peaks (Del Pero et al., 2018). Energy in residential built environments is used for heating, cooling, appliances, lighting, and domestic hot water (Bellos et al., 2023). The delivery of domestic hot water (around 50-60°C) occurs within the temperature range of the TES.POD's delivered heat (max. 60°C). As reported in **Table 4.5**, the response time of the TES.POD is also sufficient for this.

The application is crucial for optimal use of ESS. CB strengths and features aligned with the application of energy management. The justification for this stems from the assertion that general TES is highly promising in energy management; which relates to energy generation and consumption balancing, conserving resources, protecting the climate, and maintaining low expenditure while meeting the energy consumers requirements (Hossain et al., 2020). These objectives align with the sustainable motivation of PEBs, are congruent with customer demand motivations for energy efficient buildings discussed by Interviewee 5, and provide a foundation to steer the research forward. Based on Hossain et al. (2020) and gathered data, the TES.POD may also be compatible with providing emergency back-up power, time shifting, peak shaving, black-start, and standing reserve applications.

Beyond the type of building, conditions in the energy system are important. Interviewee 1 stated that solar panels are the preferred energy generation source for TES.POD coupling due to the consistency and reliability of photovoltaic panels, as opposed to wind. From PEB perspective, solar energy is a strong choice because it is free (after initial capital investment), 100% renewable, and abundant (Dumont, Carmo, Fontaine, et al., 2016). Be it a single building or community, an energy management system (visualized in **Figure 4.9)** is also crucial to design, control, and optimize an ESS (Kumar & Cao, 2021).

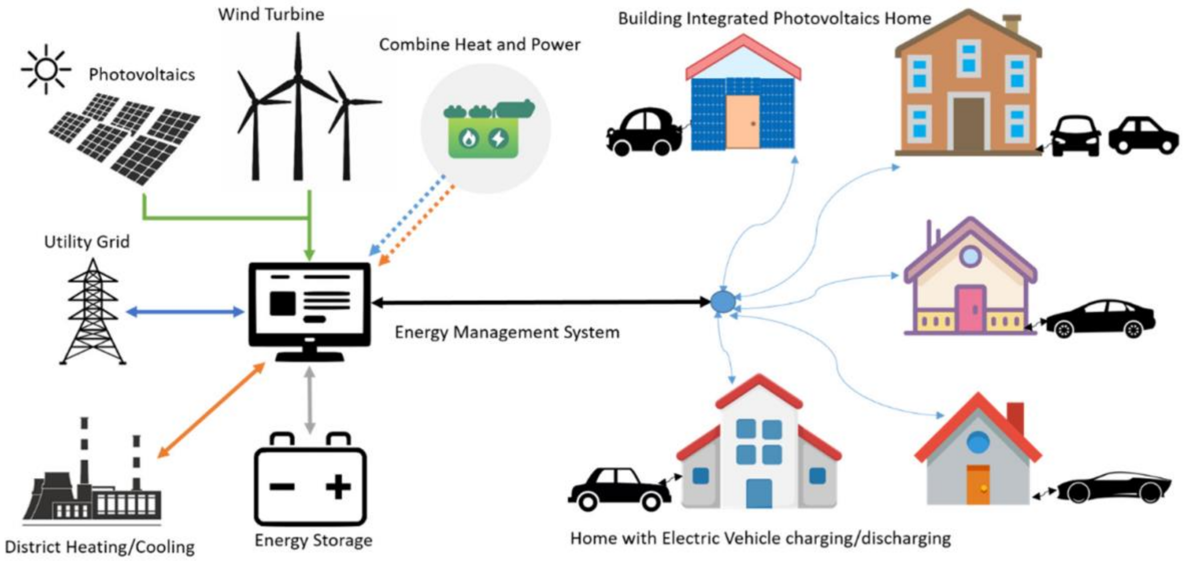


Figure 4.9. Visual example of an energy management system presented in Kumar & Cao (2021).

Furthermore, Interviewee 3 highlighted the increase of EVs at the home front that will create more microgrids and aid in relieving grid overload. This statement flows perfectly into the fact that the TES.POD can often be complementary to electrochemical batteries in practice, as stated by Interviewee 1. In this context, LiBs or another battery address the need for ESS response that is more rapid than CBs can offer at this point.

4.4 Section Summary

In this section, conditions relevant for a CB applied to the built environment are detailed to provide a base for the design. Solar panels are preferred because of their consistency, services residential buildings require align with the capabilities of the TES.POD for the application of energy management, the technical specifications of a single TES.POD module fit into the scale of a single building, and lastly, an energy management system is assumed to be necessary for optimal function. Other building types, scales, applications, and renewable energy coupling opportunities are promising, but for this research, the conditions for CB application are:

1. Type of building: residential
2. Scale: single building
3. Application: energy management (for heating, cooling, domestic hot water, appliances, and lighting)
4. Energy system: onsite solar PV panels coupled to an energy management system

4.5 Application of Carnot Battery

After building a foundation in the CB landscape, identifying important techno-economic and environmental indicators that can communicate impact, exploring and comparing mature energy storage technologies with CBs, and identifying built environment conditions relevant for CB application—this section details an example hypothetical design of a building with a CB as energy storage and a basic analysis from the perspective of an energy management application. The immediate goal of the system is to maximize economic and environmental benefits while helping to manage the energy balance of the building. The ultimate goal is an annual net-positive energy balance.

The section begins by introducing the case study building, detailing the photovoltaic system energy output potential, and then explores the impact of the TES.POD when applied to energy management (for both electricity and heat) on various timescales in a business-as-usual scenario. An energy efficient scenario is explored to conclude the section.

Introduction of the Case study Building

Location	Leiden, the Netherlands
Year built	1960s (Renovated 2009)
Type	100% residential
Size	11 stories + detached house, 168 apartments, 16 rooms per floor

Figure 4.10. Aerial view of the case study building (left) and plot. Street view of east-facing façade with detached house pictured as well (right) from Google Earth (2021).

The boundaries of the case study are limited to the immediate site of the building in Leiden. The site included a detached house (which can be seen in **Figure 4.10**), which is included in the renewable energy potential as well as in the energy consumption data. The energy balance and costs are calculated for the entire building.

A note on section nomenclature and relevant definition(s):

- **Business-as-usual**: electricity purchased from the grid and natural gas purchased from gas utility through existing infrastructure connections
- **Consumption**: actual energy use based on measured data of case study building, synonymous with demand for the purpose of this section
- **Energy balance**: the net-energy equation of the case study site, influenced by input consumption of natural gas (m^3), electricity (kWh), and CB and estimated PV system output

To provide additional context, performance specifications of the TES.POD are organized and presented in **Table 4.7.**

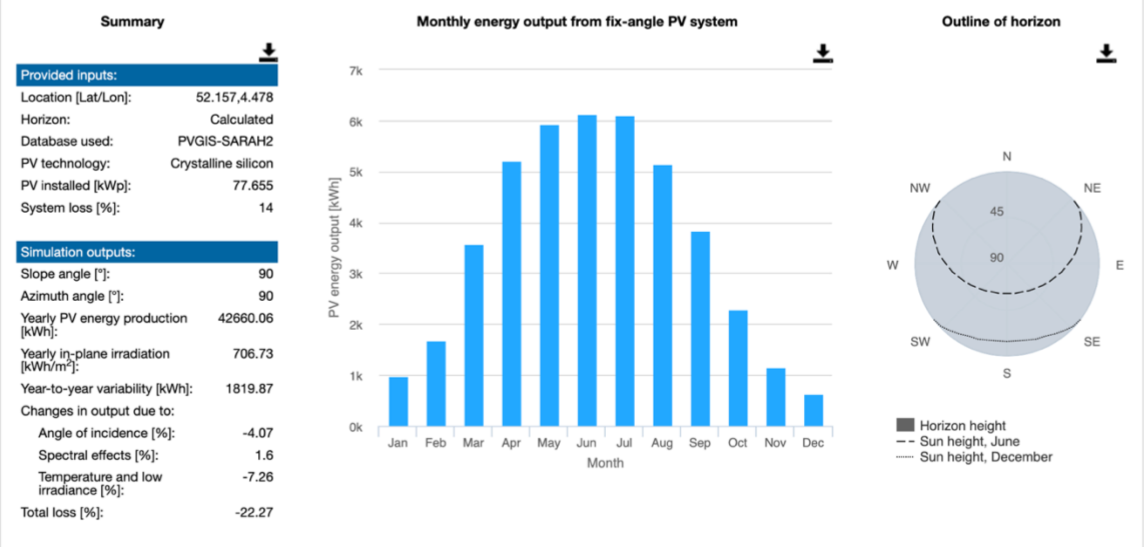
Table 4.7. Performance specifications of a CHP mode TES.POD module.

Storage Capacity	165 kWh_e 600 kWh_h
Max. Charge Power	100 kW_e
Nominal Power	11 kW_e 25 kW_h
Fastest charge time	6 hours
Discharge duration	13 to 40 hours
Temperature of Dispatched Heat	50-60 °C
$_e$ electricity $_h$ heat	

Renewable Energy System

PEBs, characterized by the generation of more energy than they consume, represent an evolution in sustainable building practices and a visionary milestone that is useful to orient towards. A crucial component of creating PEBs is energy from renewable sources (Rehman & Ala-Juusela, 2022). For this reason, a hypothetical renewable power system of onsite PV panels has been designed, applied to the Leiden building, and the energy output of the system estimated. Estimation of the case study building's photovoltaic system potential was conducted in four phases to account for different azimuths, number of panels, slope angles, and mounting capabilities of the different zones of the building. The zones are the 1) west-facing façade, 2) east-facing façade, 3) roof area of the 11-story building, and the 4) detached house rooftop area. Taken together, estimations of the suitable areas for PV panels indicate a combined potential total of 453 Aiko N-Type ABC White Hole Series 54-cell panels. The results of the RES energy output estimation (photovoltaic potential analysis) are presented in (**Figures 4.11 – 4.14**) for the four zones of panels, followed by economic estimates for the solar panels.

West-Facing façade



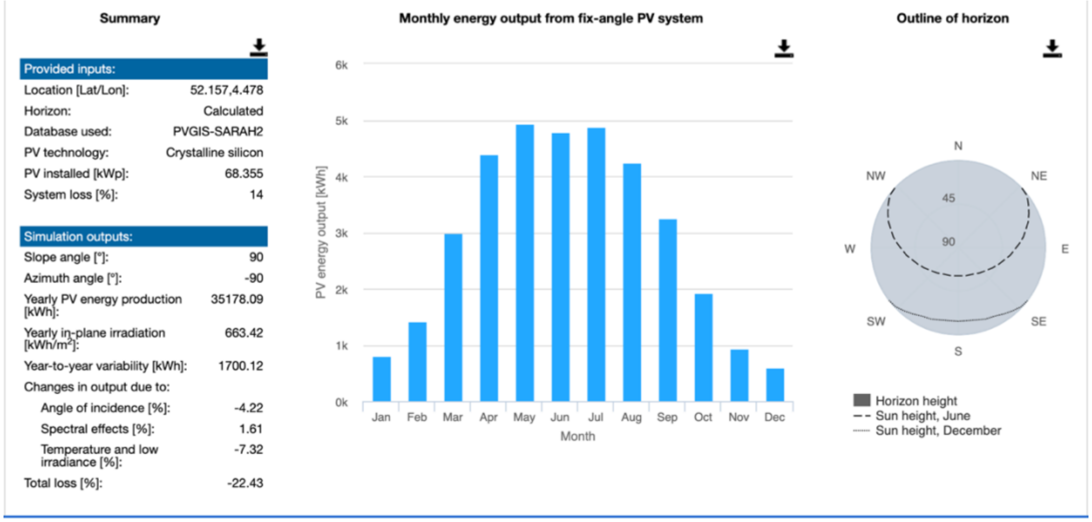
Summary

Provided inputs:	
Location [Lat/Lon]:	52.157,4.478
Horizon:	Calculated
Database used:	PVGIS-SARAH2
PV technology:	Crystalline silicon
PV installed [kWp]:	77.655
System loss [%]:	14

Simulation outputs:	
Slope angle [°]:	90
Azimuth angle [°]:	90
Yearly PV energy production [kWh]:	42660.06
Yearly in-plane irradiation [kWh/m²]:	706.73
Year-to-year variability [kWh]:	1819.87
Changes in output due to:	
Angle of incidence [%]:	-4.07
Spectral effects [%]:	1.6
Temperature and low irradiance [%]:	-7.26
Total loss [%]:	-22.27

Figure 4.11. Monthly energy output potential of 167-465W PV panels located on the west-facing façade of the case study building as calculated in the PVGIS tool (European Comission, 2022).

East-Facing Façade



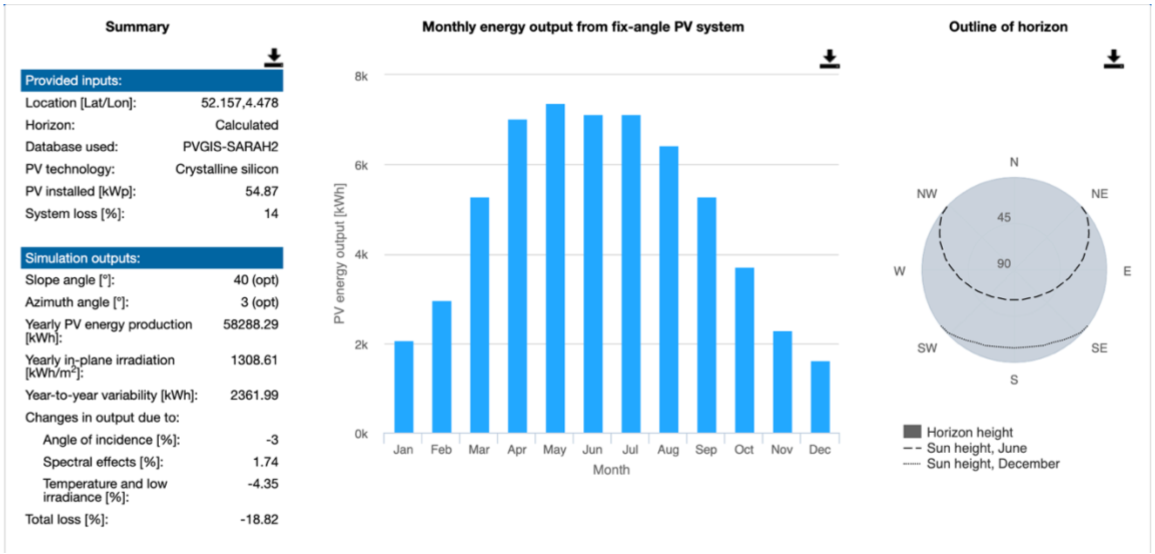
Summary

Provided inputs:	
Location [Lat/Lon]:	52.157,4.478
Horizon:	Calculated
Database used:	PVGIS-SARAH2
PV technology:	Crystalline silicon
PV installed [kWp]:	68.355
System loss [%]:	14

Simulation outputs:	
Slope angle [°]:	90
Azimuth angle [°]:	-90
Yearly PV energy production [kWh]:	35178.09
Yearly in-plane irradiation [kWh/m²]:	663.42
Year-to-year variability [kWh]:	1700.12
Changes in output due to:	
Angle of incidence [%]:	-4.22
Spectral effects [%]:	1.61
Temperature and low irradiance [%]:	-7.32
Total loss [%]:	-22.43

Figure 4.12. Monthly energy output potential of 147-465W PV panels located on the east-facing façade of the case study building as calculated in the PVGIS tool (European Comission, 2022).

11-story Rooftop Area



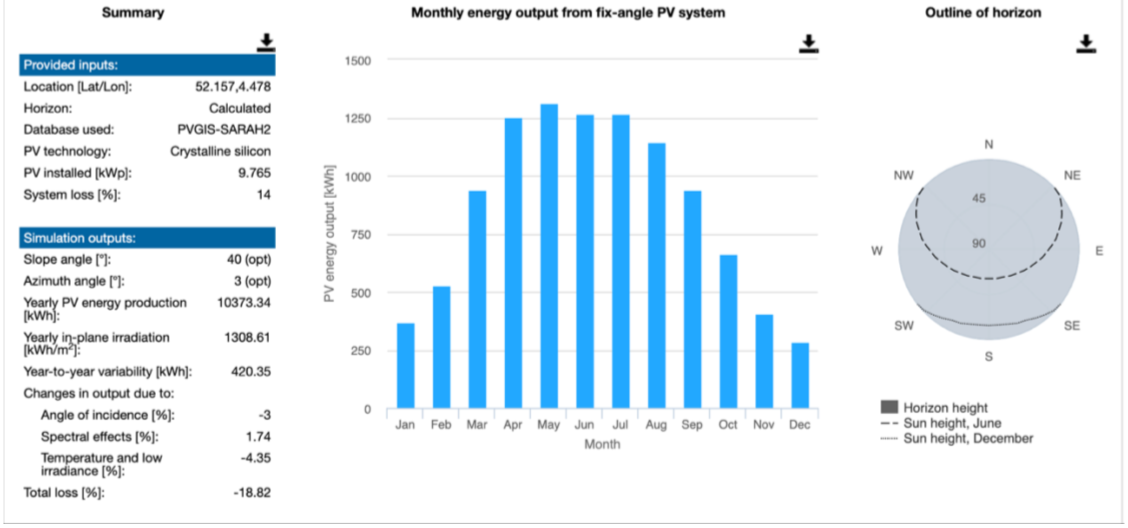
Summary

Provided inputs:	
Location [Lat/Lon]:	52.157,4.478
Horizon:	Calculated
Database used:	PVGIS-SARAH2
PV technology:	Crystalline silicon
PV installed [kWp]:	54.87
System loss [%]:	14

Simulation outputs:	
Slope angle [°]:	40 (opt)
Azimuth angle [°]:	3 (opt)
Yearly PV energy production [kWh]:	58288.29
Yearly in-plane irradiation [kWh/m²]:	1308.61
Year-to-year variability [kWh]:	2361.99
Changes in output due to:	
Angle of incidence [%]:	-3
Spectral effects [%]:	1.74
Temperature and low irradiance [%]:	-4.35
Total loss [%]:	-18.82

Figure 4.13. Monthly energy output potential of 118-465W PV panels located on the 11-story rooftop of the case study building as calculated in the PVGIS tool (European Comission, 2022).

Detached House Rooftop Area



Summary

Provided inputs:	
Location [Lat/Lon]:	52.157,4.478
Horizon:	Calculated
Database used:	PVGIS-SARAH2
PV technology:	Crystalline silicon
PV installed [kWp]:	9.765
System loss [%]:	14

Simulation outputs:	
Slope angle [°]:	40 (opt)
Azimuth angle [°]:	3 (opt)
Yearly PV energy production [kWh]:	10373.34
Yearly in-plane irradiation [kWh/m²]:	1308.61
Year-to-year variability [kWh]:	420.35
Changes in output due to:	
Angle of incidence [%]:	-3
Spectral effects [%]:	1.74
Temperature and low irradiance [%]:	-4.35
Total loss [%]:	-18.82

Figure 4.14. Monthly energy output potential of 21-465W PV panels located on the detached house rooftop of the case study building as calculated in the PVGIS tool (European Comission, 2022).

Combined Energy Output from all Four PV Arrays

Taken together, the four PV panel arrays produce an annual total of 146,419 kWh. The energy output per array is presented in **Figure 4.15**.

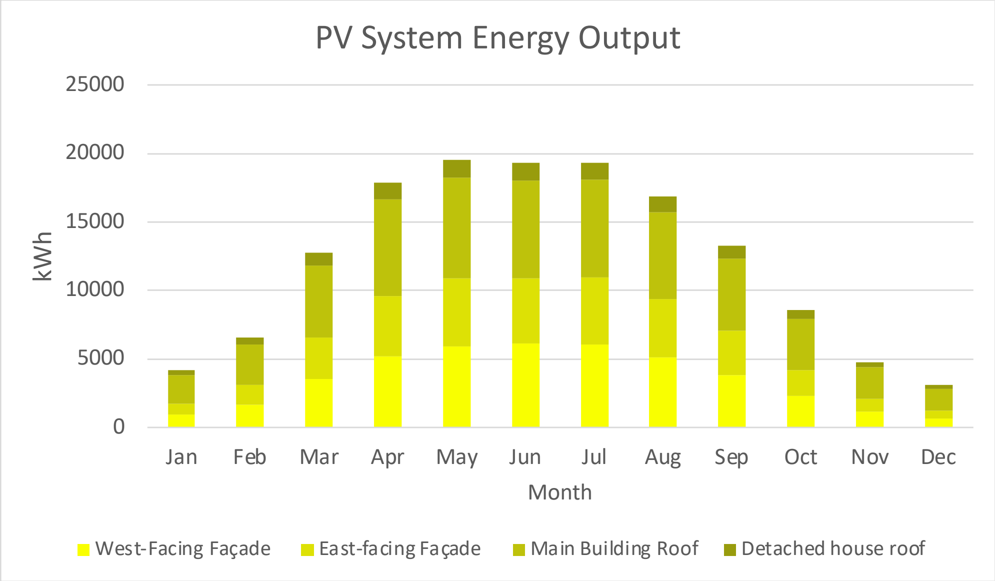
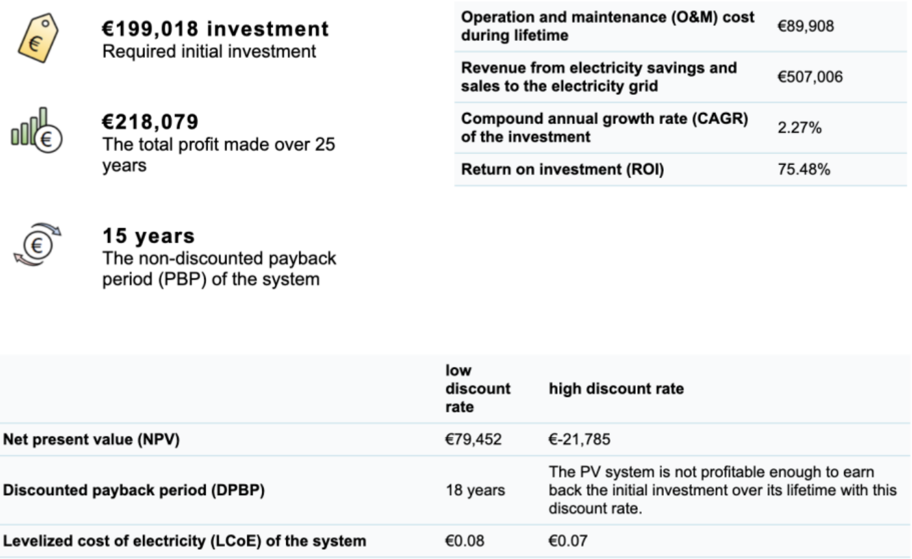


Figure 4.15. Combined energy output of the four PV arrays for the case study building over the course of a year.

Economics of PV System

The economic return, LCOE, payback period, initial investment, operating costs, and net present value of the 453 panel Aiko N-Type ABC White Hole Series 54-cell system are presented in **Figure 4.16** and **Figure 4.17** as estimated with the Detailed PV System Design tool (Klement, n.d.).



€199,018 investment
Required initial investment

€218,079
The total profit made over 25 years

15 years
The non-discounted payback period (PBP) of the system

Operation and maintenance (O&M) cost during lifetime	€89,908
Revenue from electricity savings and sales to the electricity grid	€507,006
Compound annual growth rate (CAGR) of the investment	2.27%
Return on investment (ROI)	75.48%

	low discount rate	**high discount rate**
Net present value (NPV)	€79,452	€-21,785
Discounted payback period (DPBP)	18 years	The PV system is not profitable enough to earn back the initial investment over its lifetime with this discount rate.
Levelized cost of electricity (LCoE) of the system	€0.08	€0.07

Figure 4.16. Economic estimations for 453-panel high-efficiency monocrystalline silicon PV system located in Leiden, the Netherlands calculated by Klement (n.d.).

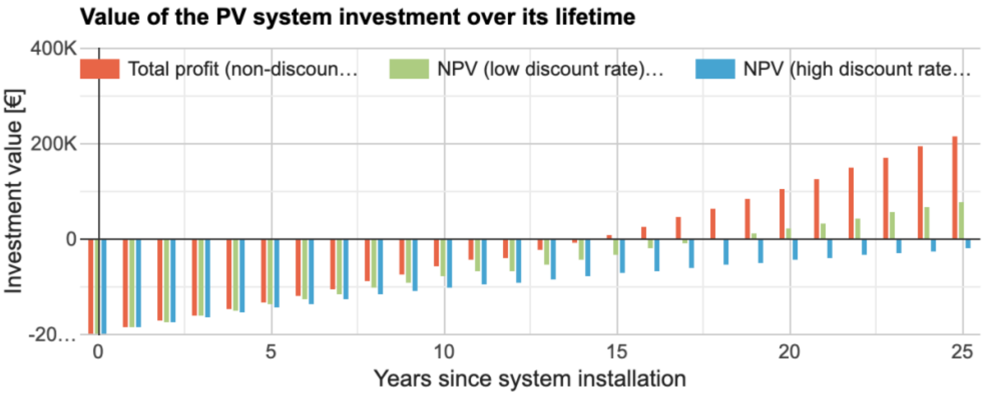


Figure 4.17. Economic value over 25-year lifetime for 453-panel high-efficiency monocrystalline silicon PV system located in Leiden, the Netherlands as calculated by Klement (n.d.).

The LCOE for the PV panel system of €0.08 is marginally cheaper than the LCOE of a combined cycle gas turbine (CCGT) natural gas power plant (€0.10) (Badouard et al., 2020). This comparison provides some economic context as gas makes up the single largest share of the Netherland's energy supply (45%) (IRENA, 2022).

Total Annual Energy Balance

The total annual energy balance is presented in **Figure 4.18**. The lion's share of the energy demand is from space heating, with the second-most energy demanded by domestic hot water.

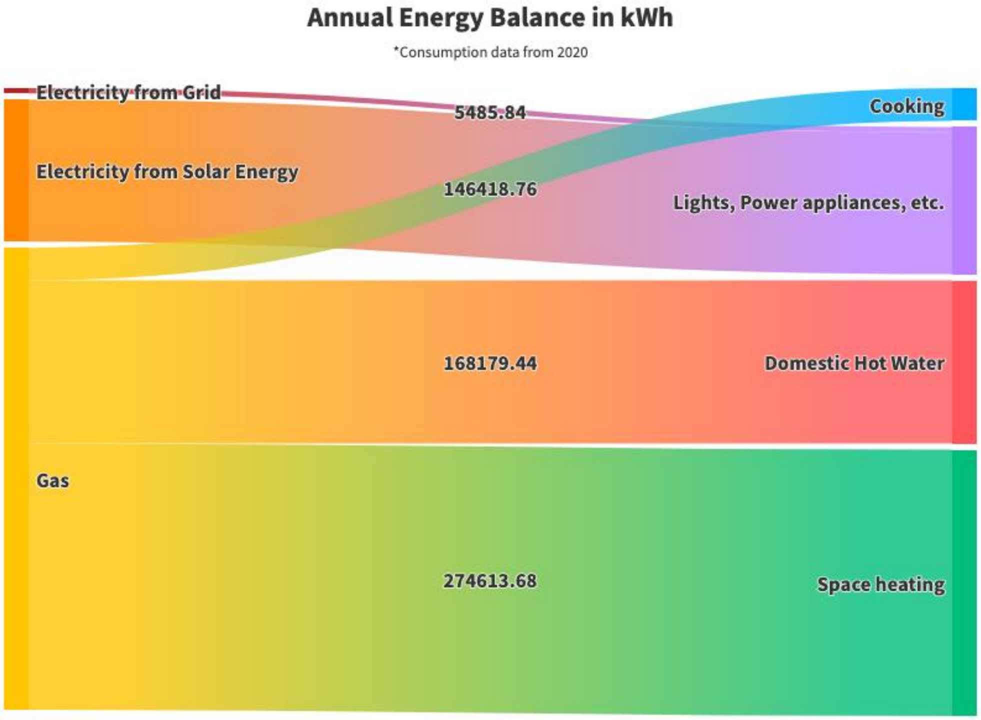


Figure 4.18. Annual energy balance including estimated PV system potential organized by proportion of demand for end-use (not labelled: gas for cooking = 33,636 kWh).

Total Monthly Energy Balance

The total monthly energy consumption and solar energy output has been depicted in **Figure 4.19**. Consumption is consistently higher than PV power system energy output for all months.

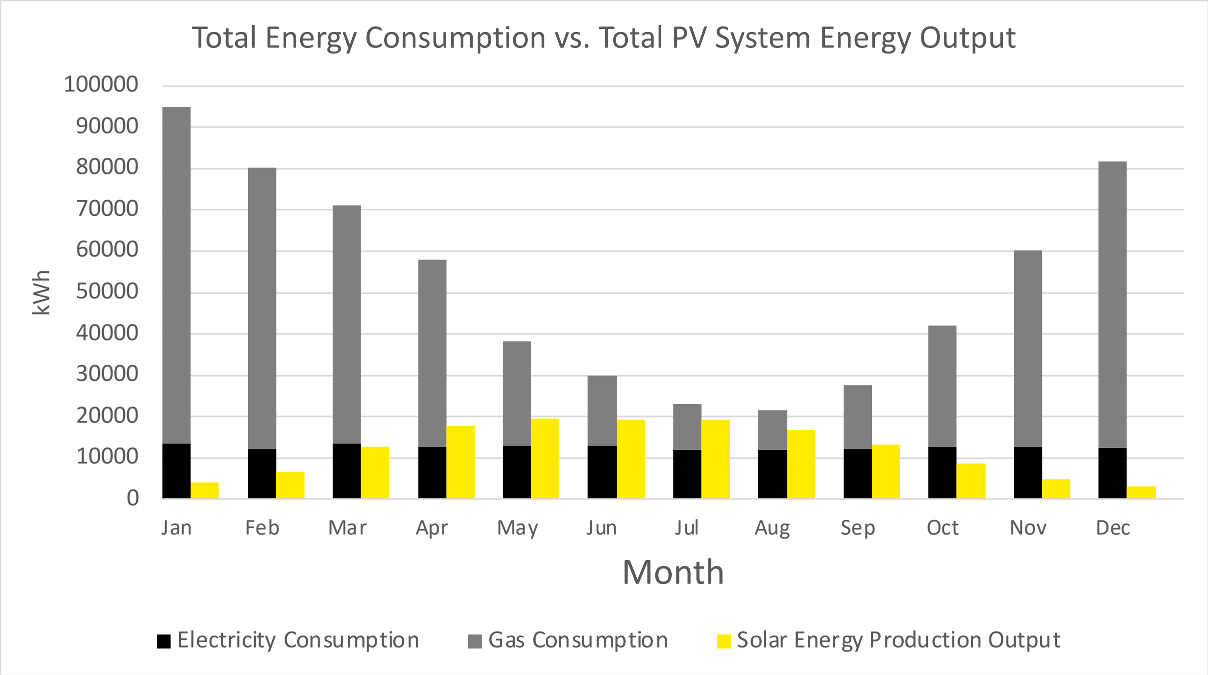


Figure 4.19. Total electricity consumption, gas consumption, and full solar system energy output for the case study building, with gas (m^3) converted to kWh.

Total Hourly Energy Balance

The hourly energy balance for representative summer and winter days is presented below (**Figure 4.20**). The energy consumption includes gas in addition to electricity. The combination of heat energy (natural gas) with energy in the form of electricity gives an idea of the energy balance for a summer and winter day, and where an energy surplus may exist for the CB's use.

June 20th

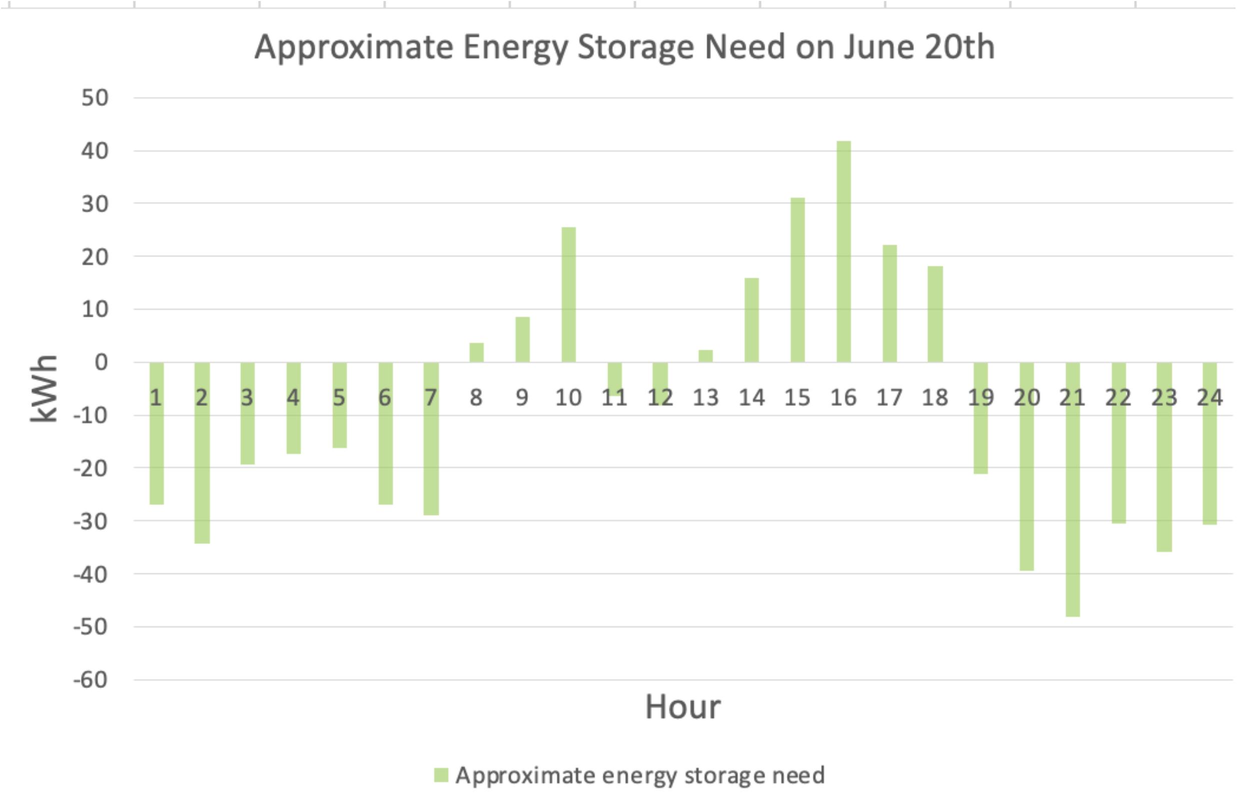


Figure 4.20. Approximate energy storage need based off total energy consumption for June 20th.

Over the course of the representative summer day, there are nine hours where an energy surplus exists. If the CB is charged with the available solar energy surplus, the TES.POD's 13-40h discharge duration would be able to shift loads to the evening of the June day, reducing demand for fossil-fuels during peak hours. The approximate energy storage need for December is presented in **Figure 4.21.**

December 23rd

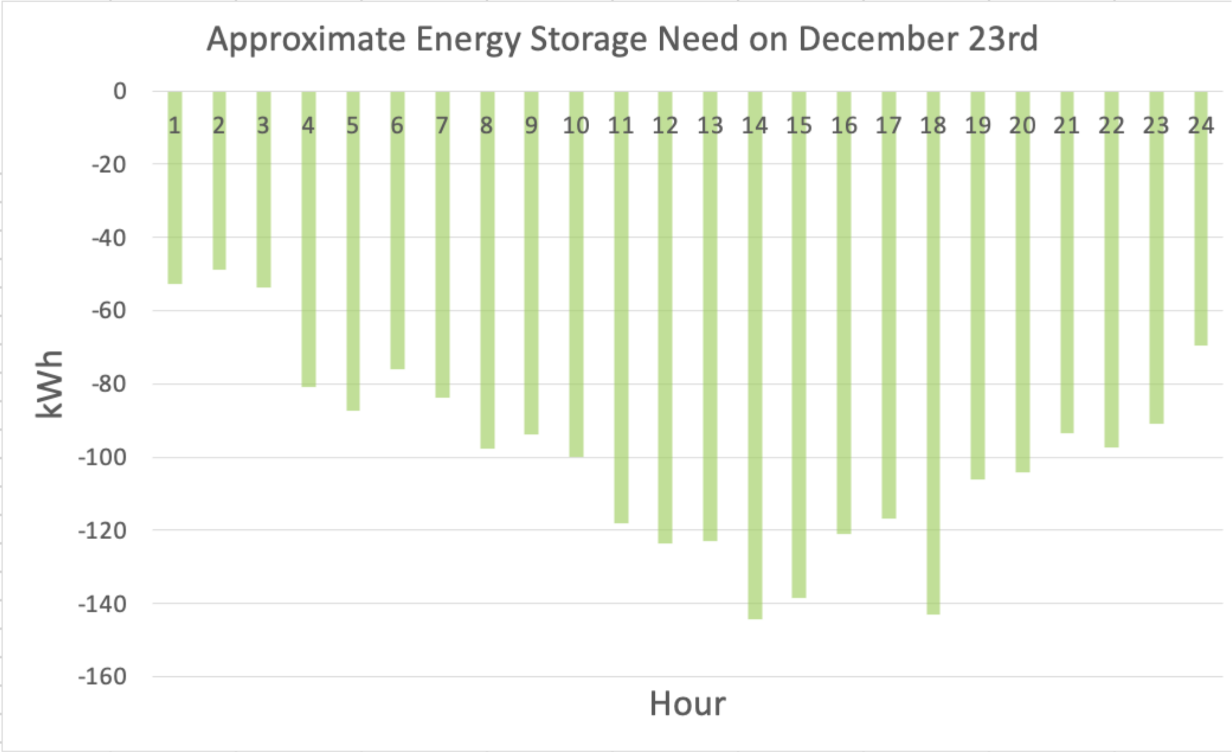
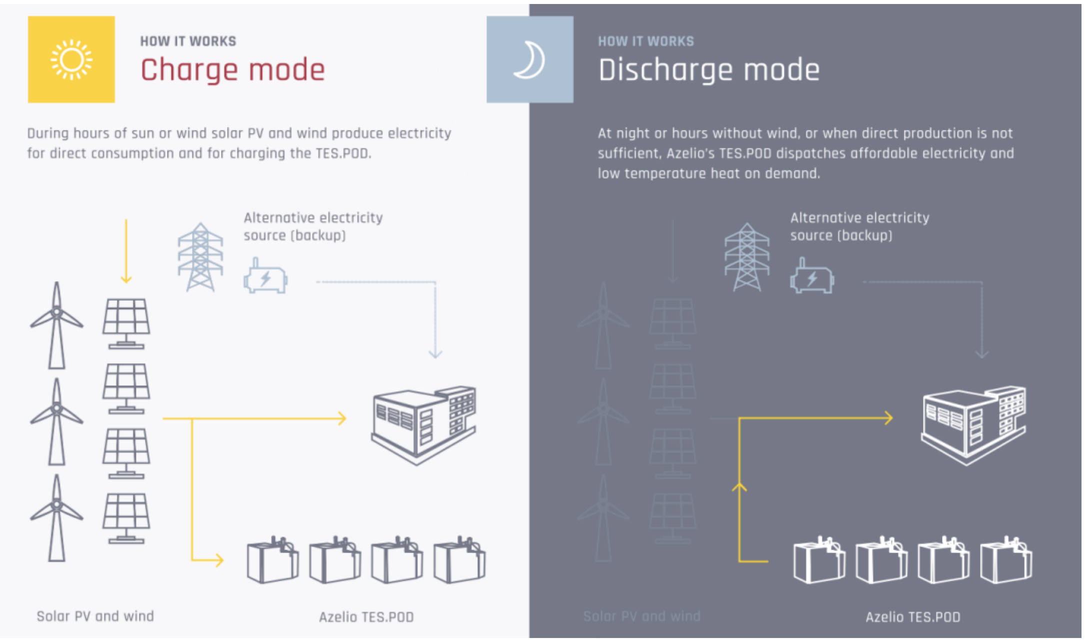


Figure 4.21. Approximate energy storage need for December 23rd.

The need for energy storage for December 23rd (**Figure 4.21)** is consistently negative. Low sunlight, shorter days, and higher demand for space heating contribute to this result.

<u>Carnot Battery Applied to Energy System for Energy Management</u>

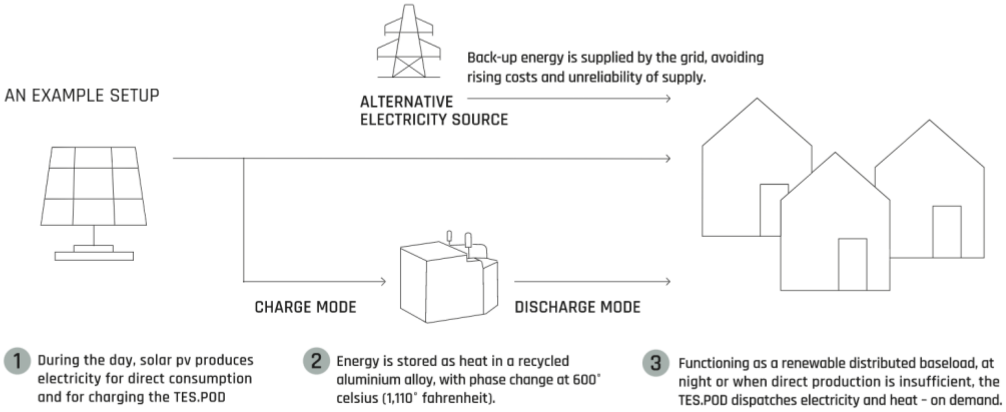
The results of applying the TES.POD for the services of energy management (for electricity and heat independently) are detailed. A basic schematic of the energy system is presented in **Figure 4.22** and **Figure 4.23**.



During hours of sun or wind solar PV and wind produce electricity for direct consumption and for charging the TES.POD.

At night or hours without wind, or when direct production is not sufficient, Azelio's TES.POD dispatches affordable electricity and low temperature heat on demand.

Figure 4.22. Example layout of building coupled TES.POD(s) supplied by a photovoltaic array from Azelio (2023a).



Back-up energy is supplied by the grid, avoiding rising costs and unreliability of supply.

① During the day, solar pv produces electricity for direct consumption and for charging the TES.POD

② Energy is stored as heat in a recycled aluminium alloy, with phase change at 600° celsius (1,110° fahrenheit).

③ Functioning as a renewable distributed baseload, at night or when direct production is insufficient, the TES.POD dispatches electricity and heat - on demand.

Figure 4.23. Example configuration of residential energy system with TES.POD as energy storage from Azelio (2023a).

Energy Management of Electricity

Energy management for a 100% residential building can be subdivided into electricity and heat. Energy in the form of electricity is used for cooling, powering appliances like refrigerators, toasters, coffee machines, and lighting in the Leiden case study building. Energy in the form of heat (natural gas in this context) is used for cooking, heats the building spaces, and its hot water for use for things like cleaning, kitchen use, bathing, and washing clothes. From a net-electricity perspective, the TES.POD applied to the case study building can increase self-consumption of onsite renewable energy generation and alleviate grid-load during the months of April, May, June, July, August, and September with a total surplus of 31,399 kWh. At a total efficiency of 30%, 9,420 kWh would be available to dispatch as electricity (**Figure 4.24**). This amount of electricity would cost €3,884.81 (at a June 2022 rate) and mitigate 1,262.6 kilograms of CO_2—the equivalent to the amount 63 trees capture over a whole year—if it was supplied by the TES.POD instead of the grid connection. Daily charging and discharging of the TES.POD is preferred to maximize benefits.

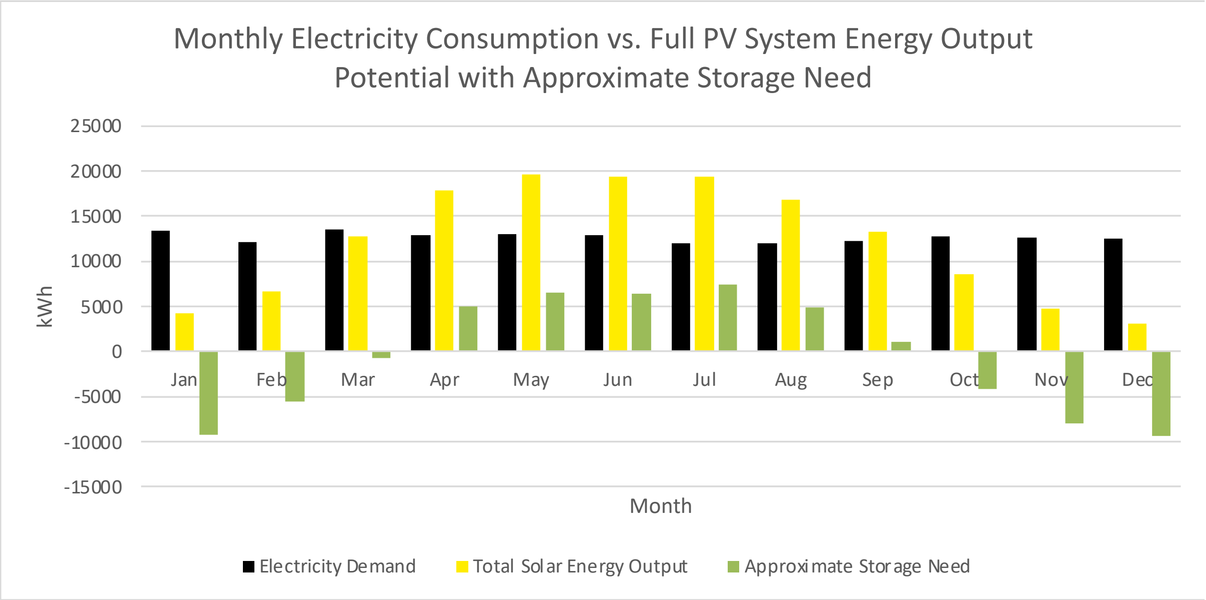


Figure 4.24. Monthly electricity consumption of case study building with PV system energy output and approximate storage need.

For a representative day in June, the surplus energy output from the PV panel arrays (after meeting the electricity demand of the building) that contributed to charging the TES.POD is presented in **Figure 4.25**.

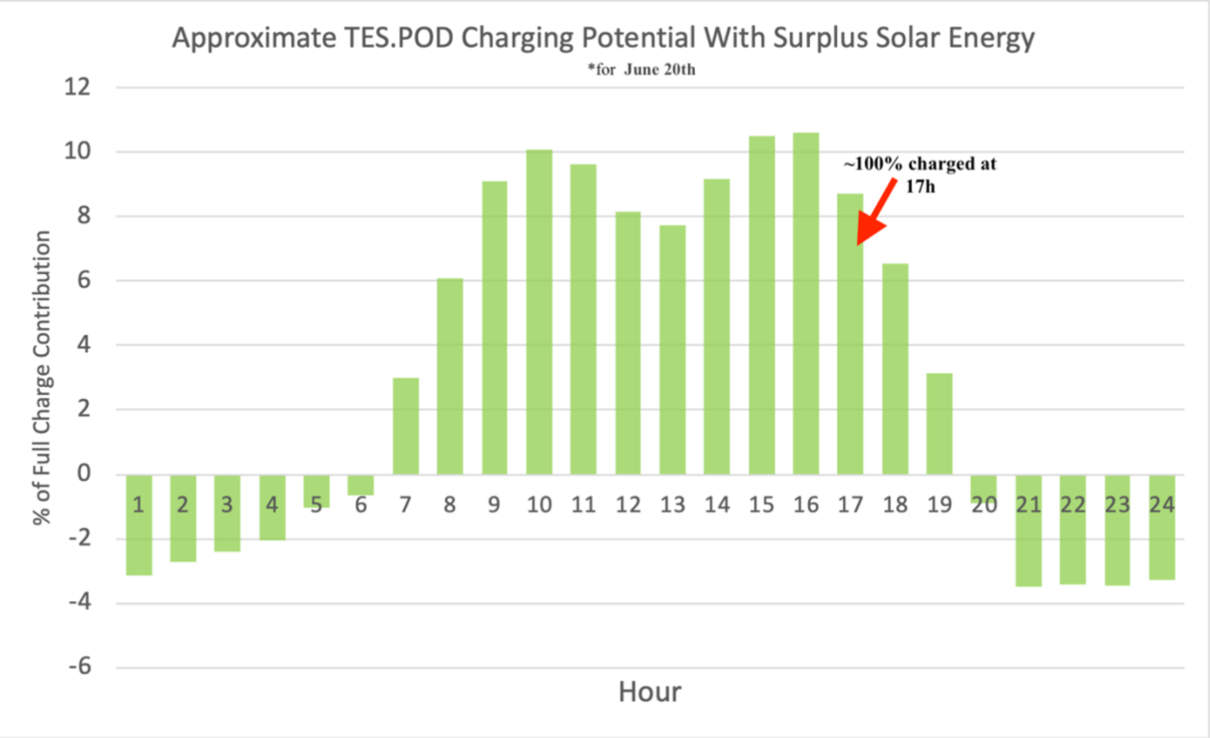


Figure 4.25. Percentage of full energy capacity of one TES.POD contributed per hour by PV energy output surplus for June 20th, after meeting building electricity demand.

Assuming the TES.POD was fully discharged the previous day and starting from a point of zero capacity, the system would be fully charged at 17h. Beginning around 18h, the CB can deliver electricity to help manage the energy balance in the building (**Figure 4.26**).

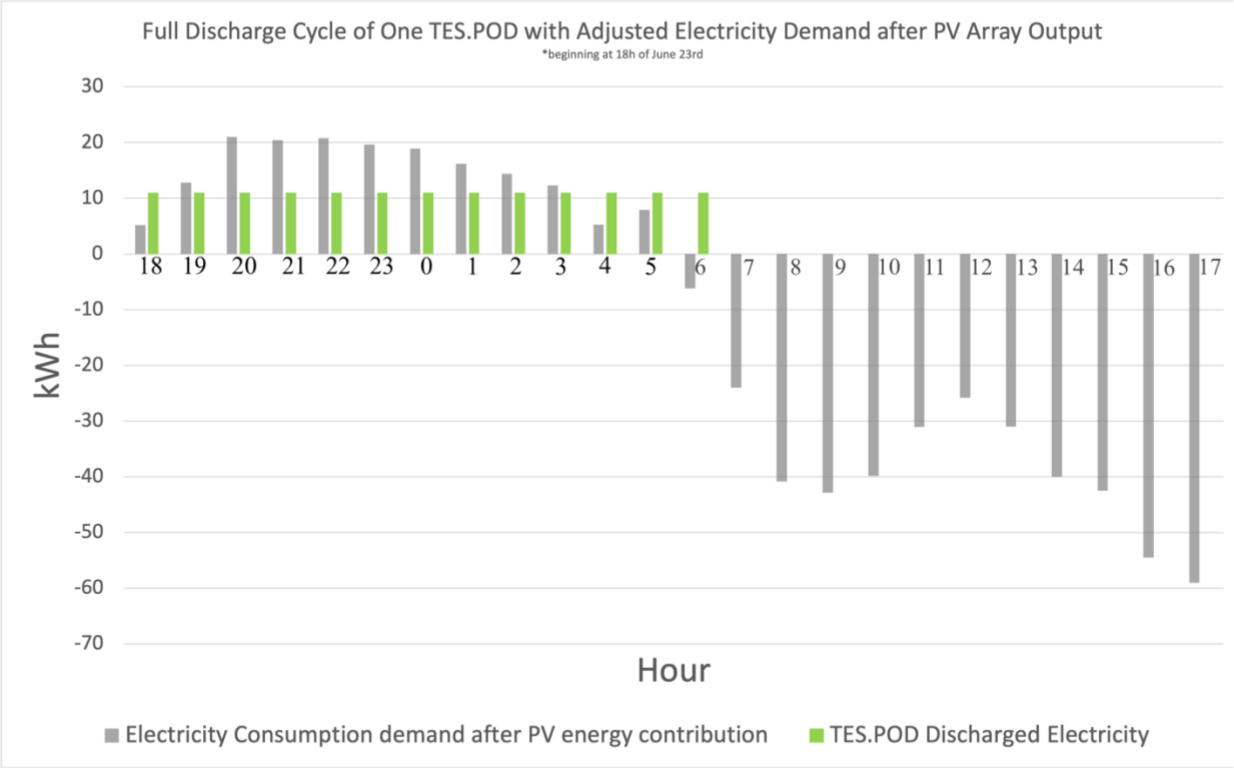


Figure 4.26. Full discharge cycle of one TES.POD CB beginning from 18h on June 23rd with adjusted electricity demand.

The TES.POD delivers 11kW (11,000 Watts) of electricity for a period of 13h at full discharge power in CHP mode, which would meet 85% (143 kWh) of the building's electricity demand during the discharge period. During the hours of 18, 4, 5, and 6 there is a total solar energy surplus of 31.936 kWh from the PV power system.

This resulted in €58.97 of savings for the representative June day over a business-as-usual scenario (at a rate of €0.4124/kWh based on data from CBS Statistics Netherlands (2023)) and mitigated 46.475 kg of CO_2 from entering our atmosphere. If the June day is taken as an average estimate for the six sunnier months (April-September) of the year, €10,614.60 can be saved and 8,366 kg of CO_2 emissions mitigated (the amount 418 trees capture a year). The 31.936 kWh surplus can further maximize benefits depending on the settings of the energy management system.

For the representative day in December, the PV system makes a significantly lower contribution to the overall electricity energy balance (**Figure 4.27**) and is net-negative for the day, which in turn, means that the potential impact of energy storage is greatly reduced. The PV system only generates 14.4 kWh over the course of the whole 24 hours of December 23rd. At an efficiency of 55% (the average of the CBs detailed in **Table 4.1**), 7.92kWh could offset €4.68 of electricity costs and 2,574 g of CO_2. At an efficiency of 30%, 4.3kWh of electricity from the TES.POD could offset €2.55 and 1,398 g of CO_2 emissions. If the December day is taken as an average for the six darker months (October-March) of the year, a total of €459.00 is saved and 251 kg of CO_2 emissions avoided.

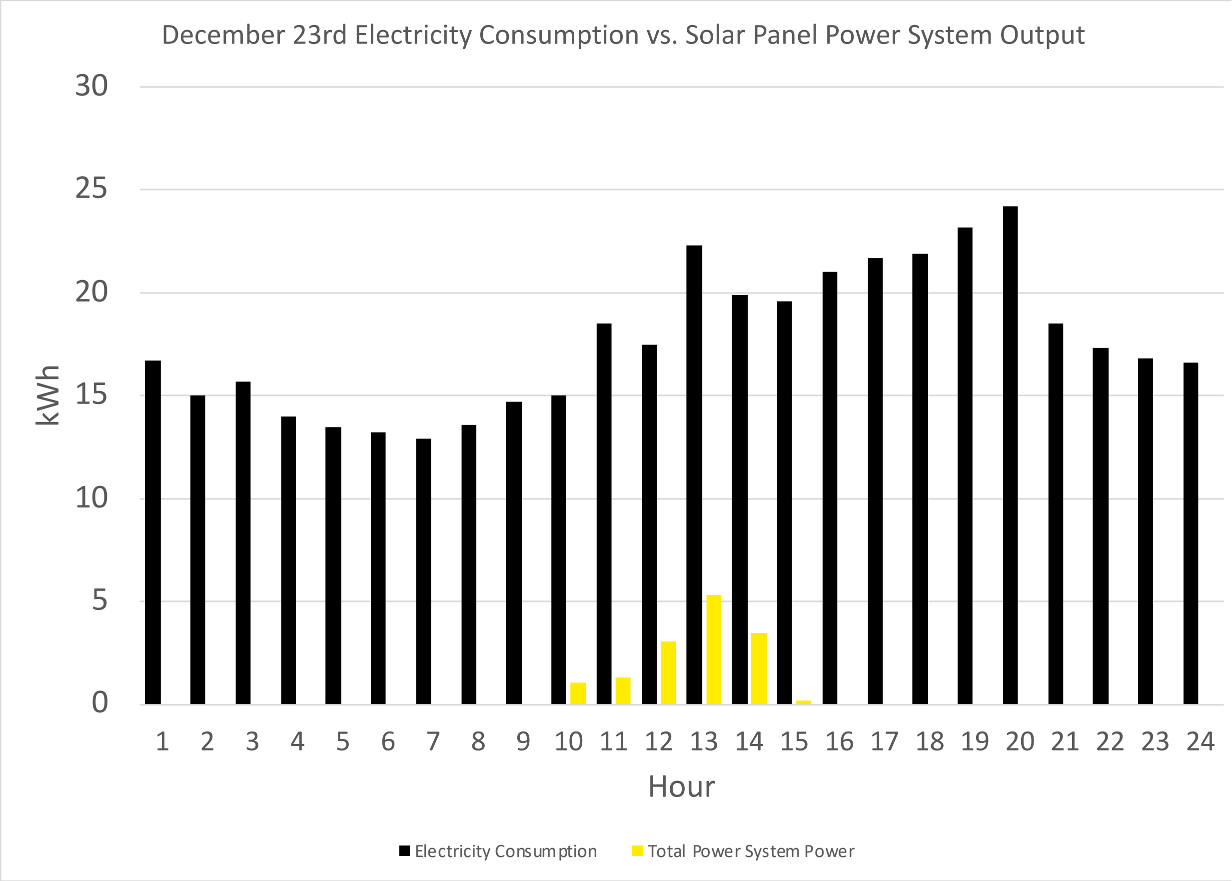


Figure 4.27. Hourly electricity consumption with hourly PV system output for December 23rd.

Employing the TES.POD for energy management of electricity saved €11,073.60 and mitigated 8,617 kg of CO_2 emissions on an annual basis over a business-as-usual scenario.

Energy Management of Heat

For the energy management of heat during the representative summer day, the building demands thermal energy for cooking, space heating, and domestic hot water. Hot water for residential purposes is supplied in the range of 60°C, which aligns with the TES.POD's capabilities (Lévesque et al., 2004).

Since the ambient temperatures in June in Leiden are relatively warm, demand for space heating drastically drops, leaving cooking and domestic hot water. Therefore, during the month of June only domestic hot water demand can be feasibly met by the TES.POD, since stovetop cooking burners required gas. This steep, seasonal contrast of gas consumption trends can be observed in **Figure 4.19** in the previous section.

One TES.POD can feasibly supply 100% of the heat demand for domestic hot water following a full charge during the representative June day. The storage system does not need to discharge its full thermal power (25kW) during any hour of the time period (**Figure 4.28**), resulting in a surplus of 86.372kWh (86,372Wh) of thermal energy over the 24h time period. This results in 23.86m^3 of natural gas consumption avoided, which would cost €42.19 at the June 2022 rate. The natural gas avoided for heating domestic hot water mitigated 55 kg of CO_2, the amount of CO_2 that about three trees capture over one year (Climate Neutral Group, n.d.; RVO, 2020). This daily value expanded to the six sunnier months saved €7,594.20 and mitigated 9,900 kg of CO_2 emissions.

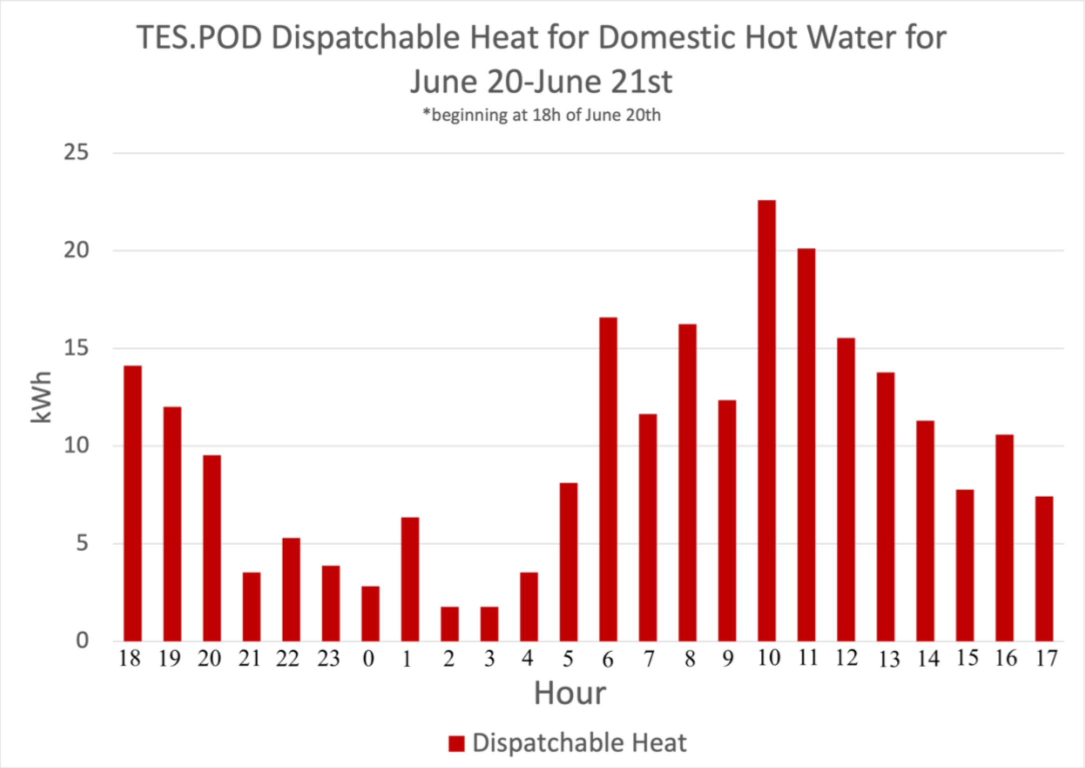


Figure 4.28. Dispatchable thermal energy from one TES.POD for domestic hot water demand beginning at 18h on June 20th.

December 23rd

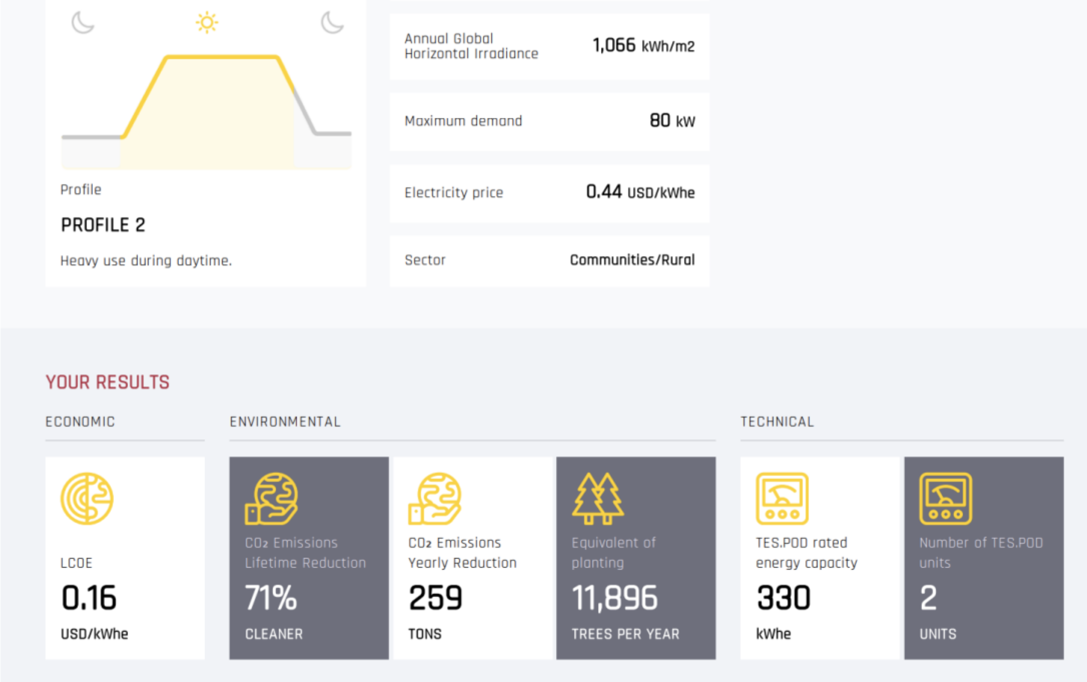
The net-total energy consumption for the month of December is over *26 times* the amount of the maximum total energy output from the solar arrays. For energy management of heat on the December day, the high demand for space heating and low solar energy output meant that there is no surplus of renewable energy at any hour. The PV system only generates 14.409 kWh (14,409Wh) on December 23rd. At an efficiency of 55%, 7.92 kWh could offset €1.83 of gas costs and 1.83 kg of CO_2. At an efficiency of 90%, 12.97 kWh of dispatchable heat from the TES.POD could offset €3.00 and 3 kg of CO_2 emissions. This daily average (at efficiency of 55%) expanded to the six darker months saved €329.40 and mitigated 329.40 kg CO_2 emissions.

Total Energy Management Benefits

With the two energy management scenarios (provisioning heat and electricity) taken together, using the TES.POD CB coupled to the RES resulted in annual savings of €18,996.80 and mitigated 18,846 kg of CO_2 emissions. A forest of 942 trees would capture this amount of CO_2

over an entire year. With these benefits, if a TES.POD module costs €200,000 (including installation, transport, etc.) the payback time would be about 10.5 years (this is a subjective estimate).

Azelio's own value calculator on the company's site provides further perspective on economic considerations and emissions reductions estimates of applying the TES.POD to Leiden's latitude. The calculator inputs the electricity rate, the peak daily demand, a representative demand profile, and the latitude of where the energy system is located to estimate PV potential. The sample output for the daily peak demand values and electricity rates of June 20th (**Figure 4.29**) are presented below.



Profile

PROFILE 2

Heavy use during daytime.

Annual Global Horizontal Irradiance 1,066 kWh/m2

Maximum demand 80 kW

Electricity price 0.44 USD/kWhe

Sector Communities/Rural

YOUR RESULTS

ECONOMIC

LCOE 0.16 USD/kWhe

ENVIRONMENTAL

CO_2 Emissions Lifetime Reduction 71% CLEANER

CO_2 Emissions Yearly Reduction 259 TONS

Equivalent of planting 11,896 TREES PER YEAR

TECHNICAL

TES.POD rated energy capacity 330 kWhe

Number of TES.POD units 2 UNITS

Figure 4.29. Output of Azelio value calculator for Leiden building June 20th peak energy demand and electricity price ($0.16 = €0.15 as of June 2023) from Azelio (2023c).

With the addition of Azelio's estimate of the LCOE of the TES.POD with a solar array, the economic values between the different power systems can be compared (**Figure 4.30**).

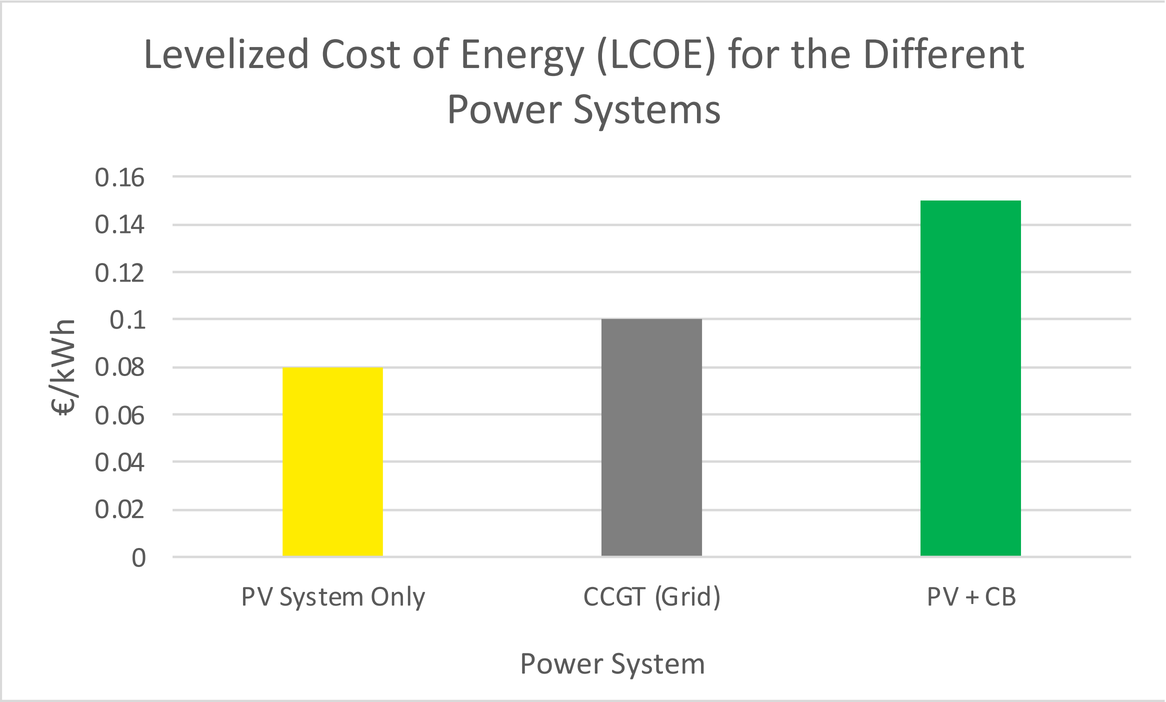


Figure 4.30. Comparison of the LCOE of different power systems: photovoltaic system only, natural gas, and photovoltaic panels with the TES.POD.

Spatial Analysis of TES.POD Placement

Physically, the TES.POD can fit on the building site. The 9.75m^2 footprint of the storage system is relatively compact (seen in **4.31**), although the TES.POD stands 2.81m tall which could limit the compatible installation areas. As Interview 1 stated, the most immense component of the system is the TES medium: a few tons of aluminum. This fact could present limitations on its placement due to stresses on the soil structure of the environment. The soil that Leiden sits on is made up of sand, loam, and peat soil which warrant extra investigation regarding the weight bearing properties of the ground under the TES.POD and how that may impact its future functioning as well as the environment (i.e., subsidence). This investigation is beyond the scope of this study. Another environmental consideration is the high operating temperatures that the TES.POD reaches (600°C or 1110°F) that could impact the ambient environment. This impact is likely marginal relative to the sustainability benefits of the storage system.

Figure 4.31. 2D visual representation of the space one TES.POD would occupy at the Leiden building site (approximate area of 9.75m^2), images from Google Earth (2021).

Further Considerations

For the proposed energy system and application to work in the context of the case study, other aspects are important to briefly detail. For the energy storage to maximize its utility, it needs to be coupled to an energy management system that can react, control, and dynamically optimize the energy balance throughout the year. This energy management system should also be coupled to the PV system. The transmission cables, grid-connection, electrical hardware, inverters, and other technical requirements are assumed to be present and correctly sized for the energy system's functional needs. The inclusion of these technical necessities in the analysis is outside of the scope of the research, since the focus is on the CB and its principal interaction with the energetic balance of the case study.

An Energy Efficient Scenario

A hypothetical scenario where the energy demand is reduced for the Leiden building provided further perspective on the challenge of sustainability in the built environment. The simplified energy efficient scenario for the case study building is detailed as follows.

The Leiden case study building is a good representative case of an outdated, underperforming building with a high demand for heat (visible in **Figure 4.18**). While this research centered on CB technology, pursuing the goal of PEBs requires more interventions than the output from energy systems. Energy efficiency (using less energy to produce the same result or perform the same task) is one of the most cost-effective, easiest ways to achieve net-positive emissions of carbon dioxide and combat climate change (Energy.gov, n.d.).

As a result of techniques aimed at reducing thermal bridging, increasing wall insulation values, installing tighter doors, and better windows-- a massive reduction of the space heating demand of a building can be achieved (X. Liang et al., 2017). In addition: replacing gas boilers with heat pumps, installing a heat recovery system for DHW, swapping gas burners for electric (induction) cooking, installing LED lighting, and replacing old appliances with newer, more efficient models can reduce the energy consumption of the building significantly. The results of these calculations are presented in **Table 4.8** and **Figures 4.32-4.35**.

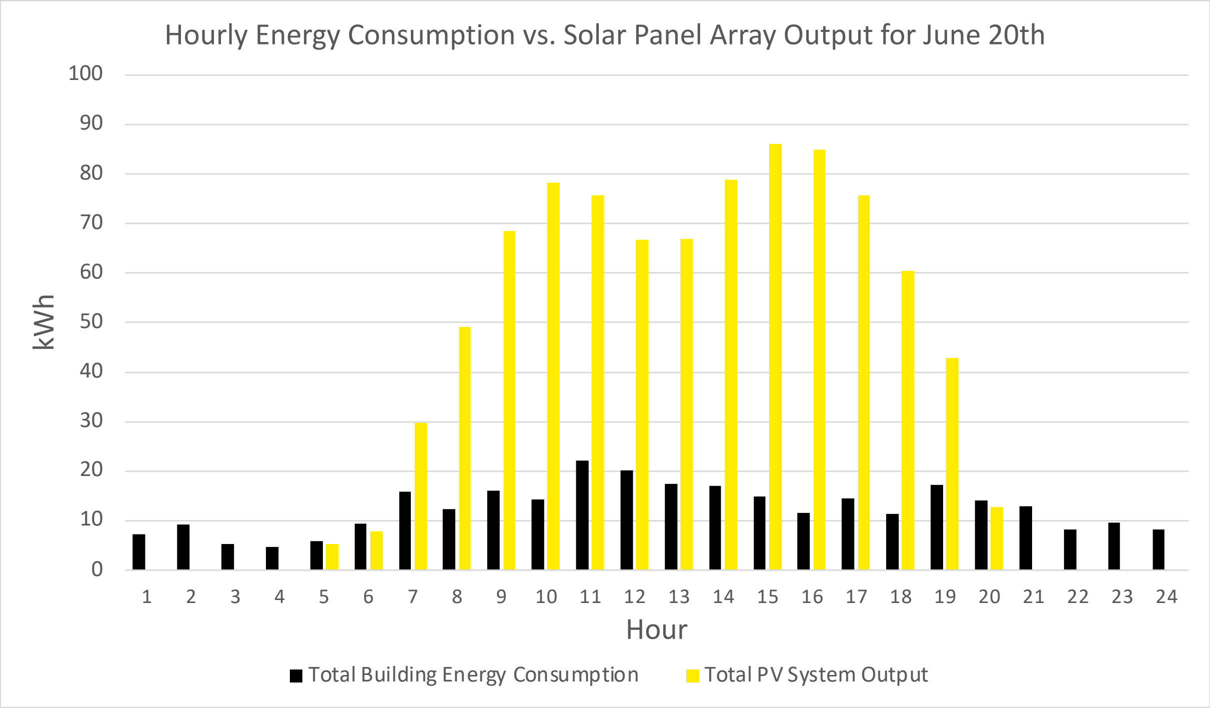


Figure 4.32. Hourly electricity consumption with hourly PV system output of an energy efficient scenario for the case study building on June 20th.

After meeting the energy consumption (300 kWh) of the entire June day, there is a surplus of 590 kWh of solar energy. This surplus amount of energy would charge one TES.POD module to 98% capacity.

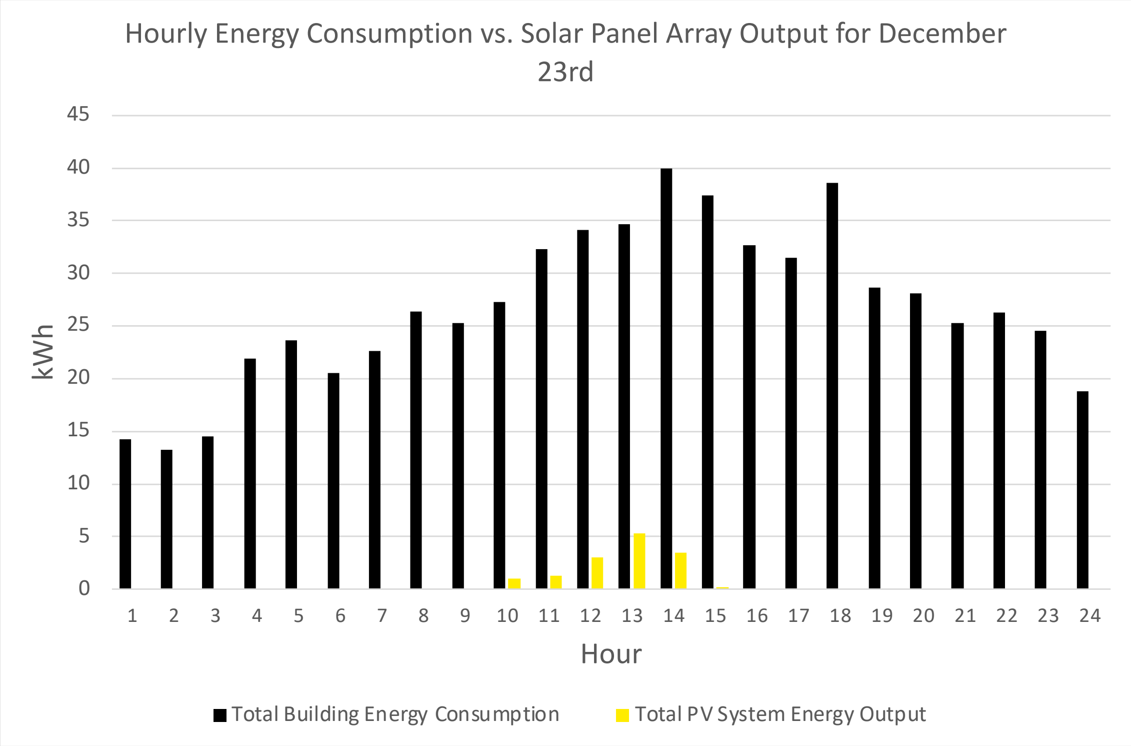


Figure 4.33. Hourly electricity consumption with hourly PV system output of an energy efficient scenario for the case study building on December 23rd.

Despite massive reductions of energy consumption under the energy efficient scenario (average December hourly consumption of 27 kWh vs. 99 kWh business-as-usual), less sunlight and shorter days contribute to a similar pattern and drastically decrease the amount of energy available for storage in the CB.

Table 4.8. New annual demand values for an energy efficient scenario for the Leiden case study building.

Space Heating Demand	11,442 kWh
Cooking Demand	16,818 kWh
Electricity Demand	113,726 kWh
Domestic Hot Water Demand	28,030 kWh

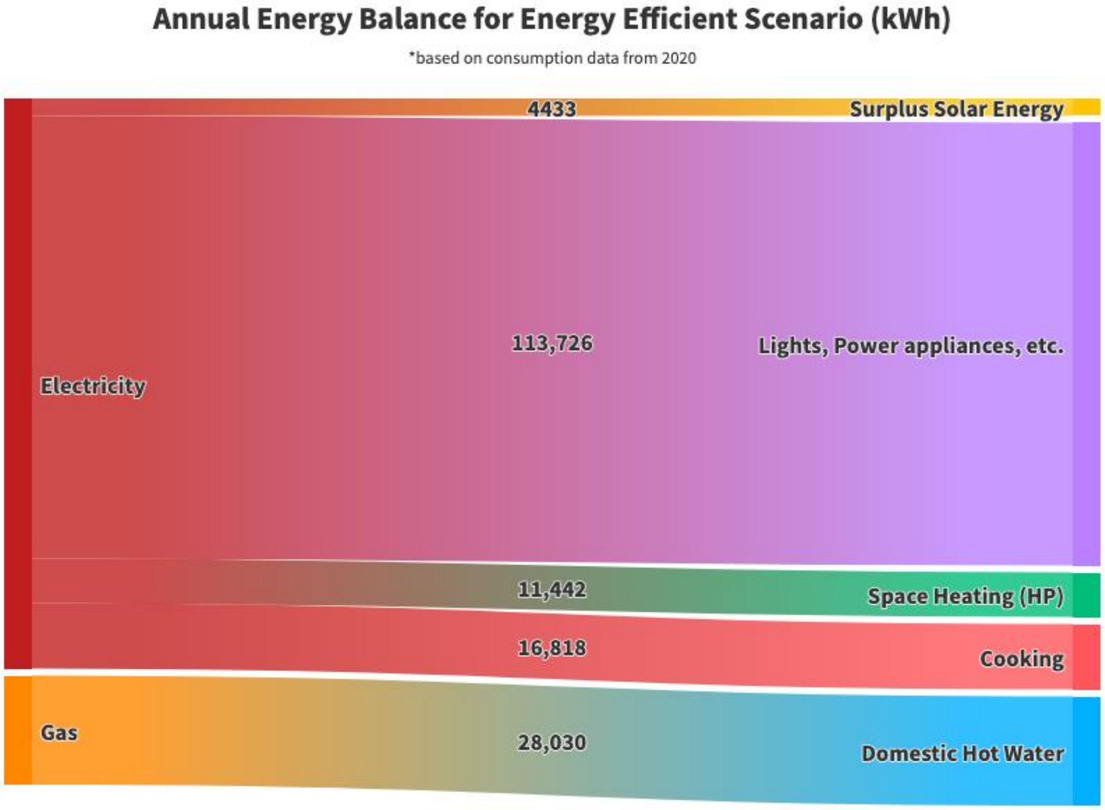


Figure 4.34. Annual energy balance of energy efficient scenario organized by proportion of demand for end-use.

In the energy efficient scenario, total gas consumption is reduced by 414,762 kWh annually (**Figure 4.34**). This resulted in 41,476 m^3 of natural gas consumption avoided which mitigated 95,860 kilograms of CO_2 (the amount that 4,793 trees capture in a year) and reduced the building's annual energy bill by €73,325.42 compared to the business-as-usual scenario (at June gas price).

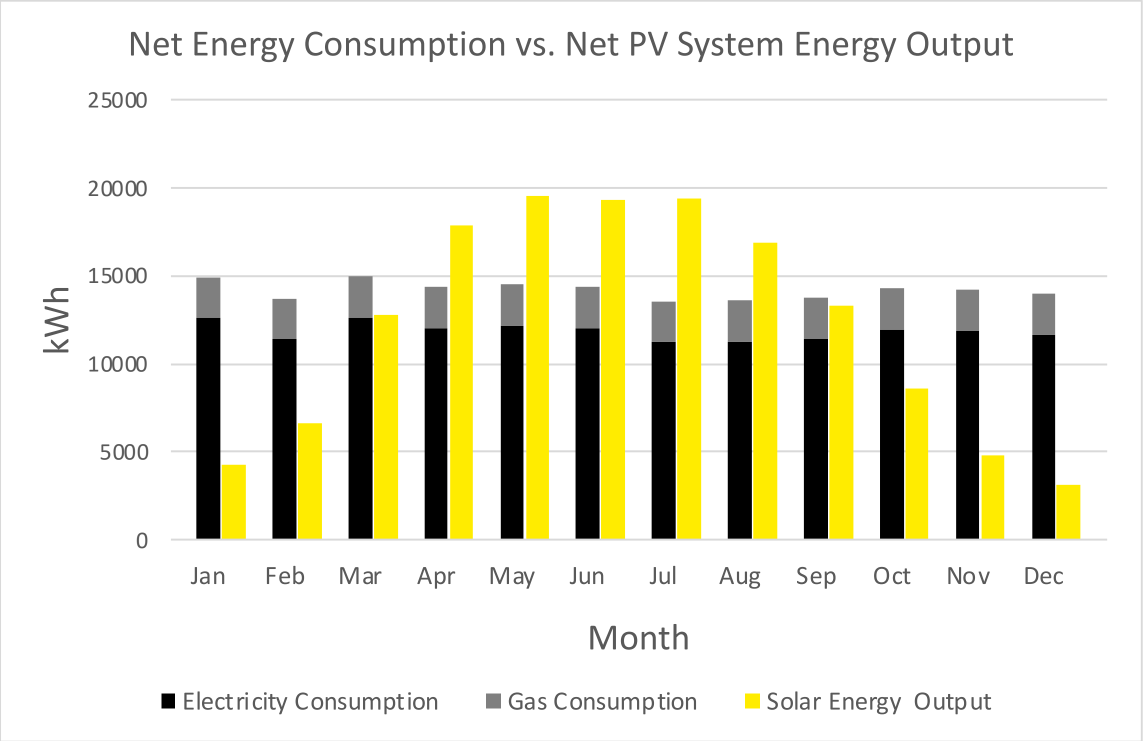


Figure 4.35. Net-total monthly electricity consumption, gas consumption, and full solar system energy output for the energy efficient scenario for the Leiden case study building.

The new monthly energy balance over the course of the year is presented in **Figure 4.35**. The energy efficient scenario reduced the net-total annual energy consumption by approximately 73% (from 628,334 kWh to 170,273 kWh). From a net-annual perspective, the PV panel system covers 86% (146,419 kWh) of the total demand.

The impacts of energy efficiency and the application of sustainable architectural techniques come into focus through this lens. Reducing the energy intensity of buildings and metropolitan environments is also aligned with the government of the Netherland's sustainable development goals. The Netherlands is driving the building sector towards 'Almost Energy Neutral Buildings' (*Bijna Energie Neutrale Gebouwen*) which require all new construction from January 1, 2021 to account for the applying of sustainable energy, good insulation, and energy efficient installations (Rijkswaterstaat, 2021).

4.5 Section Summary

In this section, the results of implementing a CB (represented by Azelio's TES.POD) on an existing building for the application of energy management were presented and the design realized. The case study building, located in Leiden, the Netherlands, is a good representative case of an outdated building that has a high demand for space heating. The annual energy consumption of the case study building in the business-as-usual scenario is higher than the annual energy output potential of the renewable energy system (PV arrays) but applying the TES.POD CB as energy storage for energy management still provides economic and environmental benefits.

In a business-as-usual scenario, the CB saved €18,996.80 and mitigated 18,846 kg of CO_2 emissions annually. For the representative day in June, the use of the TES.POD (CHP mode) can cover 85% of the electricity consumption and 100% of domestic hot water demand during its 13-hour discharge cycle following a full charge from the PV system. The potential for energy storage greatly decreases on the December day due to lower solar radiation and a net-negative energy balance. In the context of this study, the quantified economic and environmental benefits of utilizing the CB are greater for electricity services than provisioning of heat. The ability for the CB to simultaneously provide both forms of energy bolster its value in the built environment.

Finally, an energy efficient scenario for the Leiden case study building was analyzed and results presented. In the energy efficient scenario, the net-total annual energy consumption was reduced by approximately 73% (from 628,334 kWh to 170,273 kWh), which in turn, increased the building's potential self-consumption rate (23% vs. 83%). This resulted in 41,476 m^3 of natural gas consumption avoided which mitigated 95,860 kg of CO_2 and reduced the building's annual energy bill by €73,325.42 compared to a business-as-usual scenario. With the energy efficient reductions, the building is still slightly net-negative in its total energy balance, with 28,030 kWh needed for domestic hot water. The entire electricity demand—including cooking, lighting, ventilation, and powering appliances—can feasibly be met by the renewable energy system and CB during April-September, providing 24h coverage.

5: Discussion

In this research, a diverse group of professionals were consulted for their qualitative insight (seen in **Figure 5.1**), a review of literature and commercial data conducted, and a design case study including a basic analysis carried out. The major results, limitations, and recommendations for future research are described below.

Figure 5.1. Approximate locations of the expert participants interviewed for this research.

Discussion of Results

The state of CB research and commercial development is at an exciting place. The working principal of the CB, power-to-heat-to-power, can be applied to numerous cases and engineered many ways at different scales. CBs have captured the interest of commercial and research stakeholders because they have no geographical limitations, low specific cost, the ability to cogenerate heat and electricity, clean operation, long lifetimes, and can use many “off-the-shelf” components already on the market (Dumont & Lemort, 2020; Frate et al., 2020; Mitali et al., 2022; Sadeghi, 2022; Vecchi et al., 2022). A further CB strength is related to the wide range of TES mediums: from cheap, abundant rocks and sand to highly technical phase-change materials that have higher energy densities. This aspect of the thermal storage mechanism further bolsters the versatile range of applications for CBs in all different kinds of environments, especially metropolitan areas. TES mediums can be charged and discharged with little to no degradation in performance, although the moving parts of the engines need to be monitored more closely. The results of the literature review encompass a lively landscape of companies, research institutions, and academics that believe in the promise behind CBs. To unravel the merits behind the performance of CBs in relation to other storage technologies, techno-economic and environmental performance indicators were extracted from the literature. Major techno-economic KPI's included parameters such as fastest discharge and charge time, storage capacity, total efficiency, mass and volume densities of energy, discharge power, specific cost of the stored energy, and durability. Environmental impact was captured through the LCA method.

The performance indicators used to describe energy storage systems shed light on how the utilization of the technology impacts the energy nexus, the environment, and consumer wallets. Mature technologies were selected using the TRL, and then compared with a CB. A specific CB product: Azelio's TES.POD was selected to represent the CB class and enable deeper comparison. Techno-economically, the ability to discharge for long durations, long lifetime, and its large power range are all aspects that CB technology performs well in compared to the mature energy storage technologies (Mostafa et al., 2020). The cogeneration ability of the CB is especially unique and opens doors for a wide range of potential use-cases and applications.

To further build knowledge for the case study design, conditions relevant to the application of the CB to the built environment were identified. The findings suggested that the case study should be centered on the single building scale for a residential building. Although in theory, the CB is incredibly versatile over a range of potential use-cases; supermarkets, industry, greenhouses, incinerators, electrolyzers, datacenters, and district heating are just a few of the possibilities (Dumont, Thomé, et al., 2022). The application of ESS to the residential environment and the necessary functionality (response time, temperature of delivered heat, etc.) of the storage aligned with the TES.POD's performance nicely. The CB could deliver electricity services for power appliances, lighting, and cooling in addition to supplying heat for domestic hot water and space heating. This relates to the application focus as well: energy management. The basis for selecting the application was a synergy of interview input as well as criteria defined in Hossain et al. (2020) where the authors outlined a framework of required power capacity, response time, and discharge duration to determine compatibility for the specific application. The application of energy management aimed at balancing energy generation and consumption, conserving resources, and reducing expenditures while meeting requirements of the consumers energy demand—a role that further aligns with the TES.POD's capabilities and the aims of this research. In addition, renewable energy in the form of solar panels was found to be desired for optimal functioning of the ESS due to more predictable power supply as opposed to wind. Realistically, as seen in the results of the design, solar panels may not be enough to meet the demands of energy intensive, outdated buildings without further energy efficiency improvements in the Netherland's context.

The design was then executed based on the knowledge built in the previous sub questions. A 100% residential, 11-story building (with an additional detached house) in Leiden, the Netherlands was used for the case study. This choice was made based mainly on qualitative input from the interviewees, alignment with a defined storage application, and the availability of real consumption data. On a daily basis, the CB demonstrated the potential to manage the electricity consumption as well as provision heat services for the entire domestic hot water supply of the case study building during the representative summer day. In the winter months, the increase in space heating demand and decrease in sunlight in the northern latitude of the Netherlands reduced the overall impact the CB had on the energy balance greatly. The techno-economic and environmental benefits were greater for the energy management of electricity rather than heat at the current rates and carbon emission estimates used in the work.

Although the building's energy balance was still net-negative when considering an energy efficient scenario, the impact of the reduction in energy demand increased the utility of energy storage in the CB and the potential to achieve net-positive energy performance. This can be captured in-part by the self-consumption rates: 23% for the business-as-usual vs. 83% for the energy efficient scenario. This is a generous estimate, as the actual ratee would be impacted by energy losses when converting to and from heat for storage in the aluminum alloy of the CB and the intermittency of solar energy.

In a business-as-usual scenario, the CB and PV system saved €18,996.80 and mitigated 18,846 kg of CO_2 emissions annually. This is extremely positive, despite the relatively small fraction of total energy consumption coverage. For the energy efficient scenario, the building's energy bill was reduced by €73,325.42 and 95,860 kg of CO_2 were mitigated annually. In addition, the reduced demand meant that the TES.POD could likely provide full 24h coverage and discharge surplus solar energy daily during the months of April-September. Reducing the demand for electricity from a largely fossil-fuel powered grid to zero—for six months of the year—is extraordinary. This contributes to sustainability in the built environment and reduces the stress on the grid. A specific analysis of the detailed, simulated monthly dynamics of the PV-to-TES.POD-to-energy management system would be a promising direction for future research that further investigates the potential of the TES.POD CB in our metropolitan environments.

Limitations and Assumptions of the Research

However, there are limitations and weaknesses in this research that are worth noting. Firstly, the small sample size of interviews weakens larger assertions drawn from the qualitative data. Related to the design, several assumptions underpin the results. Most significantly, the case study site is assumed to have a compatible location to place the TES.POD system and the accompanying electrical/thermal transport infrastructure to facilitate its provisioning of services to the building. The entire energy system is assumed to have an energy management system that can control, respond, and effectively handle the power system based on the defined application. Further, the cogeneration of heat and electricity could present practical technical challenges not mentioned in this work. The TES.POD's power specifications were measured at an ambient temperature of 25°C and atmospheric pressure of 1, however, its performance has been tested across a breadth of climate conditions (Azelio, 2023c).

Regarding the solar array, it is also assumed to be effectively connected to the energy storage system and to have an appropriate 150000W inverter with rated voltage of 300V. The east and west facing facades are estimated to be able to fit 314 465W monocrystalline silicon Aiko N-Type ABC White Hole Series 54-cell panels with no structural consequences to the building. This estimation was made as precise as possible using spatial matching to the scaling of the design drawings to represent the size of the panels, but a margin of error remains using this method. The solar energy output simulation for the four arrays was run under the conditions that the panels were bracket-mounted, with air flow able to pass between the façade/roof and the back of the panel. The Aiko panel itself is a relatively new, high-performance product. These assumptions certainly impact the modelling of the power system potential for the four zones of arrays, and thus conclusions based off these numbers. The impact of shading was also not considered as it was outside the scope of the study. The economic estimations of the PV system were made under conditions of a flat, 25-degree slope, south-facing roof so the actual results may differ. However, there was only a 2.88% difference between the total energy output estimation of the same-sized system between the two PV analysis tools employed so this difference is likely minimal.

To unravel economic considerations the LCOE, the total electricity price, and total gas price were focal points. Since LCOE and other techno-economic estimates were derived from literature and commercial data, there is a margin of error in the accuracy of any conclusions drawn. The basic, conceptual nature of the design and analysis lacks a certain technical depth. Capturing benefits by calculating avoided natural gas consumption and electricity from the grid simplifies the analysis of the impacts and can neglect the (often high) costs of CAPEX considerations. The unavailability of the TES.POD's system cost meant that an estimate within a subjective, but reasonable range needed to be made. Azelio will likely not have a standard price until the technology matures more over the coming years. Environmentally, the use of grams of CO_2 and the focus on carbon emissions may omit other interesting insights that could convey further details of the ESS's impact. Differing sources assigned different values to the emissions intensity of the Netherland's electricity. One source asserts 325gCO_2/kwh (Statista, 2022) while another claims 282gCO_2/kwh (IRENA, 2022) for example. Both general electricity emissions intensity values are greater than the 231gCO_2/kwh carbon intensity defined for natural gas however (RVO, 2020), so comparisons between the impacts of provisioning heat vs. electricity would not drastically change. Furthermore, one cubic meter of gas was assumed to convert to ten kilowatt-hours of electricity. This simplified conversion could be impacted by the exact type of gas, the refining process, and other factors.

Exploration of Different Contexts

The necessity for energy storage in the first place is another important point to touch on, as conditions at every level impact this. Interviewee 6 talked about how some buildings have moved away from energy storage due to net metering, which also saves on infrastructure costs. In the larger picture, the share of RES will continue to increase and continue to present intermittency challenges as societies evolve. ESS are seen as the most reliable and effective way to manage the intermittency of clean energy sources (Hossain et al., 2020). In the context of more and more wind, solar, etc., coming online, there will be more instances of negative electricity prices, where grids are overloaded with energy. Interviewee 1 and 2 emphasized the promise that this has for the business case of CB energy storage, since in this scenario, owners of energy storage assets get paid to consume energy, which can be released later to meet demand. In this case, efficiency matters less than the ability to store energy for long durations—a strength that TES based systems like CBs possess. Siemens Gamesa is already doing this in Germany, says Interviewee 2. Because of economies of scale, the LCOE also decreases as the duration of energy storage increases (Rahman et al., 2020). In the context of a society with a high penetration of renewables, the most effective scale (environmentally, economically, socially) is likely much larger than a single building. In this context, the modularity and scalability of CBs like Azelio's TES.POD furthers its potential impact by acknowledging this scale range. The retrofitting and addition of CBs to existing power plants for grid-scale services is already being practically explored as well.

At the regional and local level, coupling to systems like district heating networks, EVs, LiB arrays, PV thermal, and sources of waste heat like datacenters, industry, greenhouses, or power plants are especially interesting for CBs. Thermodynamically, these technological pairings can increase the performance and attractiveness of CB systems, as Interviewee 2 detailed. Interviewee 3 discussed the case for complementary systems with stationary LiBs or part of EVs as well as the increase in smart electrical systems that can manage them. This coincides with Interviewee 1 indicating that the TES.POD's niche complements LiBs, and often replaces diesel generators. Given the demand for rare and often toxic materials that are needed for many electrochemical batteries (Mitali et al., 2022), CBs can reduce this need by covering storage niches that free up technologies like LiBs to play to their strengths more effectively. In the

Netherlands context with many greenhouses, industrial processes, and more datacenters coming online, the ability for CBs to utilize waste heat could open more opportunities to offset natural gas consumption for heat. In the light of the European energy crisis catalyzed by the Russo-Ukrainian War, moving away from fossil fuel sourced-heat like natural gas is not only more secure and economical, but more environmentally positive as well. Waste heat can used for many purposes, including thermoelectric generation (Wahlroos et al., 2018). Economically, waste heat that would otherwise be fed into the ambient environment to simply dissipate is an extremely cheap, even free source of energy.

The application of CBs to buildings is not novel. To the author’s knowledge at the time of writing, this research is the first of its kind to be conceptualized and conducted in the context of a residential apartment building in the Netherlands.

6: Conclusion

This work investigated the potential of a Carnot battery applied to an existing building. To answer the main research question, conclusions are organized by the two domains of approach: techno-economic considerations and environmental impacts.

Related to techno-economic considerations, CBs as a whole show a lot of promise to provide medium to long-term energy storage services with a LCOE that is competitive. A strength of CBs is the ability to be built with existing, off-the-shelf components—a fact that is true at all scales, reduces costs, and opens exciting doors for power plant asset retrofitting and conversion. Constituent parts of CBs like Rankine cycle machines and heat engines are already widespread throughout global energy infrastructures, production supply chains, and have decades of research behind them. The ability for CBs to input and output both heat and electricity make it a Swiss army knife of energy storage technology in theory—in practice, the niche of these systems is still being investigated thoroughly by researchers and commercial entities all over the globe.

Although the CB in the case study context could only meet a fraction of the total energy consumption, the TES.POD can store heat and electricity from both the grid and renewable power systems. It can shift the consumption of renewable energy, increase self-consumption rates, and provide a residential building with electricity and heat for various services. The application of energy management aligns with the functionality of the TES.POD, which is a relatively mature CB product. As with any ESS, a surplus of energy is needed to charge the CB and maximize its impact in energy systems. While deep energy efficiency retrofits yielded more impact in this research, the sympatheia of an energy efficient building, intermittent renewable energy, and CB energy storage cannot be understated. These technologies work best when working together.

The ability for CBs to create PEB conditions is largely dependent on the RES potential of a site or building and the building’s energy efficiency. In Northern latitudes like the Netherlands, the performance of PV panels may not be substantial enough to facilitate PEBs without profound reductions in gas consumption and energy efficiency improvements such as the use of heat pumps, better insulation, more efficient appliances, and less thermal bridging, for example. Societies with high penetrations of RES that experience negative electricity prices and the availability of waste heat stand out as techno-economic conditions that CBs can immediately take advantage of. These factors relate to the pursuit of sustainability and environmental impacts as well.

From an environmental impact perspective, CBs are estimated to be some of the least-impactful energy storage technologies on the market. This fact alone is part of the reason they have garnered massive interest despite the falling price of mature technologies like LiBs and VRBs. However, the impact of CBs on the environment is dependent on the exact system configuration and material selection for the working fluid, thermal energy storage containers, and the source emissions from inputted energy that charges the storage system. Azelio's TES.POD is already estimated to outperform frontrunning mature technologies like LiBs and diesel generators in a life cycle assessment, with a longer expected lifetime, no degradation of the storage medium, and the ability to be fully recycled at its end-of-life and disposal stage. The technology is modular, scalable, has been field proven, and can withstand a range of different environmental conditions from deserts of Egypt to the taigas of Sweden.

In conclusion, the implementation of Carnot batteries to existing buildings can manage electricity and heat services, provide a cost-competitive energy storage option, and reduce carbon emissions released into the environment when coupled to renewable energy systems over the lifetime of the technology.

Recommendations for Future Research

Recommendations for future research are an investigation of waste heat potential coupled to CBs at local, regional scales in urban or industrial areas in the Netherlands to meet the heat demand of the metropolitan environment, with community ownership schemes that work at the effective scale of CB systems. Coupling to district heating networks, such as those found in Amsterdam or New York for example, are a further promising direction especially in the context of Amsterdam's historic canal district. Research that investigates aqua-thermal energy storage and heat pumps in conjunction with CBs is also interesting in the Netherlands. The increasing number of datacenters, vertical farms, and greenhouses in the Netherlands present opportunities to research the exploitation of waste heat sources and storing energy in CBs that would otherwise be lost. Lastly, a more granular and modelled simulation study of the hourly/daily dynamics of charging and discharging a CB, its impact on the amount and quality of energy available, and different applications of energy storage would be interesting.

References

Anand, V., Kadiri, V. L., & Putcha, C. (2023). Passive buildings: A state-of-the-art review. *Journal of Infrastructure Preservation and Resilience*, *4*(1), 3. https://doi.org/10.1186/s43065-022-00068-z

Andlinger Center for Energy + the Environment. (2014). Article 2: Key Concepts in Electricity Storage. *Princeton University*. https://acee.princeton.edu/wp-content/uploads/2014/06/Andlinger-Energy-Tech-Distillate-Storage-Article-2.pdf

Azelio. (2020). *Azelio's energy storage technology shown to be significantly more sustainable than lithium-ion batteries* (p. 2) [LCA Press Release]. https://storage.mfn.se/proxy/release.pdf?url=https%3A%2F%2Fmb.cision.com%2FMain%2F16031%2F3199588%2F1308661.pdf

Azelio. (2023a). *Renew Your Energy* [Azelio Value Calculator Report]. Azelio. https://www.azelio.com/value-calculator/

Azelio. (2023b). *Communities Case Study* [Company site]. Azelio.Com. https://www.azelio.com/communities-case-study/

Azelio. (2023c). *The Solution* [Company site]. Azelio.Com. https://www.azelio.com/the-solution/

Badouard, T., Moreira de Oliveira, D., Yearwood, J., & Torres, P. (2020). *Final Report Cost of Energy (LCOE): Energy costs, taxes and the impact of government interventions on investments* [EU Commission Contract].

Balezentis, T., Streimikiene, D., & Siksnelyte-Butkiene, I. (2021). Energy storage selection for sustainable energy development: The multi-criteria utility analysis based on the ideal solutions and integer geometric programming for coordination degree. *Environmental Impact Assessment Review*, *91*, 106675. https://doi.org/10.1016/j.eiar.2021.106675

Bashiri Mousavi, S., Ahmadi, P., Hanafizadeh, P., & Khanmohammadi, S. (2022). Dynamic simulation and techno-economic analysis of liquid air energy storage with cascade phase change materials as a cold storage system. *Journal of Energy Storage*, *50*, 104179. https://doi.org/10.1016/j.est.2022.104179

Basta, A., Basta, V., Spale, J., Dlouhy, T., & Novotny, V. (2022). Conversion of combined heat and power coal-fired plants to Carnot batteries—Prospective sites for early grid-scale applications. *Journal of Energy Storage*, *55*, 105548. https://doi.org/10.1016/j.est.2022.105548

Bellos, E., Lykas, P., & Tzivanidis, C. (2022). Pumped Thermal Energy Storage System for Trigeneration: The Concept of Power to XYZ. *Applied Sciences*, *12*(3), 970. https://doi.org/10.3390/app12030970

Bellos, E., Lykas, P., & Tzivanidis, C. (2023). Performance Analysis of a Zero-Energy Building Using Photovoltaics and Hydrogen Storage. *Applied System Innovation*, *6*(2), 43. https://doi.org/10.3390/asi6020043

Blakers, A., Stocks, M., Lu, B., & Cheng, C. (2021). A review of pumped hydro energy storage. *Progress in Energy*, *3*(2), 022003. https://doi.org/10.1088/2516-1083/abeb5b

Blanquiceth, J., Cardemil, J. M., Henríquez, M., & Escobar, R. (2023). Thermodynamic evaluation of a pumped thermal electricity storage system integrated with large-scale thermal power plants. *Renewable and Sustainable Energy Reviews*, *175*, 113134. https://doi.org/10.1016/j.rser.2022.113134

Cao, Y., Bashiri Mousavi, S., & Ahmadi, P. (2022). Techno-economic assessment of a biomass-driven liquid air energy storage (LAES) system for optimal operation with wind turbines. *Fuel*, *324*, 124495. https://doi.org/10.1016/j.fuel.2022.124495

CBS Statistics Netherlands. (2023). *Average Energy Prices for Consumers* [Governmental Organization]. Cbs.Nl. https://www.cbs.nl/en-gb/figures/detail/84672ENG

Chakraborty, M. R., Dawn, S., Saha, P. K., Basu, J. B., & Ustun, T. S. (2022). A Comparative Review on Energy Storage Systems and Their Application in Deregulated Systems. *Batteries*, *8*(9), 124. https://doi.org/10.3390/batteries8090124

Climate Neutral Group. (n.d.). *What Exactly Is 1 Tonne of CO2?* [Company site]. Climateneutralgroup.Com. https://www.climateneutralgroup.com/en/news/what-exactly-is-1-tonne-of-co2/

Del Pero, C., Aste, N., Paksoy, H., Haghighat, F., Grillo, S., & Leonforte, F. (2018). Energy storage key performance indicators for building application. *Sustainable Cities and Society*, *40*, 54–65. https://doi.org/10.1016/j.scs.2018.01.052

Dickerson, R. H., & Mottmann, J. (2019). The Stirling cycle and Carnot's theorem. *European Journal of Physics*, *40*(6), 065103. https://doi.org/10.1088/1361-6404/ab3532

Dumont, O., Carmo, C., Fontaine, V., Randaxhe, F., Quoilin, S., Lemort, V., Elmegaard, B., & Nielsen, M. P. (2016). Performance of a reversible heat pump/organic Rankine cycle unit coupled with a passive house to get a positive energy building. *Journal of Building Performance Simulation*, *11*(1), 19–35. https://doi.org/10.1080/19401493.2016.1265010

Dumont, O., Carmo, C., Georges, E., Quoilin, S., & Lemort, V. (2017). Economic assessment of electric energy storage for load shifting in positive energy building. *International Journal of Energy and Environmental Engineering*, *8*(1), 25–35. https://doi.org/10.1007/s40095-016-0224-2

Dumont, O., Carmo, C., Randaxhe, F., Quoilin, S., & Lemort, V. (2016). Performance Comparison of Two Types of Technologies Associated with a Positive Energy Building: A

Reversible Heat Pump/orc Unit and a Heat Pump Coupled with PV Panels. *Proceedings of the ISES Solar World Congress 2015*, 1–6. https://doi.org/10.18086/swc.2015.04.13

Dumont, O., & Lemort, V. (2020). Mapping of performance of pumped thermal energy storage (Carnot battery) using waste heat recovery. *Energy*, *211*, 118963. https://doi.org/10.1016/j.energy.2020.118963

Dumont, O., & Lemort, V. (2022). Life cycle analysis of a carnot battery (Pumped thermal energy storage). *34th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2021)*, 98–103. https://doi.org/10.52202/062738-0009

Dumont, O., Léonard, A., & Lemort, V. (2022, September 27). Life Cycle Analysis of a Carnot battery using a reversible 10 kWe HP/ORC system. *3rd International Workshop on Carnot Batteries*. 34th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Stuttgart, Germany.

Dumont, O., Thomé, O., & Lemort, V. (2022). Techno-economic assessment of a Carnot battery based on a Rankine cycle with waste heat integration. *SDEWES 2022*. https://orbi.uliege.be/bitstream/2268/295189/1/SDEWES2022.pdf

DUWO. (2013). *Rijn en Schiekade 100 – 110 Design Drawings*.

Eggers, J. R., von der Heyde, M., Thaele, S. H., Niemeyer, H., & Borowitz, T. (2022). Design and performance of a long duration electric thermal energy storage demonstration plant at megawatt-scale. *Journal of Energy Storage*, *55*, 105780. https://doi.org/10.1016/j.est.2022.105780

Energy.gov. (n.d.). *Energy Efficiency: Buildings and Industry* [Governmental Organization]. Energy.Gov. https://www.energy.gov/eere/energy-efficiency-buildings-and-industry

European Comission. (2022). *PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM* [Tool]. PVGIS. https://re.jrc.ec.europa.eu/pvg_tools/en/

Fan, R., & Xi, H. (2022). Energy, exergy, economic (3E) analysis, optimization and comparison of different Carnot battery systems for energy storage. *Energy Conversion and Management*, *252*, 115037. https://doi.org/10.1016/j.enconman.2021.115037

Frate, G. F., Baccioli, A., Bernardini, L., & Ferrari, L. (2022). Assessment of the off-design performance of a solar thermally-integrated pumped-thermal energy storage. *Renewable Energy*, *201*, 636–650. https://doi.org/10.1016/j.renene.2022.10.097

Frate, G. F., Ferrari, L., & Desideri, U. (2020). Rankine Carnot Batteries with the Integration of Thermal Energy Sources: A Review. *Energies*, *13*(18), 4766. https://doi.org/10.3390/en13184766

Frate, G. F., Ferrari, L., Sdringola, P., Desideri, U., & Sciacovelli, A. (2023). Thermally integrated pumped thermal energy storage for multi-energy districts: Integrated modelling, assessment and comparison with batteries. *Journal of Energy Storage*, *61*, 106734. https://doi.org/10.1016/j.est.2023.106734

Gao, Y., Pan, Z., Sun, J., Liu, Z., & Wang, J. (2022). High-Energy Batteries: Beyond Lithium-Ion and Their Long Road to Commercialisation. *Nano-Micro Letters*, *14*(1), 94. https://doi.org/10.1007/s40820-022-00844-2

Google Earth. (2021). *Google Earth* (2021st ed.) [Map]. Google. https://earth.google.com/web/search/Rijn-+en+Schiekade+101-110/@52.15346464,4.48128436,2.86516645a,130.85447962d,35y,237.61069356h,0t,0r/data=CigiJgokCXD7aR0mpjdAEXL7aR0mpjfAGSPaOyfZb0xAISfaOyfZb0zA

Hebner, R., Beno, J., & Walls, A. (2002). Flywheel batteries come around again. *IEEE Spectrum*, *39*(4), 46–51. https://doi.org/10.1109/6.993788

Hossain, E., Faruque, H., Sunny, Md., Mohammad, N., & Nawar, N. (2020). A Comprehensive Review on Energy Storage Systems: Types, Comparison, Current Scenario, Applications, Barriers, and Potential Solutions, Policies, and Future Prospects. *Energies*, *13*(14), 3651. https://doi.org/10.3390/en13143651

International Energy Agency. (n.d.). About – Task 36 [Intergovernmental Organization]. *About - Task 36*. https://www.eces-a36.org/index.php/about-annex-36/

International Organization for Standardization. (2022). *ISO 14044:2006: Environmental management—Life cycle assessment—Requirements and guidelines*. ISO. https://www.iso.org/standard/38498.html

IPCC. (2023, March 19). *AR6 Synthesis Report* [Intergovernmental Agency]. IPCC. https://www.ipcc.ch/report/ar6/syr/resources/spm-headline-statements

IRENA. (2022). *Energy Profile: Netherlands*. https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Europe/Netherlands_Europe_RE_SP.pdf

Jacob, R., & Liu, M. (2022). Design and Evaluation of a High Temperature Phase Change Material Carnot Battery. *Energies*, *16*(1), 189. https://doi.org/10.3390/en16010189

Joulz. (2023). *Joulz e-DataPortal* [Energy Monitoring Data Portal]. E-DataPortal. https://joulz.e-dataportal.nl/

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022). Sustainable Energy Transition for Renewable and Low Carbon Grid Electricity Generation and Supply. *Frontiers in Energy Research*, *9*, 743114. https://doi.org/10.3389/fenrg.2021.743114

Kim, S., Lee, J. W., Choi, H. W., Lee, G. J., Xu, R., Yoon, S. H., Xu, Z., Wang, R., & Tae Kang, Y. (2022). CO2 capture-driven thermal battery using functionalized solvents for plus energy building application. *Energy Conversion and Management*, *260*, 115606. https://doi.org/10.1016/j.enconman.2022.115606

Klement, M. (n.d.). *Detailed PV System Design* [Online tool]. Dutch PV Portal. https://www.tudelft.nl/?id=59084&L=1

Koohi-Fayegh, S., & Rosen, M. A. (2020). A review of energy storage types, applications and recent developments. *Journal of Energy Storage*, *27*, 101047. https://doi.org/10.1016/j.est.2019.101047

Krishan, O., & Suhag, S. (2019). An updated review of energy storage systems: Classification and applications in distributed generation power systems incorporating renewable energy resources. *International Journal of Energy Research*, *43*(12), 6171–6210. https://doi.org/10.1002/er.4285

Kumar, G. M. S., & Cao, S. (2021). State-of-the-Art Review of Positive Energy Building and Community Systems. *Energies*, *14*(16), 5046. https://doi.org/10.3390/en14165046

Kurşun, B., & Ökten, K. (2022). Comprehensive energy, exergy, and economic analysis of the scenario of supplementing pumped thermal energy storage (PTES) with a concentrated photovoltaic thermal system. *Energy Conversion and Management*, *260*, 115592. https://doi.org/10.1016/j.enconman.2022.115592

LDES. (2023). *LDES - Members* [Global non-profit]. Long Duration Energy Storage Council. https://www.ldescouncil.com/members/

Lee, K.-J., Seo, S.-H., Cho, J., Oh, S.-D., Choi, S.-O., & Kwak, H.-Y. (2022). Exergy and Thermoeconomic Analyses of a Carnot Battery System Comprising an Air Heat Pump and Steam Turbine. *Energies*, *15*(22), 8672. https://doi.org/10.3390/en15228672

LeVan, S. L. (1995). Life Cycle Assessment: Measuring Environmental Impact. *United States Department of Agriculture*. https://www.fpl.fs.usda.gov/documnts/pdf1998/levan98b.pdf?q=life-cycle-assessment-measuring-environmental-impact

Lévesque, B., Lavoie, M., & Joly, J. (2004). Residential Water Heater Temperature: 49 or 60 Degrees Celsius? *Canadian Journal of Infectious Diseases*, *15*(1), 11–12. https://doi.org/10.1155/2004/109051

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 and Sustainable Energy Reviews*, *163*, 112478. https://doi.org/10.1016/j.rser.2022.112478

Liang, T., Webley, P. A., Chen, Y.-C., She, X., Li, Y., & Ding, Y. (2022). The optimal design and operation of a hybrid renewable micro-grid with the decoupled liquid air energy storage. *Journal of Cleaner Production*, *334*, 130189. https://doi.org/10.1016/j.jclepro.2021.130189

Liang, T., Zhang, T., Lin, X., Alessio, T., Legrand, M., He, X., Kildahl, H., Lu, C., Chen, H., Romagnoli, A., Wang, L., He, Q., Li, Y., Yang, L., & Ding, Y. (2023). Liquid air energy storage technology: A comprehensive review of research, development and deployment. *Progress in Energy*, *5*(1), 012002. https://doi.org/10.1088/2516-1083/aca26a

Liang, X., Wang, Y., Royapoor, M., Wu, Q., & Roskilly, T. (2017). Comparison of building performance between Conventional House and Passive House in the UK. *Energy Procedia*, *142*, 1823–1828. https://doi.org/10.1016/j.egypro.2017.12.570

Liu, Q., Arabkoohsar, A., Liu, Y., & He, Z. (2023). Techno-economic analysis of a liquid air energy storage system combined with calcium carbide production and waste heat recovery. *Journal of Energy Storage*, *60*, 106689. https://doi.org/10.1016/j.est.2023.106689

Liu, S., Bai, H., Jiang, P., Xu, Q., & Taghavi, M. (2022). Economic, energy and exergy assessments of a Carnot battery storage system: Comparison between with and without the use of the regenerators. *Journal of Energy Storage*, *50*, 104577. https://doi.org/10.1016/j.est.2022.104577

Mankins, J. C. (1995). Technology Readiness Levels. *NASA - Office of Space Concepts and Technology*. https://aiaa.kavi.com/apps/group_public/download.php/2212/TRLs_MankinsPaper_1995.pdf

Martinek, J., Jorgenson, J., & McTigue, J. D. (2022). On the operational characteristics and economic value of pumped thermal energy storage. *Journal of Energy Storage*, *52*, 105005. https://doi.org/10.1016/j.est.2022.105005

McTigue, J. (2019, December 4). *"Carnot Batteries" for electricity storage*. Yale Blueprint Webinars: The Next Step? NREL and Malta discuss Thermal Energy Storage Solutions, NREL.

McTigue, J. D., Farres-Antunez, P., J, K. S., Markides, C. N., & White, A. J. (2022). Techno-economic analysis of recuperated Joule-Brayton pumped thermal energy storage. *Energy*

Conversion and Management, *252*, 115016. https://doi.org/10.1016/j.enconman.2021.115016

Mitali, J., Dhinakaran, S., & Mohamad, A. A. (2022). Energy storage systems: A review. *Energy Storage and Saving*, *1*(3), 166–216. https://doi.org/10.1016/j.enss.2022.07.002

Mostafa, M. H., Abdel Aleem, S. H. E., Ali, S. G., Ali, Z. M., & Abdelaziz, A. Y. (2020). Techno-economic assessment of energy storage systems using annualized life cycle cost of storage (LCCOS) and levelized cost of energy (LCOE) metrics. *Journal of Energy Storage*, *29*, 101345. https://doi.org/10.1016/j.est.2020.101345

Mostert & Bringezu. (2019). Measuring Product Material Footprint as New Life Cycle Impact Assessment Method: Indicators and Abiotic Characterization Factors. *Resources*, *8*(2), 61. https://doi.org/10.3390/resources8020061

Nadeem, F., Hussain, S. M. S., Tiwari, P. K., Goswami, A. K., & Ustun, T. S. (2019). Comparative Review of Energy Storage Systems, Their Roles, and Impacts on Future Power Systems. *IEEE Access*, *7*, 4555–4585. https://doi.org/10.1109/ACCESS.2018.2888497

Nijhuis, S., & Bobbink, I. (2012). Design-related research in landscape architecture. *J. of Design Research*, *10*(4), 239. https://doi.org/10.1504/JDR.2012.051172

Nilsson, M., Gioia, F., Oggioni, N., Lindquist, T., & Azelio. (2022). *Azelio TES.POD with Combined Heat & Power (CHP) production* (p. 4) [White paper]. Azelio. https://www.azelio.com/wp-content/uploads/2022/11/Azelio_Whitepaper_TESPOD-with-CHP-Production.pdf

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

Oxford Advanced American Dictionary. (2023). Impact. In *Oxford Learner's Dictionaries*. Oxford University Press. https://www.oxfordlearnersdictionaries.com/definition/american_english/impact_1

Palomba, V., & Frazzica, A. (2019). Comparative analysis of thermal energy storage technologies through the definition of suitable key performance indicators. *Energy and Buildings*, *185*, 88–102. https://doi.org/10.1016/j.enbuild.2018.12.019

Park, J. H., Heo, J. Y., & Lee, J. I. (2022). Techno-economic study of nuclear integrated liquid air energy storage system. *Energy Conversion and Management*, *251*, 114937. https://doi.org/10.1016/j.enconman.2021.114937

Paul, A., Holy, F., Textor, M., & Lechner, S. (2022). High temperature sensible thermal energy storage as a crucial element of Carnot Batteries: Overall classification and technical review based on parameters and key figures. *Journal of Energy Storage*, *56*, 106015. https://doi.org/10.1016/j.est.2022.106015

Rahman, M. M., Oni, A. O., Gemechu, E., & Kumar, A. (2020). Assessment of energy storage technologies: A review. *Energy Conversion and Management*, *223*, 113295. https://doi.org/10.1016/j.enconman.2020.113295

Rehman, H. U., & Ala-Juusela, M. (2022). Research-Based Definition of a PEB. In R. Lavikka, H. U. Rehman, F. Reda, & A. S. Kazi (Eds.), *Positive Energy Buildings* (pp. 19–44). Springer International Publishing. https://doi.org/10.1007/978-3-030-87702-6_2

Rijkswaterstaat. (2021). *Nearly Zero Energy Buildings (NZEB)* [Governmental Organization]. https://www.infomil.nl/onderwerpen/integrale/omgevingsloket/@242585/bijna-energieneutrale-gebouwen-beng/

Rindt, K. A. S., Hrdlička, F., & Novotný, V. (2021). *Preliminary prospects of a Carnot-battery based on a supercritical CO2 Brayton cycle* [Preprint]. engrXiv. https://doi.org/10.31224/osf.io/zuct2

RVO. (2020). *The Netherlands: List of fuels and standard CO2 emission factors*. Netherlands Enterprise Agency. https://english.rvo.nl/sites/default/files/2020/03/The-Netherlands-list-of-fuels-version-January-2020.pdf

Sadeghi, G. (2022). Energy storage on demand: Thermal energy storage development, materials, design, and integration challenges. *Energy Storage Materials*, *46*, 192–222. https://doi.org/10.1016/j.ensm.2022.01.017

Scharrer, D., Bazan, P., Pruckner, M., & German, R. (2022). Simulation and analysis of a Carnot Battery consisting of a reversible heat pump/organic Rankine cycle for a domestic application in a community with varying number of houses. *Energy*, *261*, 125166. https://doi.org/10.1016/j.energy.2022.125166

Statista. (2022). *Carbon intensity of the power sector in the Netherlands from 2000 to 2021*. Statista. https://www.statista.com/statistics/1290441/carbon-intensity-power-sector-netherlands/#:~:text=In%202021%2C%20the%20carbon%20intensity,hour%20(gCO%E2%82%82%2FKWh).

Tafone, A., Pili, R., Pihl Andersen, M., & Romagnoli, A. (2023). Dynamic modelling of a compressed heat energy storage (CHEST) system integrated with a cascaded phase change materials thermal energy storage. *Applied Thermal Engineering*, *226*, 120256. https://doi.org/10.1016/j.applthermaleng.2023.120256

Tassenoy, R., Couvreur, K., Beyne, W., De Paepe, M., & Lecompte, S. (2022). Techno-economic assessment of Carnot batteries for load-shifting of solar PV production of an office building. *Renewable Energy*, *199*, 1133–1144. https://doi.org/10.1016/j.renene.2022.09.039

Topalović, Z., Haas, R., Ajanović, A., & Sayer, M. (2023). Prospects of electricity storage. *Renewable Energy and Environmental Sustainability*, *8*, 2. https://doi.org/10.1051/rees/2022016

Trieb, F., Liu, P., & Koll, G. (2022). Thermal Storage Power Plants (TSPP)—Operation modes for flexible renewable power supply. *Journal of Energy Storage*, *50*, 104282. https://doi.org/10.1016/j.est.2022.104282

Uchino, T., Yasui, T., & Fushimi, C. (2023). Biomass power plant integrated with a thermochemical heat storage system using a fluidized bed reactor worked by variable renewable energy: Dynamic simulation, energetic and economic analyses. *Journal of Energy Storage*, *61*, 106720. https://doi.org/10.1016/j.est.2023.106720

UNFCCC. (n.d.). *Key aspects of the Paris Agreement* [Intergovernmental Agency]. Retrieved March 13, 2023, from https://unfccc.int/most-requested/key-aspects-of-the-paris-agreement#:~:text=The%20Paris%20Agreement's%20central%20aim,further%20to%201.5%20degrees%20Celsius.

Vecchi, A., Knobloch, K., Liang, T., Kildahl, H., Sciacovelli, A., Engelbrecht, K., Li, Y., & Ding, Y. (2022). Carnot Battery development: A review on system performance, applications and commercial state-of-the-art. *Journal of Energy Storage*, *55*, 105782. https://doi.org/10.1016/j.est.2022.105782

Vrenne, T., Syverud, E., & Muller, G. (2021). Conceptual modeling of energy storage systems. *INCOSE International Symposium*, *31*(1), 31–46. https://doi.org/10.1002/j.2334-5837.2021.00824.x

Wahlroos, M., Pärssinen, M., Rinne, S., Syri, S., & Manner, J. (2018). Future views on waste heat utilization – Case of data centers in Northern Europe. *Renewable and Sustainable Energy Reviews*, *82*, 1749–1764. https://doi.org/10.1016/j.rser.2017.10.058

Wang, P., Li, Q., Liu, C., Wang, R., Luo, Z., Zou, P., & Wang, S. (2022). Comparative analysis of system performance of thermally integrated pumped thermal energy storage systems based on organic flash cycle and organic Rankine cycle. *Energy Conversion and Management*, *273*, 116416. https://doi.org/10.1016/j.enconman.2022.116416

Weitzer, M., Müller, D., Steger, D., Charalampidis, A., Karellas, S., & Karl, J. (2022). Organic flash cycles in Rankine-based Carnot batteries with large storage temperature spreads. *Energy Conversion and Management*, *255*, 115323. https://doi.org/10.1016/j.enconman.2022.115323

Yu, X., Qiao, H., Yang, B., & Zhang, H. (2023). Thermal-economic and sensitivity analysis of different Rankine-based Carnot battery configurations for energy storage. *Energy Conversion and Management*, *283*, 116959. https://doi.org/10.1016/j.enconman.2023.116959

Zhang, T., She, X., You, Z., Zhao, Y., Fan, H., & Ding, Y. (2022). Cryogenic thermoelectric generation using cold energy from a decoupled liquid air energy storage system for decentralised energy networks. *Applied Energy*, *305*, 117749. https://doi.org/10.1016/j.apenergy.2021.117749

Zhang, Y., Xu, L., Li, J., Zhang, L., & Yuan, Z. (2022). Technical and economic evaluation, comparison and optimization of a Carnot battery with two different layouts. *Journal of Energy Storage*, *55*, 105583. https://doi.org/10.1016/j.est.2022.105583

Zhao, D., Sun, S., & Alavi, H. (2022). Simulation and optimization of a Carnot battery process including a heat pump/organic Rankine cycle with considering the role of the regenerator. *International Journal of Low-Carbon Technologies*, *17*, 870–878. https://doi.org/10.1093/ijlct/ctac057

Appendix A: Table 4.1 Sources

Sources used in Table 4.1 are listed below.

Abarr, M., Geels, B., Hertzberg, J., & Montoya, L. D. (2017). Pumped thermal energy storage and bottoming system part A: Concept and model. *Energy*, *120*, 320–331. https://doi.org/10.1016/j.energy.2016.11.089

Ayachi, F., Tauveron, N., Tartière, T., Colasson, S., & Nguyen, D. (2016). Thermo-Electric Energy Storage involving CO2 transcritical cycles and ground heat storage. *Applied Thermal Engineering*, *108*, 1418–1428. https://doi.org/10.1016/j.applthermaleng.2016.07.063

Benato, A. (2017). Performance and cost evaluation of an innovative Pumped Thermal Electricity Storage power system. *Energy*, *138*, 419–436. https://doi.org/10.1016/j.energy.2017.07.066

Davenne, T. R., & Peters, B. M. (2020). An Analysis of Pumped Thermal Energy Storage With De-coupled Thermal Stores. *Frontiers in Energy Research*, *8*, 160. https://doi.org/10.3389/fenrg.2020.00160

Desrues, T., Ruer, J., Marty, P., & Fourmigué, J. F. (2010). A thermal energy storage process for large scale electric applications. *Applied Thermal Engineering*, *30*(5), 425–432. https://doi.org/10.1016/j.applthermaleng.2009.10.002

Eppinger, B., Steger, D., Regensburger, C., Karl, J., Schlücker, E., & Will, S. (2021). Carnot battery: Simulation and design of a reversible heat pump-organic Rankine cycle pilot plant. *Applied Energy*, *288*, 116650. https://doi.org/10.1016/j.apenergy.2021.116650

Farres-Antunez, P., Xue, H., & White, A. J. (2018). Thermodynamic analysis and optimisation of a combined liquid air and pumped thermal energy storage cycle. *Journal of Energy Storage*, *18*, 90–102. https://doi.org/10.1016/j.est.2018.04.016

Ge, Y. Q., Zhao, Y., & Zhao, C. Y. (2021). Transient simulation and thermodynamic analysis of pumped thermal electricity storage based on packed-bed latent heat/cold stores. *Renewable Energy*, *174*, 939–951. https://doi.org/10.1016/j.renene.2021.04.094

Georgiou, S., Shah, N., & Markides, C. N. (2018). A thermo-economic analysis and comparison of pumped-thermal and liquid-air electricity storage systems. *Applied Energy*, *226*, 1119–1133. https://doi.org/10.1016/j.apenergy.2018.04.128

Guo, L., Gao, Z., Ji, W., Xu, H., Chen, L., & Wang, J. (2020). Thermodynamics and Economics of Different Asymmetric Cold Energy Transfer in a Liquid Air Energy Storage System. *Energy Technology*, *8*(5), 1901487. https://doi.org/10.1002/ente.201901487

Hamdy, S., Morosuk, T., & Tsatsaronis, G. (2019). Exergoeconomic optimization of an adiabatic cryogenics-based energy storage system. *Energy*, *183*, 812–824. https://doi.org/10.1016/j.energy.2019.06.176

Howes, J. (2012). Concept and Development of a Pumped Heat Electricity Storage Device. *Proceedings of the IEEE*, *100*(2), 493–503. https://doi.org/10.1109/JPROC.2011.2174529

Jockenhöfer, H., Steinmann, W.-D., & Bauer, D. (2018). Detailed numerical investigation of a pumped thermal energy storage with low temperature heat integration. *Energy*, *145*, 665–676. https://doi.org/10.1016/j.energy.2017.12.087

Kim, Y.-M., Shin, D.-G., Lee, S.-Y., & Favrat, D. (2013). Isothermal transcritical CO2 cycles with TES (thermal energy storage) for electricity storage. *Energy*, *49*, 484–501. https://doi.org/10.1016/j.energy.2012.09.057

König-Haagen, A., Höhlein, S., & Brüggemann, D. (2020). Detailed exergetic analysis of a packed bed thermal energy storage unit in combination with an Organic Rankine Cycle. *Applied Thermal Engineering*, *165*, 114583. https://doi.org/10.1016/j.applthermaleng.2019.114583

Legrand, M., Rodríguez-Antón, L. M., Martinez-Arevalo, C., & Gutiérrez-Martín, F. (2019). Integration of liquid air energy storage into the spanish power grid. *Energy*, *187*, 115965. https://doi.org/10.1016/j.energy.2019.115965

McTigue, J. D., White, A. J., & Markides, C. N. (2015). Parametric studies and optimisation of pumped thermal electricity storage. *Applied Energy*, *137*, 800–811. https://doi.org/10.1016/j.apenergy.2014.08.039

McTigue, J., Farres-Antunez, P., Ellingwood, K., Neises, T., & White, A. (2020). *Pumped thermal electricity storage with supercritical CO2 cycles and solar heat input*. 190024. https://doi.org/10.1063/5.0032337

Mercangöz, M., Hemrle, J., Kaufmann, L., Z'Graggen, A., & Ohler, C. (2012). Electrothermal energy storage with transcritical CO 2 cycles. *Energy*, *45*(1), 407–415. https://doi.org/10.1016/j.energy.2012.03.013

Meroueh, L., & Chen, G. (2020). Thermal energy storage radiatively coupled to a supercritical Rankine cycle for electric grid support. *Renewable Energy*, *145*, 604–621. https://doi.org/10.1016/j.renene.2019.06.036

Morandin, M., Mercangöz, M., Hemrle, J., Maréchal, F., & Favrat, D. (2013). Thermoeconomic design optimization of a thermo-electric energy storage system based on transcritical CO2 cycles. *Energy*, *58*, 571–587. https://doi.org/10.1016/j.energy.2013.05.038

Morgan, R., Nelmes, S., Gibson, E., & Brett, G. (2015). An analysis of a large-scale liquid air energy storage system. *Proceedings of the Institution of Civil Engineers - Energy*, *168*(2), 135–144. https://doi.org/10.1680/ener.14.00038

Peng, X., She, X., Cong, L., Zhang, T., Li, C., Li, Y., Wang, L., Tong, L., & Ding, Y. (2018). Thermodynamic study on the effect of cold and heat recovery on performance of liquid air energy storage. *Applied Energy*, *221*, 86–99. https://doi.org/10.1016/j.apenergy.2018.03.151

Schneider, G., Maier, H., Häcker, J., & Siegele, S. (2021). *Electricity Storage With a Solid Bed High Temperature Thermal Energy Storage System (HTTES)—A Methodical Approach to Improve the Pumped Thermal Grid Storage Concept:* 14th International Renewable Energy Storage Conference 2020 (IRES 2020), Bonn, Germany. https://doi.org/10.2991/ahe.k.210202.005

Sciacovelli, A., Vecchi, A., & Ding, Y. (2017). Liquid air energy storage (LAES) with packed bed cold thermal storage – From component to system level performance through dynamic modelling. *Applied Energy*, *190*, 84–98. https://doi.org/10.1016/j.apenergy.2016.12.118

She, X., Peng, X., Nie, B., Leng, G., Zhang, X., Weng, L., Tong, L., Zheng, L., Wang, L., & Ding, Y. (2017). Enhancement of round trip efficiency of liquid air energy storage through effective utilization of heat of compression. *Applied Energy*, *206*, 1632–1642. https://doi.org/10.1016/j.apenergy.2017.09.102

Wang, L., Lin, X., Zhang, H., Peng, L., & Chen, H. (2021). Brayton-cycle-based pumped heat electricity storage with innovative operation mode of thermal energy storage array. *Applied Energy*, *291*, 116821. https://doi.org/10.1016/j.apenergy.2021.116821

Wu, S., Zhou, C., Doroodchi, E., & Moghtaderi, B. (2020). Techno-economic analysis of an integrated liquid air and thermochemical energy storage system. *Energy Conversion and Management*, *205*, 112341. https://doi.org/10.1016/j.enconman.2019.112341

Xu, M., Zhao, P., Huo, Y., Han, J., Wang, J., & Dai, Y. (2020). Thermodynamic analysis of a novel liquid carbon dioxide energy storage system and comparison to a liquid air energy storage system. *Journal of Cleaner Production*, *242*, 118437. https://doi.org/10.1016/j.jclepro.2019.118437

Zhang, H., Wang, L., Lin, X., & Chen, H. (2020). Combined cooling, heating, and power generation performance of pumped thermal electricity storage system based on Brayton cycle. *Applied Energy*, *278*, 115607. https://doi.org/10.1016/j.apenergy.2020.115607

Zhang, Y., Yang, K., Hong, H., Zhong, X., & Xu, J. (2016). Thermodynamic analysis of a novel energy storage system with carbon dioxide as working fluid. *Renewable Energy*, *99*, 682–697. https://doi.org/10.1016/j.renene.2016.07.048

Zhao, Y., Liu, M., Song, J., Wang, C., Yan, J., & Markides, C. N. (2021). Advanced exergy analysis of a Joule-Brayton pumped thermal electricity storage system with liquid-phase storage. *Energy Conversion and Management*, *231*, 113867. https://doi.org/10.1016/j.enconman.2021.113867

Appendix B: Interviews

	Function/Affiliation	**Date**	**Comments**
Interviewee 1 (Sweden)	Systems and Research Engineer – Azelio	April 20th, 2023	Employee at one of the leading companies manufacturing turnkey Carnot battery systems
Interviewee 2 (Belgium)	Thermodynamics expert, Aerospace and Mechanical Engineering Department – University of Liège	April 28th, 2023	One of the top published Carnot battery researchers
Interviewee 3 (Chicago, U.S.)	Electrical Engineer—Energy Storage and Microgrid professional	May 3rd, 2023	10+ years of diverse electrical engineering experience on small-to-large scales, including ESS, nuclear power plant systems, data center power architecture, grid, and micro-grid services
Interviewee 4 (Washington D.C., U.S.)	Senior Energy Storage Engineer—NAT Energy LLC, Former Application Engineer for GKN Hydrogen	May 8th, 2023	10+ years of experience in energy sector in Germany and United States
Interviewee 5 (United Kingdom)	Technical Director for PassivHaus/Energy Efficient Home Building Company	May 16th, 2023	15+ years in data analysis and building sector
Interviewee 6 (Mumbai, India)	Green Building Consultant with expertise in net zero buildings and energy simulations	May 25th, 2023	10+ years of experience in U.S. and India as building scientist, educator, and consultant

Appendix C: Electricity Rates

Table X. Calculated energy prices by source from data from CBS Statistics Netherlands (2023).

Energy Prices
*for year 2022

Month	**Gas price (€/m^3)**	**Gas price (€/kWh)**	**Electricity Price (€/kWh)**
June	1.7679	0.1768	0.4124
December	2.3154	0.2315	0.5905